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Workpiece-Based Signatures for Machine Diagnostics in Die Forging with Flash

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Abstract. In forging, parallelism deviations between upper and lower dies lead to asymmetric flash formation and affect forming forces, die filling, and part integrity. The flash gap influences local flow resistance and is closely linked to flow behavior and dimensional precision. Conventional diagnostics often assess such deviations under no-load or quasi-static conditions and therefore may not capture the effective closing state at bottom dead centre (BDC) under process load. While modern approaches such as high-resolution optical tracking of ram deflection can provide valuable insight, they require dedicated and sensitive instrumentation and are often limited in scalability. In contrast, workpiece-based signatures inherently reflect process effects such as elastic deflections, guide clearances, frictional conditions, and thermal influences. This study investigates whether workpiece-related geometric features can serve as diagnostic signatures for detecting and quantifying closing-gap inclinations under load. The focus is on the locally resolved flash thickness, which reflects the effective closing gap at BDC. Because this gap results from both geometric alignment and load-dependent deformation, the evaluation targets the final load-bearing state. Comparative forging trials are performed on a press equipped with active parallelism control, where controlled misalignments are introduced. The resulting flash geometry is measured by laser triangulation to determine the resolution limit and to identify the deviation magnitude at which reproducible signatures can be detected under process-relevant conditions. In the investigated setup, flash-thickness asymmetry shows an increasing trend from closing-gap inclinations of ~0.25°, providing a markedly higher diagnostic sensitivity than the maximum forming force. Designed as a non-invasive and retrofit-capable method, the approach supports inline monitoring in high-volume forging. It further enables scalable, data-driven correlation of machine, process, and product data for condition-aware process optimization.

Introduction

In closed-die forging (according to German standard DIN 8583-4), the workpiece material is formed between contoured die halves, and excess material flows out along the flash land area in the parting plane [1]. The dimensioning of the flash gap determines the local flow resistance and influences die filling, forming forces, and component quality [2, 3]. Spatial variations of the gap height in the parting plane can be attributed to different causes, including ram tilting due to guiding clearance, misalignment of the die halves, eccentric billet positioning, or deviations in billet placement [4]. In addition, parallelism errors arise from frame or tool deflection [5, 6] as well as thermal gradients during operation [7]. In industrial practice, forming tools are typically mounted in a floating arrangement or via adjustable guides and wedge connections. Small guiding or mounting clearances further promote wedge-shaped variations in the closing gap and direction-dependent pressure fields. On the product side, such conditions manifest as direction-dependent variation of the flash thickness and as mismatch along the parting plane, which results in an uneven formation of the flash surfaces and may reduce dimensional accuracy and impair trimming robustness [8]. On the machine side, guides with adjustable clearance passively ensure parallelism by transmitting transverse forces into the frame and limiting tilting moments [9]. The friction conditions and the guiding principle (hydrodynamic sliding guides or rolling-element guides) govern stiffness, damping, and drive forces. Modern hydraulic and servo presses complement this by active parallelism control based on multi-point position measurement and electrohydraulic proportional valves or multi-axis drives, which compensate tilting even under asymmetric loading [10].

Despite constructive and control-related measures, deviations from parallelism during operation cannot be completely avoided. In a study by Ziemba et al. on a 13 MN mechanical crank press with a column-guided slide, it was demonstrated that the geometry of the forged part can act as an indirect sensor for the machine geometry under load [4]. Using 3D scanning, systematic mismatch and twist signatures along the parting plane were detected, while static inspections of the press and tooling did not reveal abnormalities. The findings were attributed to small lateral displacements and elastic torsion of the upper tooling system at BDC. After readjustment of guides and wedge connections, these deviations were significantly reduced [4]. This confirms that product-side features reflect parallelism and alignment errors under process load.

