

# Hybrid Analysis of Tool Geometry and Process Noise in Fine Blanking Through Simulation and Experiment

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**Abstract.** In fine blanking, a mass production process for safety-critical components, a discrepancy exists between deterministic modeling approaches and the stochastic nature of real-world measurements, often termed process noise. This work combines Finite Element Method simulations with data from industrial-scale fine blanking experiments, featuring long stroke series across multiple coils with systematically varied die clearances. The analysis shows a strong correlation between force curve characteristics and the formation of tears, a relationship that holds across all tested geometries. In contrast, only weak and inconsistent correlations were found between the force signal and the resulting die roll. This weakness is explained by the finding that multiple physical effects, such as material strength and friction, have competing influences on die roll that are not separable in the single force signal. These results demonstrate that the utility of the force signal for quality prediction is highly dependent on the tool geometry, providing a basis for more reliable tool design strategies in fine blanking.

## Introduction

In the domain of sheet metal processing, fine blanking stands out as a highly productive precision shearing process that enables the economical manufacture of sheet metal parts with strict quality requirements. It is characterized by three independently acting process forces: blank holder, counter, and blanking force, along with a small die clearance and a chamfered shearing edge on a die, which collectively contribute to the formation of compressive stresses and controlled material flow [1]. However, in industrial practice, addressing stochastic process fluctuations, referred to as process noise [2], remains a significant challenge, as its underlying causalities from a complex interplay of material variations, tool wear, and thermomechanical drift are difficult to disentangle from macroscopic process signals.

The inability of Finite Element Method (FEM) simulations to capture this real-world process noise highlights the need for a more data-driven, hybrid approach. While simulations offer valuable insights into the mechanical behavior of materials under idealized conditions, the simplifying assumptions and abstractions inherent to the method fundamentally limit their ability to capture the real-world variability that occurs during manufacturing. These unpredictable factors show as deviations between simulated and measured behaviors, which can significantly impact the quality and consistency of the final product. Rather than being treated as errors, these deviations can be systematically analyzed in research as a source of information on unmodeled physical phenomena.

Several studies have demonstrated the potential of data-driven signal analysis in fine blanking. For example, works by Baer et al. [3] and Unterberg et al. [4] have explored the mechanical punch loads and used force signals for wear monitoring, respectively, highlighting the importance of real-time data in understanding the process. However, a systematic investigation into how key tool design

parameters, such as die clearance and chamfer geometry, influence the stochastic characteristics of the punch force signal in large stroke series (several coils) itself remains largely unexplored.

This paper contributes to the methodological discourse by presenting a hybrid analysis framework that interrogates the deviations between FEM simulations and experimental data. The methodology is centered on a systematic comparison of simulated and measured force curves resulting from variations in die clearance for a long stroke series (1 coil per parameter). The key contribution is therefore a framework for analyzing how tool geometry modulates the characteristics of the process noise, and how this modulation affects the signal's ability to predict distinct types of quality metrics, namely large-scale geometric features (die roll) and localized defects (tears).

The paper is structured as follows: Section 2 reviews the state of the art regarding the sources and impact of process noise in fine blanking. Section 3 details the integrated methodology, encompassing the experimental approach, the data analysis methods, and the setup of the numerical model. Section 4 presents and discusses the results from the hybrid analysis, establishing the link between tool geometry, process signatures, and final part quality. Finally, Section 5 concludes the work and outlines directions for future research.

### **State of the Art - Sources and Impact of Process Noise in Fine Blanking**

In forming and sheet metal separation processes, such as fine blanking, the interactions between the sheet metal material and tool active elements are influenced by unavoidable process noise. Process noise in fine blanking can be attributed to several key factors, including material inhomogeneities, machine behavior, tool wear, reaching steady-state process heating, and environmental factors. The methodological approach proposed in this work focuses on understanding and the explainability of causalities of process noise, aiming to identify and analyze the underlying factors that drive these variations.

Material inhomogeneities along the length of a fine blanked coil, such as variations in thickness, mechanical strength, and microstructure, are a source of real-world stochastic variations in process outcomes. While certain material-related effects, such as non-metallic inclusions affecting ductility and increasing susceptibility to tearing, are known, these microstructural variations and their precise impacts are not yet incorporated into current simulation models [2]. These inhomogeneities, often caused by fluctuations in the rolling process or variations in heat treatment of sheet metal strip, lead to inconsistent blanking forces and sheared surface quality [5, 1]. For example, variations in material properties can cause locally uneven stress distribution during the shearing process, resulting in defects such as tears. Tool wear introduces a slow shift in process conditions, which can be difficult to detect and compensate for in real-time [3, 8]. For example, worn tools may require higher blanking forces, leading to increased loads on the machine and potential defects like burr or tears in the final product. Thermal expansion of the tool due to process heating during a stroke series can alter the die clearance, leading to variations in part quality [9, 2]. Additionally, fluctuations in the ambient temperature can affect the material properties, further increasing process instability.

The impact of process noise on fine blanking is multifaceted. Variations in sheared surface quality, such as inconsistent smoothness and flatness, are direct consequences of process noise [5]. Furthermore, process noise can destabilize the fine blanking process, leading to higher reject rates and thus reduced production efficiency [6].

### **Methodology**

**Experimental setup.** The experimental setup was designed to systematically investigate the effects of tool design parameters on the fine blanking process under conditions reflective of industrial mass production. The machine setup consisted of a state-of-the-art fine blanking line, centered around a

Feintool XFT 2500 Speed press equipped with a servomechanical main drive system. The line included a decoiler and a leveler, as depicted in Fig. 1, as well as an automatic lubrication system.

