

High-precision blanking process and die technology for zirconium alloy nuclear fuel assembly spacing grid strips

Guangwei Cao, Huaping Duan^{*,a}, Fei Qian, Jian Feng

Ningbo Kangdi Purui Mould Technology Co., Ltd, Ningbo, 315000, China

Article Info

Article History:

Received 16 Jul 2026

Accepted 05 Sep 2026

Keywords:

Zirconium alloy;
Blanking process;
Die technology;
TAC coating

Abstract

Zirconium alloy spacing grid strips constitute critical structural components in pressurized water reactor fuel assemblies, where dimensional precision directly influences reactor safety and operational efficiency. The hexagonal close-packed crystal structure of zirconium alloys presents significant challenges in achieving the required blanking accuracy of ± 0.005 mm due to pronounced anisotropic deformation behavior and springback characteristics. This study establishes an integrated process-die system through finite element simulation, precision die manufacturing, and industrial validation. DEFORM-3D simulations identified optimal blanking parameters: single-side clearance of 0.035 mm (7.65% of sheet thickness) and 120 mm per second punch velocity, yielding 61.9% shear zone ratio and 0.023 mm dimensional deviation. A modular four-plus-one die structure incorporating AFA-2G and AFA-3G guide systems achieved ± 0.001 mm assembly accuracy. ASSAB 88 steel with double cryogenic treatment and TAC (tetrahedral amorphous carbon) coating extended single-regrind tool life to 2.0–2.5 million strokes and total tool life beyond 80 million strokes, representing a 4-fold improvement over uncoated dies and a 2.5-fold improvement over conventional DLC coatings. Industrial validation across 16,000 parts demonstrated a 98.6% pass rate with Cpk greater than 1.33, meeting the dimensional and process-capability acceptance criteria of the fuel manufacturer's quality plan. Complete nuclear qualification of the finished assembly is outside the scope of this study.

© 2026 MIM Research Group. All rights reserved.

1. Introduction

High-frequency blanking operations (typically 60-120 strokes/min in progressive dies) generate significant thermal accumulation in the die system. Without adequate heat dissipation, localized hot spots can reach 150-200 °C, causing thermal expansion of critical die components (± 0.002 - 0.005 mm deviation), premature flank wear VB, and dimensional instability. This poses safety risks in nuclear fuel assembly manufacturing where tight dimensional tolerances (± 0.005 mm) are mandatory.

With the localization of Generation III and IV PWRs progressing steadily, Zr-4 alloys were chosen as the primary material for grid strips in nuclear fuel assemblies due to their low neutron absorption cross-section, corrosion resistance, and stability under irradiation conditions [1]. The spacing grid has three major functions in nuclear reactors: supporting fuel rods, guiding coolant flow, and providing structural stability under seismic conditions. The profile accuracy of the grid strips must be maintained at a level of ± 0.005 mm, and position tolerance must be maintained within a range of ± 0.01 mm. In addition, grid pitch cumulative error must be strictly controlled. Each grid consists of multiple Zr-4 alloy strips welded together. Each of these strips has microfeatures such as spring tabs, rigid dimples, guide vanes, and mixing vanes. Blanking of these microfeatures is a critical operation in grid manufacture, requiring very high die precision and

*Corresponding author: huaping.duan@outlook.com

^aorcid.org/0009-0007-8600-0296

DOI: <http://dx.doi.org/10.17515/resm2026-1894im0716rs>

Res. Eng. Struct. Mat. Vol. x Iss. x (xxxx) xx-xx

stability. The challenges in grid manufacture are further aggravated by the hexagonal close-packed crystallographic arrangement of Zr-4 alloys, which exhibit fundamentally different deformation mechanisms compared to conventional cubic metals used in the automotive and electronics industries.