Spatially resolved flash-thickness measurements provide a product-side signature of the effective closing gap at BDC and thus a reference metric for die parallelism. Since press closing behavior is load-dependent, early stroke phases are influenced by clearance take-up, whereas the final state at BDC is dominated by elastic deflection [11]. Accordingly, the present study evaluates flash-thickness asymmetry in the final load-bearing state at BDC and relates it to the corresponding peak forming force.

In direct contrast to the workpiece-based signature, Alimov et al. [12] and Martinitz et al. [5] address machine diagnostics via a contactless, machine-side measurement chain. The work of Alimov et al. aims at a direct acquisition of the press kinematics in closed-die forging using high-frequency radar sensors. In this way, ram tilting and frame elongation can be quantified with stroke resolution and related to eccentric billet positioning, but the approach requires dedicated on-machine sensor integration and calibration, is less easily retrofittable and scalable across different press types, and does not directly provide information on the resulting workpiece geometry and product quality.

The present work pursues a complementary approach by interpreting product-side geometric features as a process-integrated signature of the closing gap at the BDC. Although an imposed inclination is expected to induce asymmetric flash, the contribution of this work is the validated quantification of detectability under production-like scatter, i.e., establishing a reproducible reference dataset and estimating resolution limits for process-accompanying flash-based signatures. This validation step supports subsequent attribution of observed anomalies (e.g., force deviations) to geometric closing-gap changes rather than to uncontrolled variability. Given the practical limits imposed by metrology resolution and part-to-part scatter, the central hypothesis is that it is sufficiently sensitive to detect systematic, process-relevant deviations in die alignment under load. Accordingly, the study addresses three central questions: (i) whether locally resolved flash thickness can be used as a quantitative signature of closing-gap inclination, (ii) which minimum misalignment can be reliably distinguished from process-related scatter given the limits of laser-based metrology, and (iii) how the diagnostic sensitivity of this signature compares with conventional global indicators such as the maximum forming force. Instead of directly measuring the kinematics, the deviations that actually occur under load are evaluated as they are imprinted in the part geometry, inherently accounting for process-specific influences such as friction, temperature distributions, and guiding conditions. The method is non-invasive and transferable to existing production lines, enabling inline-capable condition assessment.

Rather than introducing another machine-side sensing modality, this paper establishes a geometry–centred diagnostic criterion and its practical operating range for detecting closing-gap inclinations under load.

The emphasis is placed on reproducible distinguishability from baseline scatter by combining a parallel reference series, controlled tooling-side perturbations, and quantified metrology limits. In this way, the approach provides a compact, experimentally grounded basis for deciding when flash-derived indicators can be used for condition assessment and when additional instrumentation or extended datasets are required.

Materials and Methods

To investigate the suitability of locally resolved flash thickness as a workpiece-based signature of the closing-gap parallelism, comparative experiments were carried out on a servomotor-driven screw press (Synchropress 4M-6000, maximum force 6 MN). The ram is driven via four spindles and guided along four columns, with active parallelism control implemented by continuously measuring and readjusting the positions of all four spindles. The control system enables reproducible stroke positions in the range of tens of micrometers [13]. A deliberate setpoint specification for non-parallel ram positions is not provided in the control. All trials were performed in stroke-controlled operation with a fixed BDC stroke setpoint. The imposed tooling-side inclinations are considered the primary source of closing-gap asymmetry in this study. For readability, the overall experimental and evaluation workflow is summarized below before the individual steps are described in the following.

1. Adjustment of closing-gap inclination using feeler gauges.
2. Forging under defined conditions (fixed BDC setpoint; $n = 10$ per setting).
3. Acquisition of force data (press-internal signal and external strain-gauge force measurement).
4. Acquisition of workpiece geometry (laser triangulation in the cooled state).
5. Quantification of flash thickness and flash area.
6. Referencing to BDC and statistical comparison across settings (mean ± 95% CI).