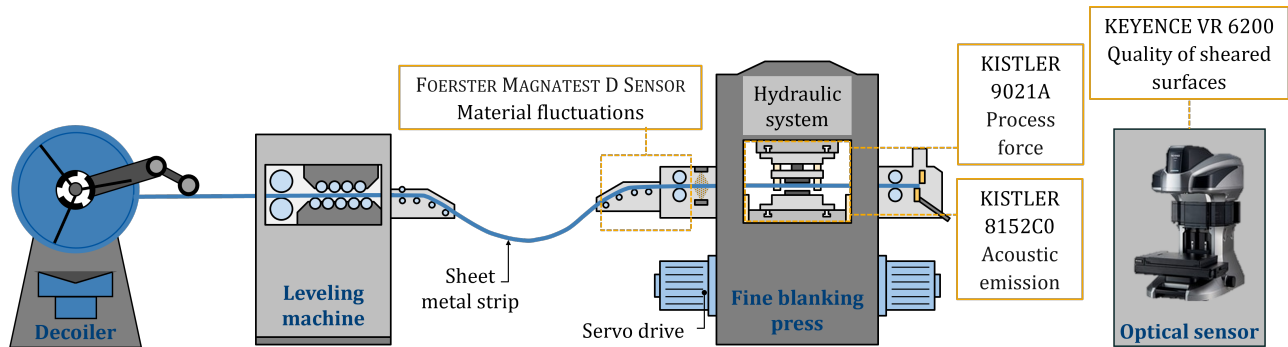


Fig. 1: Schematic of the fine blanking line used for data acquisition.

The sheet metal material used was cold rolled 58CrV4+AC (DIN EN material number 1.8161), a high-carbon steel known for its challenging shearing properties. This material was chosen for its industrial relevance and its ability to produce high-quality sheared surfaces under optimal conditions. The experiments utilized cold rolled strips with a thickness ( $s$ ) of 6, representative of industrial applications. The material was supplied in an annealed state (+AC) to achieve spheroidized carbides. A custom single-cavity fine blanking tool was utilized. The tooling components, including the punch, die, guide, and counter punch, were manufactured from tool steels (Böhler S390 and X155CrVMo12-1). The sheared part geometry was designed to produce a component with different difficulties, featuring varied radii and angles analogous to the functional features of gear teeth, as shown in Fig. 2.

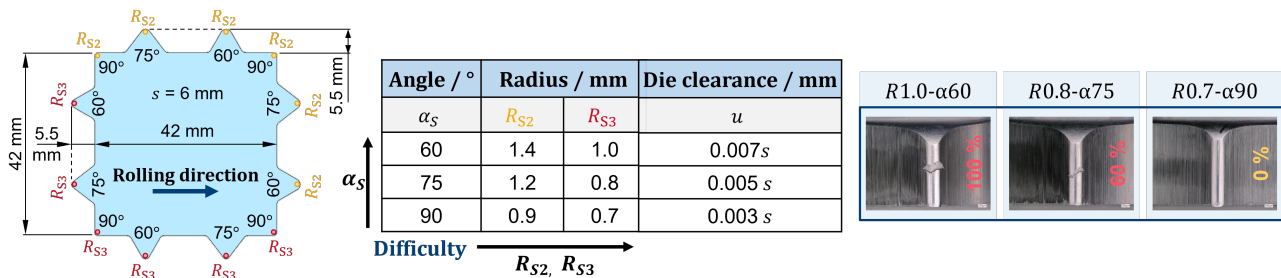


Fig. 2: Schematic representation of a fine blanking part with the tool design parameter variations.

To systematically generate a dataset encompassing a wide range of process states, a variation of the die clearance ( $u$ ) was conducted to evaluate its impact on blanking forces and part quality. Three distinct die clearance levels were investigated, as detailed in Table 1. For each of the three die clearances, a new blanking punch was installed to minimize the influence of tool wear on the process results. Each die clearance parameter was run across two separate sub-coils, which correspond to the total length of the cold rolling process. This resulted in a total of six processed sub-coils and approximately 16,200 strokes for a comprehensive evaluation.

**Data acquisition and quality evaluation.** To create a digital representation of the process, the fine blanking tool was equipped with sensors to measure blanking forces and tool displacement. Piezo-electric force sensors (Kistler 9041A and 9021A) were used to measure the punch and counter forces, providing insights into the load distribution and material resistance. The force and displacement signals were sampled at a frequency of 20 to capture the detailed dynamics of the fine blanking process. The tool displacement was measured using a laser triangulation sensor (Micro-Epsilon optoNCDT 1900).

The quality of the sheared parts was evaluated using a 3D optical profilometer (KEYENCE VR-6200). Key quality metrics included the clean-shear area, die roll height, and the presence of tears,

Table 1: Overview of the experiments. Three distinct die clearance levels were investigated, with each die clearance run on two separate sub-coils.

Description	Sub-Coil ID	Die Clearance [mm]	Chamfer Angle [deg]	Chamfer Height [mm]
Ref	R1C6	0.03	35	0.5
	R1C3	0.03	35	0.5
U040	R1C2	0.04	35	0.5
	R1C5	0.04	35	0.5
U020	R1C1	0.02	35	0.5
	R1C4	0.02	35	0.5

<sup>1</sup>Each of the three die clearances was initiated with a new blanking punch.

tear-off, or burr. The analysis in this work focuses on two of these metrics: tear formation and die roll height. Samples were taken at regular intervals (every 200 strokes) for quality analysis.

For the analysis of tear formation, a sample of 20 consecutive parts was collected. Each part was visually inspected, and the total number of tears across twelve predefined corners was recorded. To quantify the die roll height, a systematic sampling strategy was employed. From each collected sample, the 1st, 6th, 11th, and 16th parts were selected. The profiles of three specific corners on these parts (corresponding to workpiece angles of 60, 75, and 90) were digitized. The die roll height was then determined algorithmically for each corner individually. This comprehensive dataset forms the basis for the subsequent analysis.