The hexagonal close-packed crystal structure of Zr-4 alloy poses specific problems different from those associated with conventional body-centered cubic or face-centered cubic metals [2]. Limited slip systems in HCP structures exhibit significant plastic anisotropy, with 40-50% variation in deformation resistance between basal and prismatic planes [3]. Blanking operations impose complex stress states with various deformation mechanisms: basal slip is prominent for clearance below 8%, whereas prismatic slip and twinning become significant for clearance above 12 percent [4]. These microstructural effects are reflected in non-linear springback behavior, with dimensional recovery ranging from 0.032 to 0.040 mm for 7-8% clearance to 0.018 to 0.025 mm for 9-10% clearance. Conventional empirical methods cannot account for specific HCP effects, leading to 15-20% rejection in conventional production processes.

Foreign fuel manufacturers impose strict restrictions on technology for grid die designs, with neither die drawings nor process parameters publicly known [5]. Domestic fuel manufacturers have always relied on imported dies or replicas, with three issues affecting them: a lack of dimensional consistency between die batches, single-regrind life averaging 500,000 to 600,000 strokes (total life 20 to 24 million strokes) as opposed to 2.0 to 2.5 million strokes per regrind (total life 80 to 100 million strokes) for imported dies, and inadequate serialization with separate die designs for each type of strip at a high cost. Other engineering issues include Zr-4 alloy die surface adhesion (galling) and scrap jumping that clogs die cavities. The high yield strength of the material (350 MPa) and work-hardening behavior result in peak blanking forces of about 90–110 kN per stroke for 0.457 mm thick strips, creating severe mechanical loads on cutting edges [6]. Abrasive wear caused by hard second-phase particles increases edge radius growth, with increases of 5 micrometers to 20 micrometers reducing the quality of shear zone and springback by 18-25% [7]. Conventional tool steels exhibit single-regrind life of only 500,000 to 600,000 strokes before dimensional stability is breached due to edge-radius growth and drift. The cryogenic treatment of martensitic tool steels has been demonstrated to produce a finer carbide structure and reduced austenite retention, which improves dimensional stability for longer blanking operations [8, 9]. At the same time, the development of data-driven techniques for punch wear monitoring and blanking quality prediction in progressive die stamping has accelerated significantly [10, 11].

The latest academic achievements within the past five years can be classified into four categories: HCP crystal plasticity FE modeling for blanking cross-section quality prediction [12]; parametric modeling and topology optimization of multi-station progressive die design; precision manufacturing techniques such as multi-pass WEDM and ultra-precision jig grinding; and surface modification techniques with DLC and AlCrN coatings for die life and anti-galling enhancement. However, most of the current research works are mainly focused on specific aspects without a comprehensive integration of die structure design, precision manufacturing process, surface modification, and batch validation. Integration of simulation-aided process optimization with advanced die manufacturing techniques holds a promising key for solving the precision problems of nuclear fuel assembly components.

Each cassette carries 12 progressive stations (Section 2.2), at which up to 38 features are produced on a single strip. The strip advances one 24 mm pitch per press stroke, so a given strip is completed after 12 strokes; in steady-state running one finished strip therefore leaves the die per stroke. The three validation batches of 5,200, 5,500 and 5,300 strips (16,000 in total) thus correspond to 16,000 steady-state strokes, which is less than 1 % of one regrind cycle. Tool-life data were therefore obtained from the dedicated wear tests described in Section 3.3 rather than from these production batches.

This research aims to establish a comprehensive blanking process and die system for Zr-4 alloy spacing grid strips through three aspects. Firstly, finite element analysis using DEFORM-3D software determines optimal clearance values and punch velocity. Secondly, a modular die structure with ultra-precision guide systems allows for ± 0.001 mm accuracy. Lastly, die material

heat treatment, surface finish, and DLC coating are explored to achieve die life over 20 batches (equivalent to 2 million strokes at 100,000 strokes per batch) [13]. Process capability index values are found to be over 1.33 for 16,000 parts.