Defined deviations from parallelism were introduced on the tooling side by inserting feeler-gauge strip steel beneath the lower die, as schematically illustrated in Fig. 1. The strip steel was positioned at approximately two-thirds of the die diameter, such that the transition edge between the raised and the planar contact area was located at distances of 35 mm and 70 mm from the respective opposite sides of the die, based on a total diameter of 105 mm. Different strip thicknesses were used to generate variations in the closing gap, as listed in Table 1. The closing-gap angles α were estimated from geometry as $\alpha \approx \arctan(s/l)$ with $l = 70$ mm and are reported as nominal setpoint labels. The analysis is based on relative changes across configurations rather than an absolute metrological determination of α. Effects from elastic flattening of the strip and tooling, local contact compliance and positioning tolerances may alter the effective inclination, but they are expected to act as second-order influences within the investigated range and do not affect the intended ranking of the imposed configurations. Consequently, Table 1 lists nominal inclination angles for documentation and comparability of the settings.

To attribute observed changes in flash geometry and peak force primarily to the imposed tooling-side inclination rather than uncontrolled part-to-part variability, the experiments were designed with (i) active parallelism control and a fixed BDC stroke setpoint, (ii) a parallel reference series as baseline variability, (iii) recorded transfer time between furnace and forming to capture thermal-loss scatter, and (iv) two independent force acquisition chains (press-internal signal and external tooling-integrated load cell) to cross-check trend consistency and to separate systematic measurement-chain offsets from process effects.

In all experiments, the inclination was introduced on one side only and was reproducibly adjusted on the same side of the forging die. The orientation of the die in the press was documented to ensure an unambiguous assignment of the flash geometry to the position of the inclination.

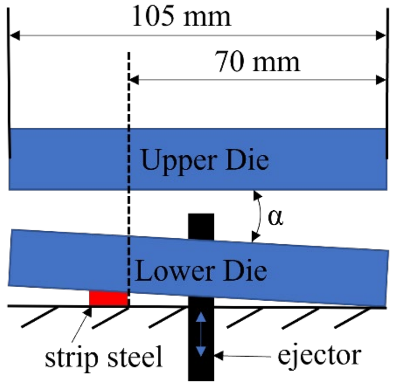

Fig. 1. Schematic of the tooling-side introduction of defined deviations from parallelism: feeler-gauge strip steel is inserted beneath the lower die at approximately two-thirds of the die diameter, ejector position is indicated for reference.

Table 1. Investigated closing-gap angles (approximate values).

thickness of strip steel in mm	closing-gap angle α in ° (approx.)
-	0
0.05	0.04
0.1	0.08
0.3	0.25
0.5	0.41
0.95	0.78
1	0.82

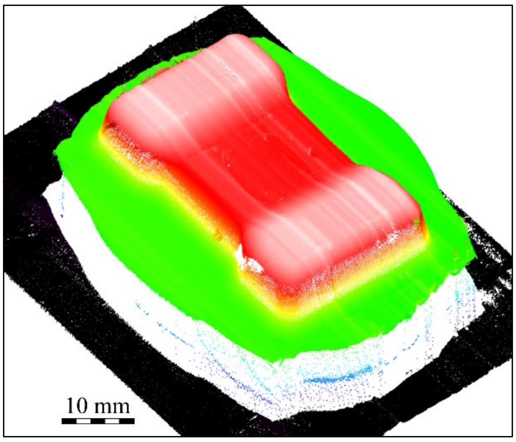

Fig. 2. Exemplary laser scan of a forged component (red) with flash land (green) on the measurement area (black); colors indicate the measured distance to the laser sensor only.

The components, exemplarily shown in Fig. 2, were formed from aluminum billets (EN AW-6082) at a temperature of 550 °C and were characterized in the cooled state. For this purpose, a line laser sensor is moved across the parts using a motorized linear axis. The measurement procedure and method for flash characterization have been validated in previous work [3, 14]. As described in [3], flash thickness was determined from profile cross-sections extracted from the measured 3D geometry. For each part, one cross-section was taken normal to the flash land on each of the two opposite sides that were compared, corresponding to the early-closing and late-closing sides. The reference plane was given by the measurement setup, using the planar surface of the measuring station on which the part was placed. In each cross-section, a line was fitted to the flash-land segment within a predefined evaluation window, and flash thickness was defined as the perpendicular distance of this fitted line to the reference plane. The flash land area was determined from the top-view representation by identifying the flash perimeter and evaluating the enclosed planar area. The laser sensor (Micro-Epsilon LLT 010-100/BL) provides an accuracy of 0.05 mm at a resolution of 2,048 points over a 100 mm measuring field [14].