**Feature extraction from force signals.** To quantitatively analyze the stroke-to-stroke variations in the force signals and to establish a basis for correlation with part quality, a set of physically meaningful features was extracted from each individual blanking force curve. The selection of these features was guided by their ability to represent distinct phases and characteristics of the shearing process, as visualized in Fig. 3. The primary extracted features are detailed below and summarized in Table 2.

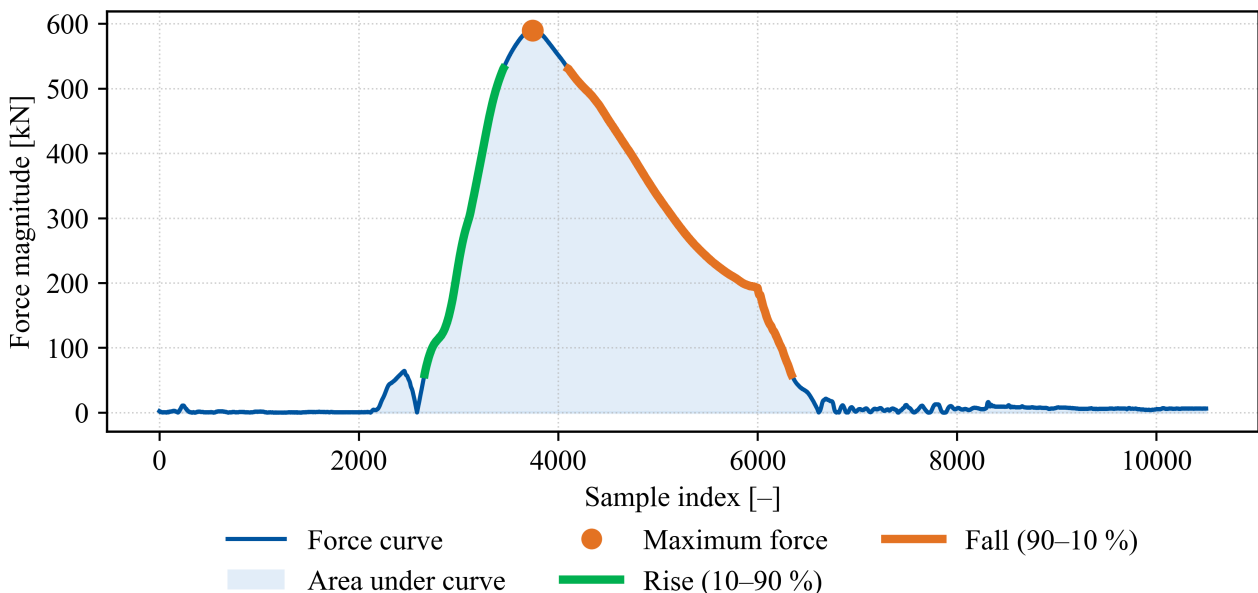


Fig. 3: Visualization of the key features extracted from a blanking force curve.

- **Maximum force (*max\_force*):** This feature represents the peak blanking force. It serves as a primary indicator of the material's resistance to deformation and is known to be highly sensitive to variations in material properties and tool condition [3].

- **Relative position of maximum force (*idx\_max\_rel*):** This feature is the normalized index at which the maximum force occurs, ranging from 0 to 1. It provides a standardized measure of the timing of the peak force, allowing for the comparison of strokes with different lengths. Shifts in this value can indicate changes in the onset of fracture or variations in the elastic-plastic transition due to factors like tool wear or lubrication state [8].
- **Area under force curve (*area\_force*):** This feature is the integral of the force curve, representing the total mechanical work required to blank the part. As an indicator of the total energy dissipated, it is highly informative for tracking long-term process drifts [8] that may be caused by changes in material flow stress, friction, or tool condition.
- **Rise slope (*rise\_slope*):** This feature quantifies the slope of the force curve on the rising portion, calculated between 10% and 90% of the maximum force. It characterizes the initial elastic-plastic response of the material and is sensitive to tool sharpness and the resulting stress concentrations [10].
- **Fall slope (*fall\_slope*):** This feature quantifies the slope of the force curve's descending portion after the peak force has been reached, calculated between 90% and 10% of the maximum force. It characterizes the plastic flow as well as the fracture behavior of the material. A steep, negative slope typically indicates a more abrupt fracture, whereas a shallower slope suggests a more ductile shearing process [11].

Table 2: Summary of extracted force curve features and their physical significance.

Feature	Description	Primary Physical Significance
<i>max_force</i>	Peak value of the force curve	Material resistance, hardness, friction [3]
<i>idx_max_rel</i>	Normalized position of the peak force	Timing of fracture initiation [8]
<i>area_force</i>	Integral of the force curve	Blanking work, shearing energy [8]
<i>rise_slope</i>	Slope of the initial rising force	Elastic-plastic material response [10]
<i>fall_slope</i>	Slope of the descending force after peak	Fracture behavior (brittle vs. ductile) [11]

**Numerical modeling.** To provide a physics-based interpretation of the data-driven findings, a Finite Element (FE) model was developed, replicating the experimental geometry and boundary conditions. The modeling approach was adapted from the framework for fine blanking simulation presented by Schweinshaupt et al. [12] and implemented in the commercial software Forge NxT 4.1. The primary purpose of the model is to serve as a tool for a sensitivity analysis designed to decompose and understand the deterministic components of process noise. By systematically varying key physical input parameters, such as the material's flow curve and friction coefficients, the model is used to investigate how these changes deterministically influence the shape of the simulated force curve. These simulated force signatures are then used to explain the physical origins of the correlations observed between the experimental force features and the measured part quality.