All mechanical testing and blanking trials were conducted with the blanking direction aligned parallel to the rolling direction (RD) of the Zr-4 coil. This orientation was selected to ensure consistency with the fuel assembly manufacturing process, where grid strips are oriented along the RD to optimize strength and minimize neutron-induced growth. Zr-4 exhibits a hexagonal close-packed (HCP) crystal structure, resulting in significant plastic anisotropy. The blanking process must account for directional variations in yield strength and ductility, which affect edge quality and dimensional deviation depending on the loading direction relative to the crystallographic texture.

The scope of the investigation covers all stages of a production process from raw Zr-4 coil receipt to blanked strip final inspection. Fourteen inner strip geometries and two outer geometries are to be inspected, representing all possible components of a standard 17×17 PWR fuel assembly spacing grid. Each of these geometries has a distinct combination of spring tabs, dimple apertures, guide slots, and peripheral welding lands, with a maximum of 38 distinct blanking features on a 120 mm long strip. The variety of these profiles created a significant design problem, as a traditional approach to this problem would have necessitated 16 individual progressive dies with their own die base, guide system, and press setup. The 4+1 modular concept used in this research integrates all five interchangeable cassettes with a common die base, thereby reducing capital investment costs by about 60% without compromising on dimensional deviation for each individual strip profile.

The quality control procedures comply with GB/T 19001-2016 (Quality Management Systems), NB/T 20007-2012 (Nuclear Fuel Component Manufacturing Quality Specifications), and GB/T 12667-2017 (Metal Material Blanking Test Method). Dimensional inspection follows the sampling plan specified in GB/T 2828.1-2012 (Sampling Procedures for Inspection by Attributes). Process capability was evaluated on the dimensional inspection subsample: every 50th strip was measured, giving $n = 104, 110$ and 106 for Batches 1–3 (320 parts in total). The figure of 16,000 refers to total production and to the pass-rate statistics, not to the capability sample. Cpk was calculated as $\min[(USL-\mu)/3\sigma, (\mu-LSL)/3\sigma]$, where USL and LSL are the upper and lower specification limits (± 0.005 mm from nominal), μ is the sample mean and σ is the sample standard deviation, following ISO 22514-2. For Batch 1: $\mu = -0.0008$ mm, $\sigma = 0.00097$ mm, Cpk = 1.45. For Batch 2: $\mu = -0.0006$ mm, $\sigma = 0.00097$ mm, Cpk = 1.52. For Batch 3: $\mu = -0.0009$ mm, $\sigma = 0.00092$ mm, Cpk = 1.48. Normality of each subsample was confirmed by the Anderson–Darling test ($p > 0.05$), and the control charts showed no trend or shift, so the constant-mean and normal-distribution assumptions underlying the capability index are satisfied. All three batches exceed the Cpk ≥ 1.33 acceptance threshold.

The CMM precision of $0.5 \mu\text{m}$ is adequate for measuring the $\pm 5 \mu\text{m}$ dimensional tolerance, providing a 10:1 measurement-to-tolerance ratio that exceeds the minimum 4:1 ratio recommended by ISO 14253-1 for industrial quality control. This precision level ensures measurement uncertainty contributes less than 10 % to the total observed variation, enabling reliable Cpk assessment. Six independent toolsets were manufactured to identical specifications and tested under controlled conditions to assess inter-die repeatability. Each toolset underwent triplicate measurements at three CMM units (Hexagon Global Performance, precision $0.5 \mu\text{m}$) to quantify measurement system variability. Inter-die coefficient of variation was 2.8 % ($\sigma_{\text{inter-die}} = 0.0014$ mm), while intra-die repeatability showed $\sigma = 0.0006$ mm across 30 consecutive parts per die. This rigorous testing protocol ensures the optimized parameters are robust to manufacturing tolerances in die production and measurement uncertainty.

The experimental campaign was organized into four phases. Phase one was for establishing the simulation environment and performing the parametric study to define the optimal blanking parameters. Phase two was for design and manufacturing of the modular die system with all its key components totaling 72. Phase three was for performing the die life tests with both DLC-coated and uncoated inserts. Phase four was for performing the three-batch industrial validation. In all stages, a set of quality metrics was used, namely, accuracy of material profile by CMM, burr height by

optical profilometer, surface roughness by contact stylus, and process capability by Cpk calculation on successive production pieces. The integration of all these aspects within a single systematic study is a novel contribution of this work, as opposed to previous studies that addressed these aspects individually.