For each closing-gap setting, ten parts were forged. The maximum forming force was recorded in two ways, via the press-internal force signal provided by the Synchropress control system and via an external strain-gauge-based load cell (LC) integrated in the tooling stack. Both signals were used to compare trends. Differences in absolute level can arise from measurement location or load path and signal processing as well as calibration and temperature-dependent drift of strain-gauge-based chains. The press closing behavior is load-dependent. At the beginning of the stroke, guide and bearing clearances are taken up, which can induce noticeable changes in ram angle even at low loads [11]. With increasing load, the response becomes dominated by elastic deflection and can be approximated as quasi-linear with respect to load moment. Therefore, all comparisons are referenced to BDC, using the peak forming force and the resulting flash geometry as indicators of the final load-bearing state after the guidance has settled. Before forming, the dies were lubricated with graphite spray. The forging operation was carried out at a ram speed of 150 mm/s. The primary metric for evaluation is the directionally resolved asymmetry of flash thickness, which is used to quantify how sensitively the signature responds to small, defined deviations and whether it can be reliably detected over a forging series.

Results and Discussion

Forming force as a macroscopic process response.

The maximum forming force, measured via load cell (LC) in the tooling stack, shows an overall increasing tendency with closing-gap inclination and is also reported in the literature as a key parameter for the design of energy-efficient and tool-friendly forging processes [15]. At the same time, peak force is a global indicator that integrates multiple influences (e.g. temperature, friction and filling), so that small alignment-related effects may remain obscured by part-to-part scatter.

Fig. 3 shows the evolution of the measured maximum forming forces as a function of the closing-gap angle. The error bars show 95% confidence intervals of the mean (n = 10). Between the parallel configuration and a small inclination of 0.04°, a slight decrease in the mean maximum forming force can be observed. However, due to the small absolute difference (approximately 30 kN), this deviation can be explained by process-related scatter. For inclinations up to 0.08°, the mean values remain at a comparable level between 445 and 470 kN and the corresponding 95% confidence intervals still overlap. Thus, inclinations up to about 0.08° lie within the range of process-induced variability and cannot be clearly detected via the maximum forming force with the present sample size.

From a closing-gap angle of 0.25° onwards, an increase in the mean maximum forming force becomes apparent. Nevertheless, the 95% confidence intervals of the 0°, 0.08° and 0.25° settings still mutually overlap, so that a misalignment of 0.25° cannot yet be identified with statistical certainty based on the maximum force alone. Only for larger inclinations of 0.41° and above do the mean values clearly exceed the force level of the nearly parallel configurations and the corresponding intervals separate, indicating a reliably detectable influence of closing-gap inclination on the force evolution. At 0.41°, mean peak forces of around 530 kN are reached, while inclinations of 0.78° and 0.82° result in values of approximately 650–670 kN. It should be noted that the maximum forming force represents an integral response influenced by multiple concurrent effects (e.g. contact conditions, frictional state, thermal boundary conditions). Therefore, the force trends are interpreted here primarily in terms of detectability of the imposed inclination rather than as a basis for a unique mechanistic attribution. Since active parallelism control minimizes ram tilting, the observed force differences are consistent with the imposed tooling-side inclination as the dominant systematic perturbation.