To ensure computational tractability, a quarter model was implemented to approximate a geometric symmetry of the component. All active tool components and the workpiece were discretized using 3D tetrahedral elements. Following a mesh convergence analysis, the workpiece in the immediate shear zone was meshed with a minimum edge length of 0.35. The tool components were modeled as elastic

bodies, the physical and thermophysical parameters used for die and blanking punch (Böhler S390) as well as blank holder and counter punch (cold work tool steel X155CrVMo12-1 or 1.2379), and all specific mechanical and thermophysical parameters for both the tool and workpiece materials were adapted directly from the validated simulation framework presented by Schweinshaupt et al. [12], where they are detailed in full.

The sheet metal material was modeled using a thermoviscoplastic material law with an integrated remeshing algorithm to handle the large deformations inherent to the process. While the model is thermomechanically coupled, the analysis in this work focuses on the mechanical results at a constant initial temperature of 20. The material's flow stress was described by the Hensel-Spittel constitutive law [13]. As the experimental material was 58CrV4+AC, and a validated model for this specific steel was not available, the parameters for the chemically similar steel 51CrV4 in a soft annealed state were sourced. The constitutive model describes the true stress ( $\sigma_f$ ) as a function of temperature ( $\theta$ ), true strain ( $\varphi$ ), and strain rate ( $\dot{\varphi}$ ) according to Eq. (1):

$$\sigma_f(\theta, \varphi, \dot{\varphi}) = A \cdot e^{m_1 \theta} \cdot \varphi^{m_2} \cdot e^{m_4 / \varphi} \cdot \dot{\varphi}^{m_3} \quad (1)$$

The specific coefficients used in the simulation are detailed in Table 3. Material separation was governed by the normalized Cockcroft-Latham ductile fracture criterion, modified by Oh et al. [14], with a critical threshold value of  $C_{crit} = 1.44$  as determined by Wai Myint et al. [15]. Frictional conditions at the tool-workpiece interface were described using a hybrid law combining a Coulomb model ( $\mu = 0.1$ ) with a shear friction limit ( $m = 0.2$ ).

Table 3: Coefficients for the Hensel-Spittel flow curve model for 51CrV4 (soft annealed state) [16].

$A$	$m_1$	$m_2$	$m_3$	$m_4$
997.51	-0.00080	0.17008	0.01324	-0.00818

To investigate the sensitivity of the force signal to key physical parameters and to provide a basis for interpreting the experimental findings, a systematic parameter variation study was conducted. A reference simulation was established using the parameters of the *Ref* experimental configuration (see Table 1). Subsequently, a series of simulations was performed where individual parameters were varied while all others were held at their reference values. The variations, detailed in Table 4, were chosen to represent plausible sources of process noise. Specifically, the flow curve was scaled by  $\pm 10\%$  to simulate the effect of material property fluctuations inherent in sheet metal coils, while friction and temperature were varied to assess their influence on the process mechanics.

Table 4: Parameters varied in the FEM sensitivity analysis.

Parameter	Low	Reference	High
Factor of flow curve coefficient A [-]	0.9 (897.76)	1.0 (997.51)	1.1 (1097.26)
Friction $\mu$ [-] / $m$ [-]	0.05 / 0.1	0.1 / 0.2	0.2 / 0.3
Tool Temperature [°C]	–	20	50

## Results and Discussion

This section presents the results of the hybrid analysis. The analysis is structured in three parts. First, the experimental process data is analyzed to characterize both the deterministic and stochastic components of the blanking force signal. Second, these signal characteristics are correlated with the measured part quality metrics to establish data-driven process-quality linkages. Finally, the experimental findings are compared with results from the FEM parameter study to provide a physics-based interpretation of the observed phenomena.

**Characterization of experimental process signatures.** To characterize the evolution of the process signatures, the experimental data was binned into stroke index ranges. For each bin, the mean and standard deviation of the key process and quality metrics were calculated to visualize their temporal trends and variability.

Fig. 4 presents the evolution of the mean maximum blanking force for the three die clearance configurations. The plot reveals a clear deterministic influence of the tool design, with the *Ref* (0.03 mm) and *U040* (0.04 mm) geometries consistently requiring a higher blanking force than the *U020* (0.02 mm) geometry. Furthermore, a temporal drift is evident across all configurations, where the mean force increases over the first  $\sim 1500$  strokes before stabilizing. This trend can be attributed to long-term phenomena such as the thermal equalization of the tool-press system [17]. The error bars, representing the standard deviation within each bin, quantify the magnitude of the process noise, showing the stochastic variability around the mean trend.

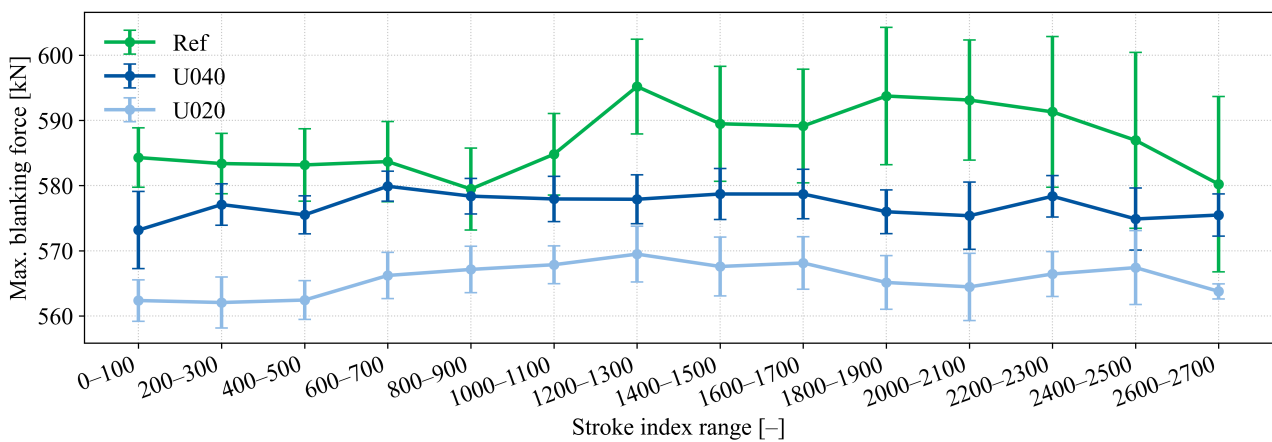


Fig. 4: Evolution of the mean maximum blanking force for each die clearance configuration. The points represent the mean value within each bin, and the error bars indicate  $\pm$  one standard deviation.