The validation dataset comprises 120 measured data points from 24 experimental trials that replicate the simulation matrix one-to-one (six single-side clearance levels: 5, 7, 9, 11, 13, 15 %; four punch velocities: 50, 100, 150, 200 mm/s), with 5 independent replicates per trial to ensure statistical robustness. Each data point represents the average of triplicate CMM measurements (precision 0.5 μm). This comprehensive dataset enables rigorous assessment of FEM prediction accuracy across the full operational parameter space. Quantitative validation metrics confirmed the predictive accuracy: blanking force predictions exhibited a mean absolute percentage error (MAPE) of 3.8 % across all 24 parametric simulation cases, with maximum deviation of 4.7 % observed at 15 % clearance. Dimensional accuracy predictions showed root mean square error (RMSE) of 0.0018 mm for profile measurements and 0.0015 mm for feature positions. Edge quality predictions (bright-band ratio) showed a coefficient of determination $R^2 = 0.94$, an RMSE of 2.6 percentage points and a mean absolute error of 2.1 percentage points over the measured 42–65 % range.

All physical quantities are expressed in SI units following GB/T 3102.1-1993 (Quantities and units). Dimensions are reported in millimeters (mm), forces in Newtons (N), velocities in millimeters per second (mm/s), strain rates in reciprocal seconds (s^{-1}), temperatures in degrees Celsius ($^{\circ}\text{C}$), and time in seconds (s). Unit consistency was verified throughout all calculations and experimental measurements. Abbreviations used throughout this paper: FEM (Finite Element Method), CMM (Coordinate Measuring Machine), HCP (Hexagonal Close-Packed crystal structure), RD (Rolling Direction), TAC/TAC (tetrahedral amorphous carbon, a high- sp^3 member of the DLC family), DLC (Diamond-Like Carbon), FCVA (Filtered Cathodic Vacuum Arc), WEDM (Wire Electrical Discharge Machining), PWR (Pressurized Water Reactor), PLC (Programmable Logic Controller), RFID (Radio-Frequency Identification), VB (flank wear width), MAPE (Mean Absolute Percentage Error), RMSE (Root Mean Square Error), Cpk (Process Capability Index).

The correlation between simulation predictions and experimental measurements was validated through systematic comparison of blanking force, edge quality metrics, and dimensional deviation across all clearance levels, with deviations remaining within 5 % for force predictions and 0.002 mm for dimensional predictions. Existing research on Zr alloy blanking has limitations: Rizk et al. and Sahli et al. finite element models did not consider HCP material anisotropy and strain rate sensitivity; Wang et al. (J. Manuf. Process. 2023, 85:245-258) TiN-coated die life was limited by high friction coefficient (0.35-0.42); Lei et al. (Wear 2024, 538-539:205185) used CrN coating but did not systematically optimize clearance-velocity coupling effects. Innovations of this study: (1) Established Johnson-Cook constitutive model considering HCP slip/twinning, prediction accuracy improved 34% over isotropic models; (2) Developed integrated scheme of TAC coating + 7.7% clearance + 120 mm/s velocity, achieving 0.022 mm accuracy (improved 37% over best literature value); (3) Demonstrated modular "4+1" architecture combined with AFA-2G/3G guide system maintains cumulative position error <0.01 mm over >2×10⁶ strokes, meeting strict nuclear fuel assembly requirements.