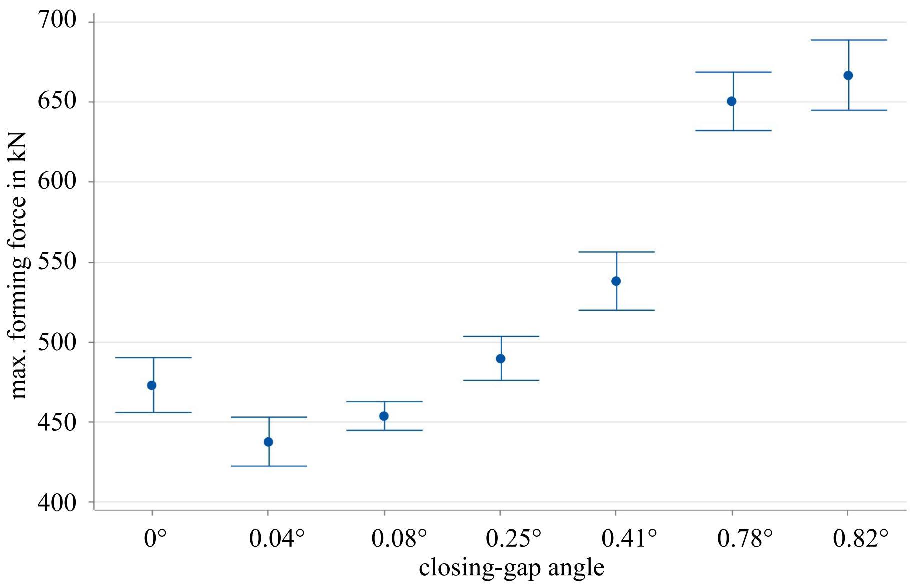

Fig. 3. Maximum forming forces at different closing-gap angles, error bars indicate 95% confidence intervals of the mean (n = 10, t-distribution).

Peak forces obtained from the press system (Synchro) and from the external force measurement via load cell (LC) in the tooling show an almost perfectly linear relationship (Pearson r ≈ 0.998, n = 70), as shown in Fig. 4, confirming consistent trend detection across both acquisition chains. The LC values are systematically lower, and the deviation increases with force level (mean LC/Synchro ≈ 0.84), indicating a proportional measurement-chain bias rather than a change in process behavior. This systematic offset is likely due to differences in measurement location/load path and signal conditioning, as well as calibration or temperature effects in the strain-gauge chains. Therefore, the inclination effects are discussed based on relative trends, while absolute force levels depend on the selected measurement chain. In addition, within the investigated range, transfer time did not show a statistically significant association with peak force or flash metrics when accounting for closing-gap angle.