The resulting distributions of the two primary quality metrics, die roll and tear count, were then analyzed. Fig. 5 summarizes the die roll height for the three different corner angles across all measured strokes. A clear, non-linear relationship with die clearance is visible. The *U020* geometry consistently produced the smallest die roll, while the *U040* geometry produced the largest. This is physically consistent with the understanding that a larger clearance allows for more extensive plastic flow before fracture, resulting in a larger radius of curvature at the die edge [18]. The individual data points overlaid on the boxes visualize the stochastic variability inherent to each configuration.

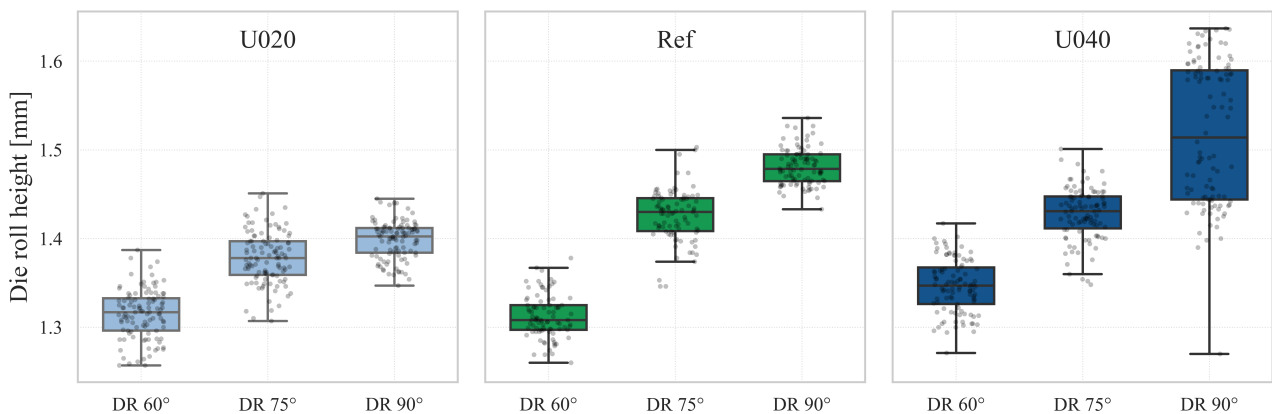


Fig. 5: Distribution of die roll height for each tool geometry at the three measured corner angles.

A similar analysis was performed for the total tear count, with the results presented in the boxplot in Fig. 6. The evolution of tear count reveals a strong, non-linear relationship with die clearance. The *U020* geometry, with the smallest die clearance, consistently produced the lowest number of tears, suggesting it represents an optimal parameter set for this material. In contrast, the *U040* geometry, with the largest die clearance, exhibited a significantly higher tear count. This is physically consistent with the understanding that an excessive die clearance can induce high tensile stresses as the material is pulled over the die edge, promoting crack initiation and a larger fracture zone [18]. Conversely, a die clearance that is too small can lead to high stress concentrations [1]. The *U020* configuration appears to achieve the optimal balance between these two competing failure mechanisms.

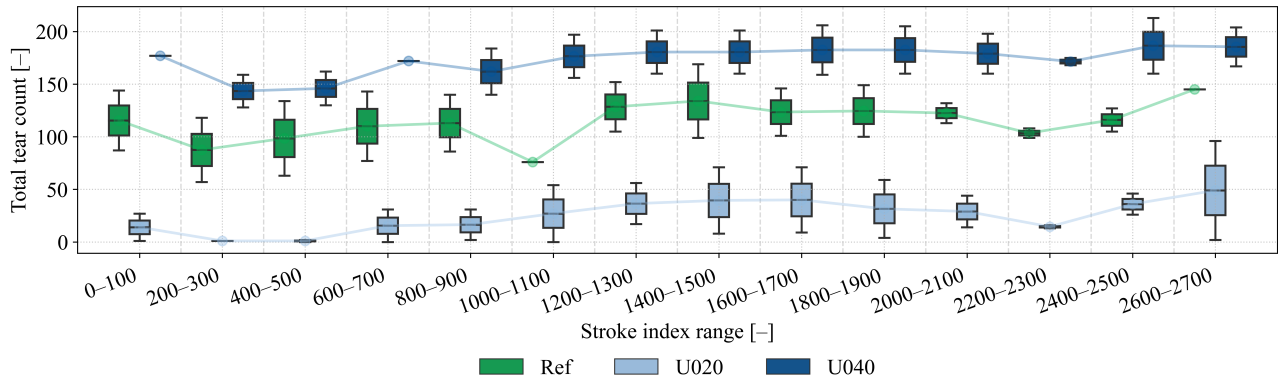


Fig. 6: Evolution of the total tear count distribution for each die clearance configuration. The box represents the interquartile range (IQR), the line inside is the median, and the whiskers show the data range. The connected line represents the evolution of the mean value.

**Correlation of process signatures with part quality.** To quantify the relationship between force curve characteristics and sheared part quality, a correlation analysis was performed, first on the aggregated dataset and subsequently on each experimental condition individually.

The die roll is a geometric feature formed by the plastic flow of material at clean-shear. The overall correlation analysis, combining all die clearance configurations, is presented in Fig. 7. The heatmap reveals only weak to moderate positive correlations between force magnitude features (*max\_force*, *area\_force*) and the die roll. This suggests that when all process conditions are aggregated, a clear linear relationship is not apparent.