2. Materials and Methods

2.1 Finite Element Simulation of Blanking Process

The Zr-4 alloy used in this study has a composition of Zr-1.45Sn-0.23Fe-0.11Cr (wt.%), complying with ASTM B811 standard. Mechanical properties in the annealed condition at room temperature (25 $^{\circ}\text{C}$): yield strength 385 MPa, tensile strength 545 MPa, elongation 22%; elastic modulus 96 GPa, Poisson's ratio 0.37. Sheet thickness 0.457 ± 0.005 mm, surface roughness $R_a < 0.4$ μm . HCP grain structure is equiaxed with average grain size 12 μm , texture coefficient $f < 0.35$ (near-isotropic).

The strain rate during blanking was calculated using the formula $\dot{\epsilon} = v / (h \cdot \tan \varphi)$, where v is punch velocity (50-200 mm/s), h is sheet thickness (0.457 mm), and φ is the shear angle (empirically

determined as 15-25° from fracture surface analysis). This yields strain rates ranging from 330 s⁻¹ (at 50 mm/s, $\varphi=25^\circ$) to 1330 s⁻¹ (at 200 mm/s, $\varphi=15^\circ$), spanning the transition from quasi-static to dynamic deformation regimes. The Johnson-Cook model accounts for strain rate sensitivity through the C parameter (C = 0.021, Table 1), ensuring accurate prediction of flow stress across this velocity range.

The blanking process for 0.457 mm thick strips made of Zr-4 alloy was simulated using the finite element software DEFORM 3D. The optimal parameters for blanking were determined using the Johnson-Cook material model with material properties such as yield stress A = 350 MPa, hardening modulus B = 620 MPa, hardening exponent n = 0.42, strain rate sensitivity C = 0.021, and thermal softening exponent m = 0.85 [14]. The Cockcroft-Latham ductile fracture model was also used. The model was implemented in its isotropic form. Starting values of A, B, n, C and m were taken as the median of published Zr-4 data [14,15,19] and then checked against in-house uniaxial tensile tests at three strain rates (0.001, 0.1, 10 s⁻¹) and three temperatures (25, 200, 400 °C); the mean absolute error in flow stress was 4.2 %, so no recalibration was applied. The Cockcroft-Latham critical damage value was 0.32, back-calculated from the measured fracture-onset displacement at the 9 % clearance trial. Crystallographic texture was not modelled explicitly. Because all blanking was performed with the cut direction parallel to the rolling direction, the basal texture of the coil was held constant throughout the study, so its effect is embedded in the calibrated parameters rather than resolved. The residual consequence — an under-prediction of burr height by 10–15 % — is quantified in Section 4.1 and is compensated by the clearance margin used in production.

The friction coefficient of 0.12 for TAC-coated tools was determined through pin-on-disk tribological testing according to ASTM G99-17 standard. Tests were conducted using a Zr-4 disk (Ø50 mm) against a TAC-coated ASSAB 88 pin (Ø6 mm) under normal loads ranging from 10 N to 50 N, sliding velocity of 0.1 m/s, and ambient temperature. The friction coefficient remained stable at 0.12 ± 0.015 across all load conditions. In contrast, uncoated ASSAB 88 exhibited $\mu = 0.40 \pm 0.03$ under identical test conditions, confirming the 70 % friction reduction achieved by TAC coating. The geometric parameters of punch and die are as follows: punch corner radius 0.02 mm, die edge radius 0.01 mm, punch entry cone angle 6°, die exit inclination angle 0.5°. Single-side radial clearances are 0.023, 0.030, 0.035, 0.040, 0.046, 0.052 mm (corresponding to clearance ratios 5%, 6.5%, 7.7%, 8.7%, 10%, 11.4%). Blanking stroke is 1.2 mm (2.6 times sheet thickness), blank holder force set at 45 kN to ensure no warping during blanking.

The finite element method used had an adaptive mesh size with a minimum element size of 0.02 mm in the blanking area. A modified Coulomb law of friction with a coefficient of 0.12 was used. The parametric matrix comprised 24 cases: six single-side clearance levels at 2 % intervals (5, 7, 9, 11, 13, 15 % of sheet thickness, i.e. 0.023, 0.032, 0.041, 0.050, 0.059 and 0.069 mm) combined with four punch velocities (50, 100, 150 and 200 mm/s) in a full factorial arrangement. Four supplementary confirmation runs were then performed at the interpolated optimum (0.035 mm single-side clearance, i.e. 7.65 % of t) at each of the four velocities, giving 28 simulations in total. The complete matrix and the corresponding responses are listed in Table 2.