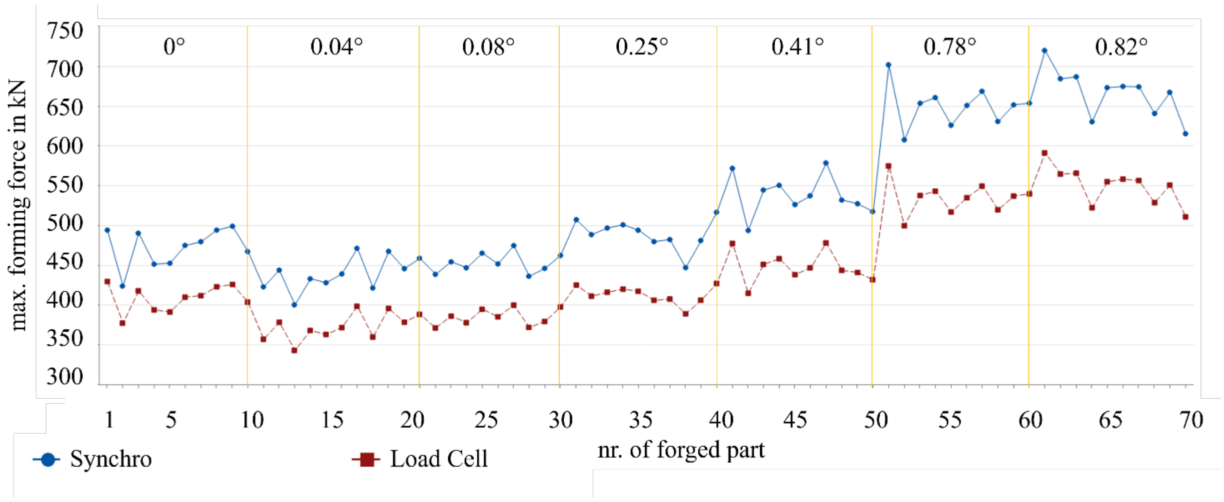

Fig. 4. Maximum forming force per forged part (n = 70) recorded by the press control system (Synchro) and by the external tooling-integrated load cell (LC).

Flash thickness as a workpiece-based signature of closing-gap inclination.

Figure 5 shows the difference in flash thickness between the early-closing and late-closing sides as a function of the closing-gap angle. Compared to the forming force, the flash-thickness difference is markedly more sensitive to closing-gap deviations. At 0.25° it increases by ~55% relative to 0°, whereas the maximum forming force rises by only ~3.5%, i.e. within its measurement noise. In the parallel configuration, a mean flash-thickness difference of ~0.15 - 0.20 mm is observed, which is attributed to measurement- and process-related influences, like optical acquisition, non-uniform cooling after ejection, and local variations in lubricant deposition. Accordingly, for small inclinations (≤0.08°) the 95% confidence intervals overlap with the parallel case, so no statistically separable increase beyond baseline variability can be demonstrated. At 0.25°, a systematic trend becomes visible but should be interpreted as an onset rather than a sharp detection threshold, since confidence intervals still partly overlap. At larger angles (0.41° - 0.82°), the flash-thickness difference increases by ~150 - 340% in total, while the forming force rises by ~14 - 41%, and the confidence intervals separate more clearly, indicating a robust inclination effect. Reference [3] discusses flash thickness as a quality-related feature, mainly with respect to geometric consistency along the parting plane and trimming robustness. In the present study, the early-to-late flash-thickness difference is used primarily as a diagnostic signature for effective closing-gap inclination at BDC; no independent product-quality validation is included in the present dataset. Mechanistically, the early-closing side experiences higher local compression and promotes radial material displacement into the flash land, while material flow on the opposite side starts with a delay, producing a characteristic flash-thickness asymmetry that reflects the effective tool inclination at BDC.