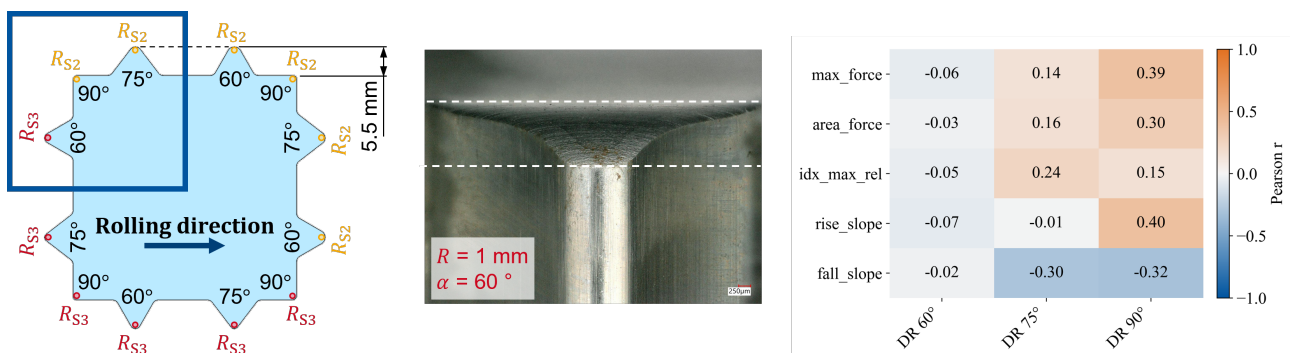


Fig. 7: Die roll as a quality metric: the three corners selected for analysis (left), an example of die roll on a sheared surface (center), and the overall correlation matrix between force features and die roll height at these corners (right).

However, a geometry-specific analysis (Fig. 8) reveals that the weak overall correlation is primarily driven by a single, specific process condition. A notable correlation only emerges for the *U040*

configuration at the 90° corner, where force magnitude features show a moderate positive correlation with die roll ( $r = 0.41$ ). For all other configurations and corners, the correlations are weak to non-existent.

This localized correlation can be explained by examining the die roll distributions (Fig. 5). The *U040* geometry at the 90° corner exhibits not only the largest absolute die roll but also the highest variability. A linear correlation can only be reliably detected when there is sufficient variation in the data; the lower variability of the other configurations may be insufficient to reveal an underlying relationship. The observed positive correlation in this specific high-variability case is physically consistent with established principles: a larger die clearance allows for more extensive plastic flow, which requires more blanking work (*area\_force*) and results in a larger die roll [1]. Given that this analysis is based on only three of the twelve component corners, however, drawing a definitive conclusion about a universal relationship is not yet possible.

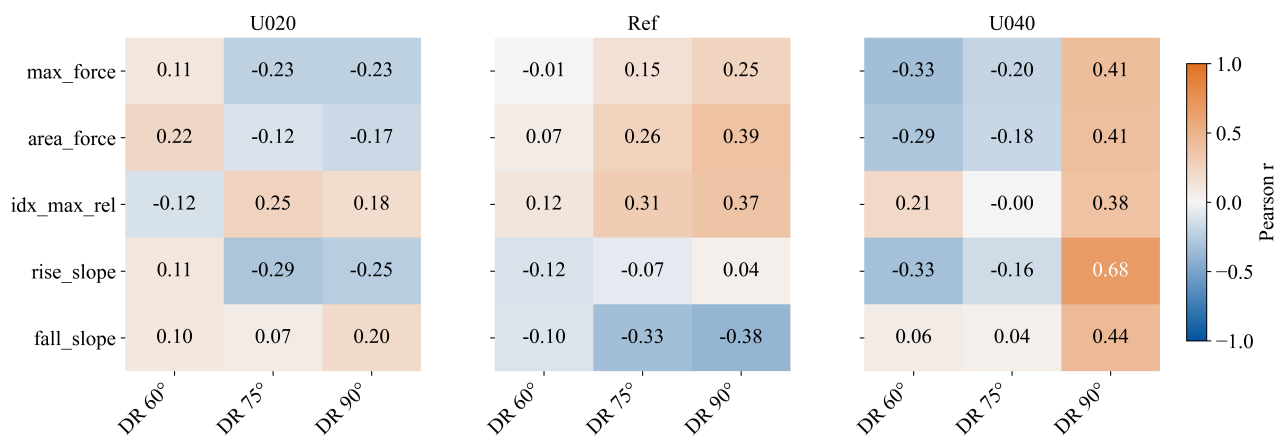


Fig. 8: Geometry-dependent correlation matrices between force features and die roll for each die clearance configuration.

A similar analysis was performed for tear count, a localized defect shown in Fig. 9 (left). The overall correlation analysis (Fig. 9 (right)) is again misleading, showing a very strong negative correlation for *idx\_max\_rel* ( $r = -0.11$ ) that is a statistical artifact that arises from combining experiments where the underlying physical mechanics are fundamentally different.

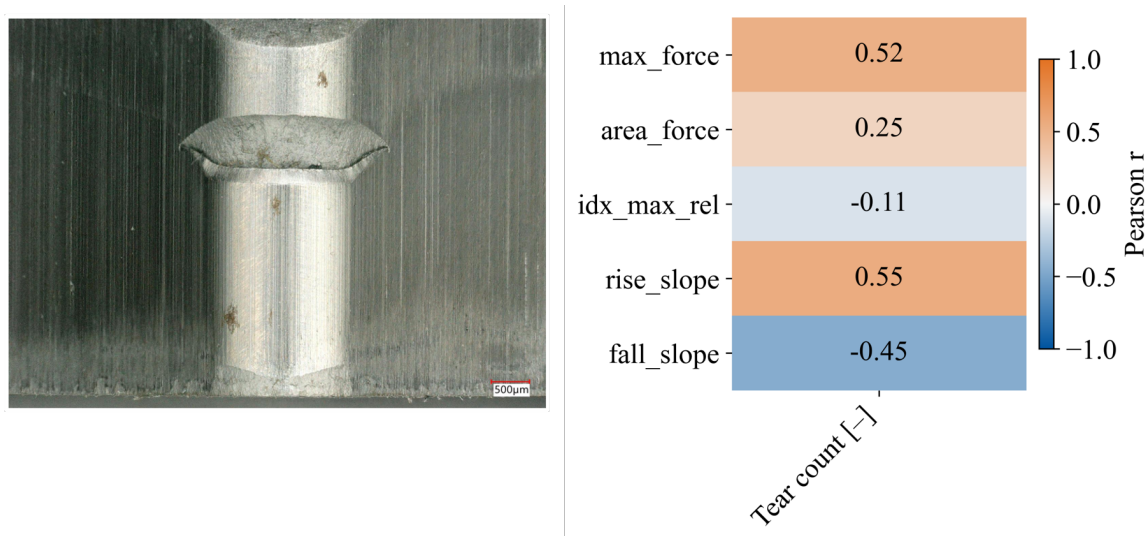


Fig. 9: Example of a tear on a sheared surface (left) and the overall correlation matrix between force features and tear count across all experiments (right).

The geometry-specific analysis in Fig. 10 reveals the true underlying trend. A consistent positive correlation is exhibited by the *rise\_slope* across all three die clearance configurations, suggesting that a more rapid initial loading rate is a key driver of the micro-fracture events, a finding consistent with studies on damage evolution in shearing [19]. However, it is only within the stable, fracture-dominated regime of the *U020* configuration that other force features, such as *idx\_max\_rel* ( $r = -0.87$ ), also become strong predictors. This is a critical finding: it demonstrates that while certain force characteristics have a consistent relationship with defects, the overall predictive utility of the force signal is maximized when the process is operating in a stable regime as dictated by the tool geometry. The physical origins of these complex, geometry-dependent relationships will be investigated in the subsequent chapter.

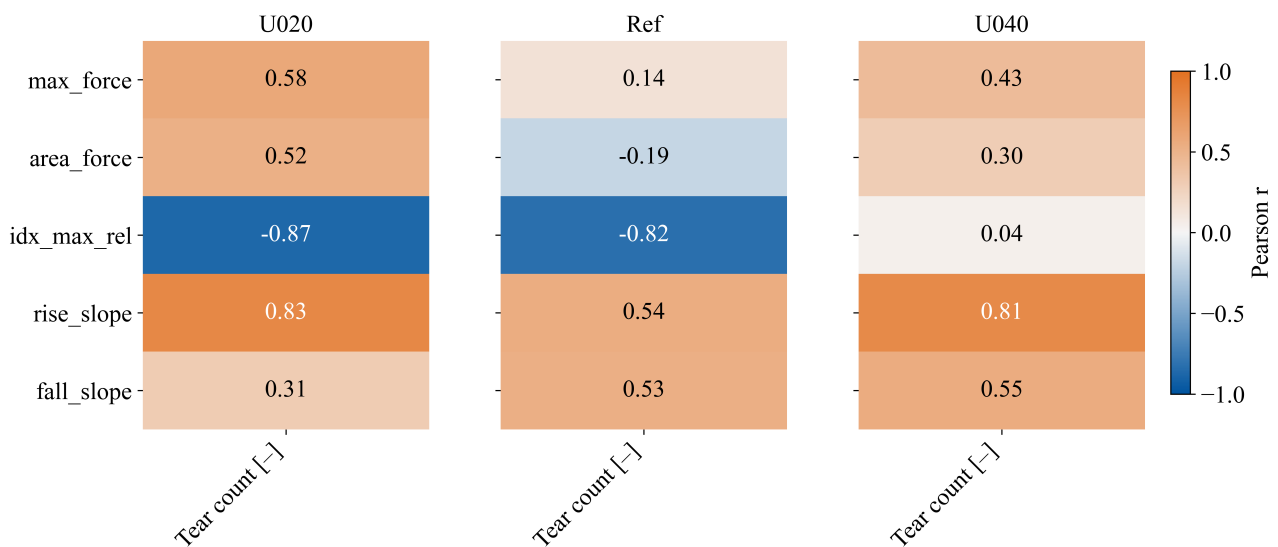


Fig. 10: Geometry-dependent correlation matrices between force features and tear count for each die clearance configuration.

**Hybrid analysis: simulation-based interpretation.** To provide a physics-based interpretation for the experimentally observed phenomena, the results from the FE model were compared with the experimental data.

The first step of the hybrid analysis is the validation of the reference FE model. The simulated force-displacement curve from the reference configuration was compared to the mean experimental force curve (see Fig. 3) from the corresponding *Ref* experiments. The model demonstrates a good overall agreement, with the simulated maximum force showing a relative deviation of only 3.92% compared to the mean experimental value.

However, discrepancies in the curve shape are apparent. The simulated curve exhibits a steeper elastic rise and a more pronounced drop after the peak force. These differences can be attributed to factors not fully captured in the idealized simulation, most notably the elastic compliance of the press frame and tool system, which is known to affect the force progression in real-world blanking operations [20]. Despite these deviations, the close agreement in peak force confirms that the model serves as a valid baseline for the subsequent sensitivity analysis.

The validated model was then used to conduct the parameter sensitivity study to explain the complex, geometry-dependent correlations found in the experimental data. Fig. 11 presents the simulated blanking force curves for each parameter variation. The analysis demonstrates that variations in the material's flow stress have a global and dominant effect on the magnitude of the force curve. In contrast, parameters like friction primarily influence the shape of the curve during the fracture phase. The effect of an elevated initial tool temperature is shown to be minimal, resulting in only a minor,

localized force reduction at the peak. This indicates that under the simulated conditions, a moderate increase in the tool's starting temperature does not significantly alter the overall process mechanics.