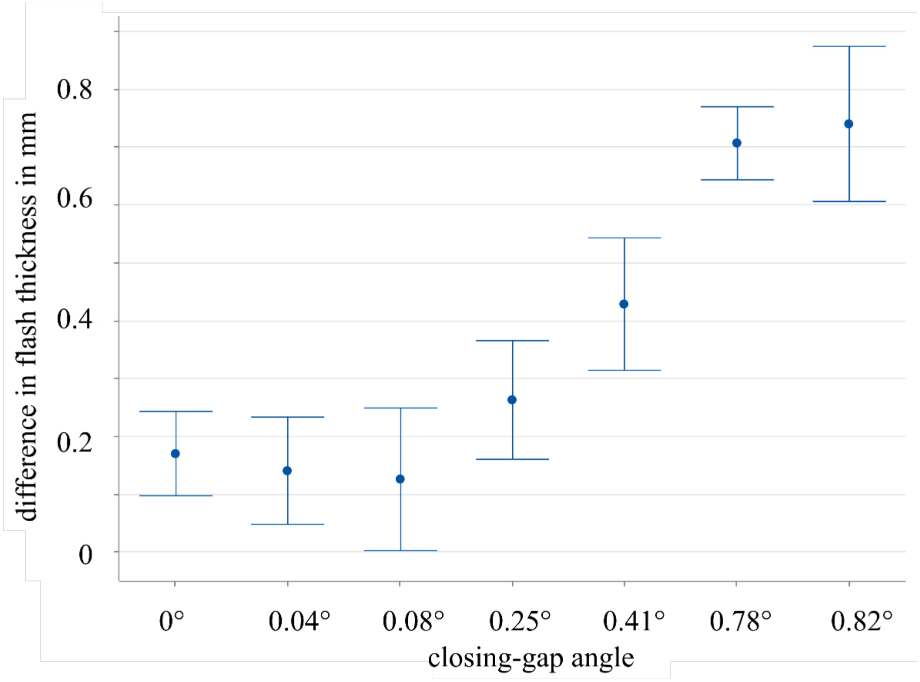

Fig. 5. Difference in flash thickness caused by closing-gap inclination (opposing flash thicknesses), error bars indicate 95% confidence intervals of the mean (n = 10, t-distribution).

Flash area as a complementary global metric.

In addition to the locally resolved flash-thickness asymmetry, the total flash area was evaluated as a global indicator of flash formation. Across the investigated closing-gap angles, the mean flash area shows no consistent trend at small inclinations and increases more clearly from about 0.25° onward, as shown in Fig. 6. Compared with the flash-thickness difference shown in Fig. 5, the flash area exhibits higher variability, as indicated by wider confidence intervals. The observed changes are attributed to modified material flow during the closing phase. Earlier contact on the inclined side increases local constraint and promotes an asymmetric redistribution of material within the flash region, which is consistent with the simultaneously observed local flash-thickness asymmetry. Figure 6 further shows opposing trends in flash area and mean flash thickness, indicating that increasing inclination primarily reflects redistribution and spreading of flash material rather than a substantial change in the overall flash fraction. A nearly constant global flash fraction does not necessarily imply unchanged component quality or identical die filling, because local flow restrictions and the resulting asymmetry can still influence local filling and surface characteristics. Consequently, flash area serves as a plausibility and consistency metric for global changes in flash formation under misalignment, but is less sensitive than flash-thickness asymmetry for detecting small inclinations.

Conclusion and Future Perspectives

The presented investigations quantify, under controlled conditions, how defined closing-gap inclinations affect both macroscopic and workpiece-based responses in die forging with flash. Within the investigated setup, the maximum forming force does not exhibit a robust, monotonic response in the small-angle range (≤0.08°). One intermediate setting (0.04°) yields a lower mean force than the parallel case, while 0.08° overlaps with 0°, indicating that minor deviations in die parallelism cannot be inferred reliably from this global measure alone. In contrast, the directionally resolved flash thickness difference exhibits a markedly higher diagnostic sensitivity. It increases systematically with closing-gap angle, with the onset of a discernible trend from approximately 0.25° and a clearly more distinct separation from the small-angle configurations from about 0.41° onwards, while the relative change in maximum force remains significantly smaller.