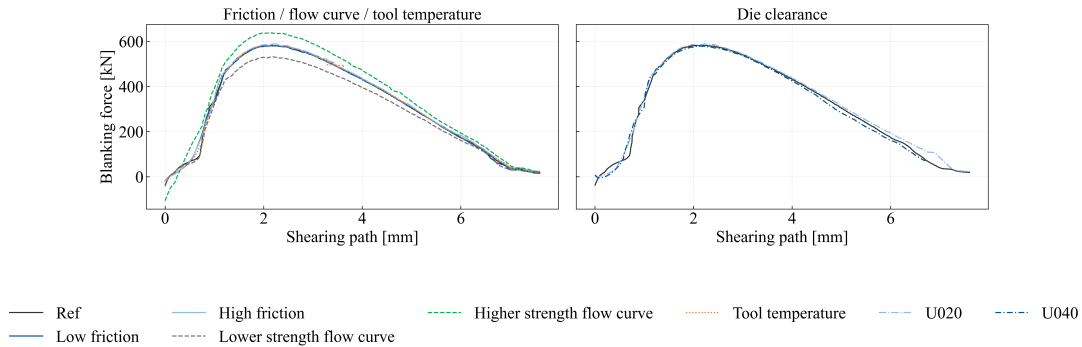


Fig. 11: Results of the FEM parameter sensitivity study.

These simulated signatures provide a direct physical basis for interpreting the experimental correlations. The experimental analysis revealed that the *rise\_slope* was a robust predictor of tear count across all die clearances. The simulation results in Fig. 11 explain this by confirming that the *rise\_slope* is a direct indicator of the material's initial resistance to deformation (the flow curve). A steeper *rise\_slope* signifies a more rapid pressure buildup at the shearing zone. This rapid loading can lead to higher local stress concentrations, which accelerate the initiation of micro-fractures at material inhomogeneities, thereby increasing the likelihood of tear formation [19].

Conversely, the experimental analysis for die roll did not reveal any clear, universal predictor, with the correlations being generally weak. The simulation provides a direct physical explanation for this weakness by revealing conflicting physical mechanisms. An analysis of the simulated die roll shows that a higher material strength flow curve leads to a higher *max\_force* but a smaller die roll (0.9 mm vs. 1.5 mm for the lower strength case). This confirms the foundational principle that a stronger material exhibits lower formability [1]. This creates a conflict: an increase in *max\_force* due to higher material strength would suggest a negative correlation with die roll. However, other process variations, such as an increase in friction, could also increase the *max\_force* while potentially increasing the die roll. Since the macroscopic force signal is an integrated measurement that is unable to distinguish between these opposing effects, it is an inherently unreliable predictor for die roll.

A further observation concerns the thermomechanical component of process noise. The *U040* configuration did not show the expected decrease in average blanking force relative to *Ref*, despite the larger die clearance. This can be attributed to competing thermal effects: while a larger clearance reduces shearing resistance, the associated increase in plastic deformation volume generates more heat, leading to thermal softening of the workpiece material [20]. These thermomechanical couplings, which accumulate over a long stroke series, are not captured by the single-stroke FE model used in this study.

The hybrid analysis therefore, leads to a key takeaway: the measurable process signature is not a universal sensor. The force signal is a robust predictor of localized defects (tears) because this quality metric is strongly linked to a single, dominant feature (*rise\_slope*). In contrast, the signal is an unreliable predictor of large-scale geometric features (die roll) because the final die roll is the result of multiple, competing physical phenomena (such as material strength and friction), which have opposing effects and cannot be distinguished from the single, integrated force signal.

## Summary and Outlook

This study presented a hybrid analysis framework to decompose and understand process noise in fine blanking by systematically interrogating the deviations between experimental data and numerical simulations. The primary objective was to investigate how tool geometry, specifically die clearance, modulates the information content of the macroscopic force signal and its ability to predict distinct quality metrics.

The experimental analysis revealed a complex, geometry-dependent relationship between process signatures and sheared part quality. For large-scale geometric features like die roll, the correlations were found to be generally weak and inconsistent, indicating that the force signal is an unreliable predictor for this metric. A likely reason for this weak correlation is the comparison of a global force signal, integrated over all twelve corners, with local die roll measurements taken from only three of those corners. In contrast, the analysis for localized defects like tears yielded a more nuanced and significant finding. A consistent trend was identified for the rising force during the shearing progress *rise\_slope*, which exhibited a positive correlation with tear count across all three die clearance configurations.

One finding remained unexplained within the current framework: the reference die clearance with 0.03 mm (*Ref*) required a higher average blanking force than the smaller die clearance with 0.02 mm (*U020*). This finding contradicts the general physical expectation that a smaller die clearance should increase shearing resistance, a relationship that has previously been studied primarily for single strokes. This discrepancy points to the influence of unmodeled sources of process noise, potentially arising from minor manufacturing deviations in the tool components or slight misalignments between the punch and die, which are known to have a significant impact on measured process mechanics [21].

Future investigations should aim to bridge this fundamental gap between single-stroke simulation and industrial stroke-series reality. This would require the development of more sophisticated thermomechanical FE models capable of accounting for the cumulative heat transfer and thermal stabilization over thousands of cycles, which remains a significant computational challenge. Such a model, validated by the integration of high-resolution temperature measurements, would allow for a direct investigation of the thermal softening effects hypothesized in this work. Second, a systematic study incorporating controlled variations in tool alignment and manufacturing tolerances could be conducted to quantify their contribution to the observed process noise. Finally, these findings form a crucial groundwork for the development of more advanced, physics-informed machine learning models, where the insights into the geometry-dependent nature of process information can be used to create more robust and explainable tool design strategies [2].

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