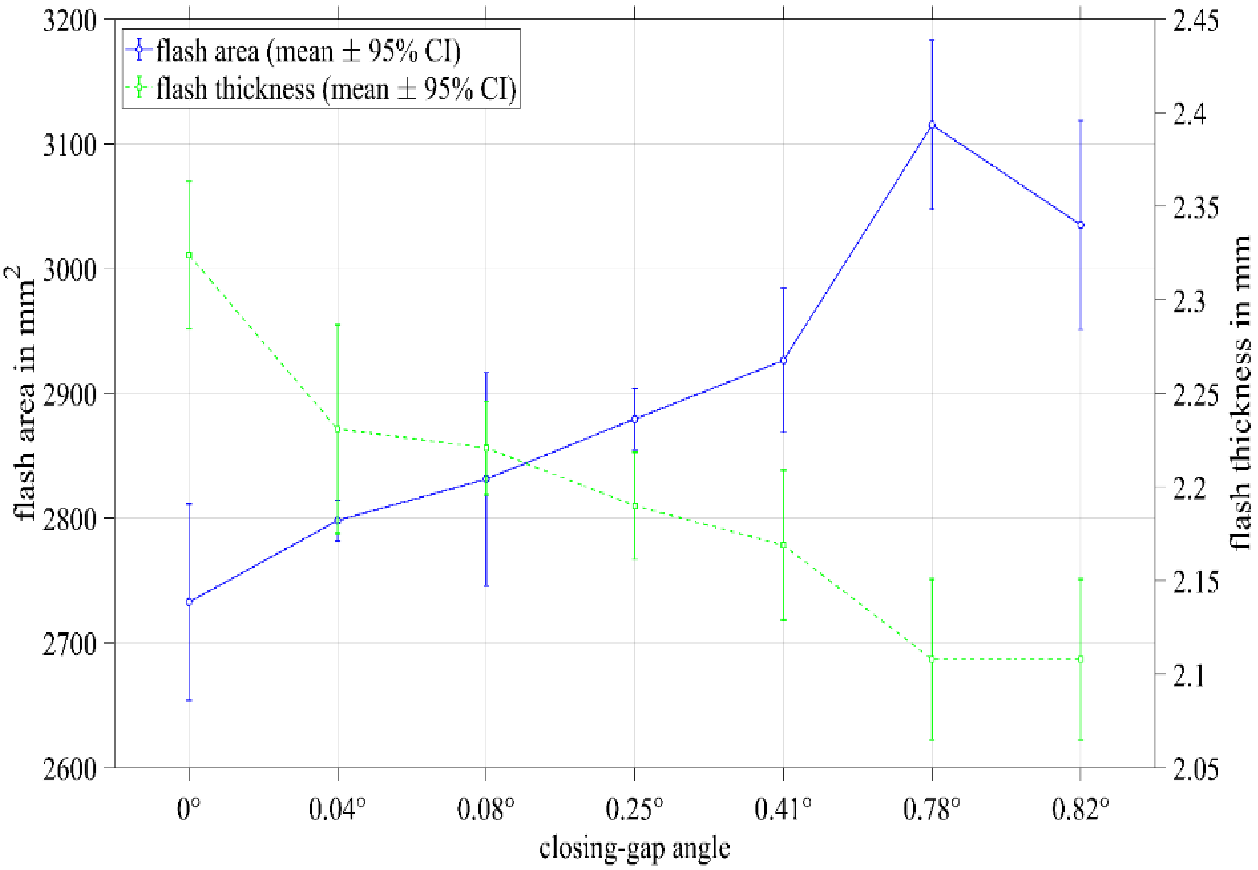

Fig. 6. Mean flash area (left axis) and mean flash thickness (right axis) vs. closing-gap angle, error bars indicate 95% confidence intervals of the mean (n = 10, t-distribution).

The flash area corroborates the modified flow behavior on a global level, but its higher scatter and dependence on temperature and lubrication make it less suitable as a primary indicator.

These results demonstrate that locally resolved flash thickness asymmetry at BDC constitutes a robust workpiece-side signature of closing gap inclinations. It directly reflects the direction-dependent redistribution of material and implicitly integrates process effects such as elastic deflection, guide clearances, frictional conditions and thermal states, without requiring additional machine-side instrumentation. Within the limits of the investigated setup, the approach enables process-relevant deviations in die alignment to be distinguished from the background of process variability in an automated series-forging environment.

In the framework of the DFG Priority Program SPP 2422, the present study provides a specific building block for transparent, data-driven process modelling by quantifying the detection limits and diagnostic sensitivity of flash-based workpiece signatures. Based on these findings, future work will first extend the methodology from the generic demonstrator to an industrial forging geometry, in order to relate flash-thickness asymmetry and flash area more directly to trimming behavior, dimensional tolerances and product-side quality criteria. A further step will be to investigate the temporal evolution of the signature under changing thermal states and progressive tool wear, assessing to what extent small misalignments can be tracked over longer production campaigns. On this basis, flash-based signatures can then be combined with selected additional sensor signals in explainable machine-learning models that map die alignment and tool state to the resulting part geometry. In this way, the workpiece-side signatures developed in this study form a practical starting point for condition-aware monitoring and root-cause analysis in industrial forging applications within SPP 2422.

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