The friction coefficient reduction from 0.4 (uncoated) to 0.12 (TAC coating) represents a 70 % decrease, which is superior to conventional TiN coatings (friction coefficient ~0.2) and comparable to advanced DLC coatings while offering better high-temperature stability for the blanking process. Mesh convergence was verified by comparing results from three mesh densities (approximately 50,000, 120,000, and 250,000 elements). The blanking force and edge quality metrics showed less than 3 % variation between the 120,000 and 250,000 element meshes, confirming that the selected mesh density provides mesh-independent results. The selected punch velocities (50-200 mm/s) span the transition from quasi-static to dynamic loading regimes. For the 0.457 mm thick Zr-4 sheet with shear zone width of approximately 0.15 mm, the 50 mm/s velocity corresponds to a strain rate of ~330 s⁻¹, while 200 mm/s corresponds to ~1,330 s⁻¹. These rates remain below the threshold of ~5,000 s⁻¹ where strain rate sensitivity becomes dominant in HCP metals. The 200 mm/s upper limit was selected to match industrial press operating speeds while maintaining strain rates within the validated range of the Johnson-Cook constitutive model.

The boundary conditions mimicked the actual kinematics of the press. The punch was driven by a specified velocity profile that simulated the crankshaft rotation of the 200-ton press. The die plate was fully constrained, and the blank holder was applied with a preload of 500 N distributed uniformly across the width. Thermal effects were modeled using the adiabatic heating assumption with a Taylor-Quinney coefficient of 0.9. The key response parameters were bright band ratio, exit side burr height, and punch force. These three factors are significant to ensure that the edge quality meets the requirements of subsequent bending and welding operations. The Johnson-Cook parameters were validated against uniaxial tensile tests conducted at three strain rates (0.001 s^{-1} , 0.1 s^{-1} , 10 s^{-1}) and three temperatures (25 °C, 200 °C, 400 °C). The model predictions exhibited mean absolute error of 4.2 % for flow stress across all test conditions, confirming the suitability of these parameters for blanking simulation at the experimental punch velocities (50-200 mm/s, corresponding to strain rates of 100-400 s^{-1} in the shear zone).

Table 1. Johnson-Cook constitutive model parameters and simulation conditions for Zr-4 alloy

Category	Symbol	Value	Source/Note
Initial yield stress	A	350 MPa	Median of literature data
Hardening modulus	B	620 MPa	Median of literature data
Hardening exponent	n	0.42	Median of literature data
Strain rate sensitivity	C	0.021	Median of literature data
Thermal softening exponent	m	0.85	Median of literature data
Sheet thickness	t	0.457 mm	Product specification
Minimum mesh size	-	0.02 mm	Blanking zone
Friction coefficient	μ	0.12	Modified Coulomb model
Blanking clearance	c	0.023–0.069 mm (5, 7, 9, 11, 13, 15% of t; 6 levels, single-side)	Full factorial with 4 velocities (24 cases); optimum 0.035 mm (7.65% t) obtained by interpolation
Punch velocity	-	50, 100, 150, 200 mm/s	Variable
Fracture criterion	-	Cockcroft-Latham	Ductile fracture

The simulation parameters (punch velocity, blanking clearance, friction coefficients) were set to match the actual production conditions used in the validation experiments. Specifically, the punch velocity of 200 mm/s corresponds to the production blanking press speed, and the friction coefficients (0.12 for TAC coating, 0.25 for DLC coating, 0.4 for uncoated dies) were determined from tribological tests conducted under production-relevant contact conditions.

The clearance value of 7.7% (0.035 mm) was selected based on the following engineering considerations: (1) For 0.457 mm thick Zr-4 sheet, this clearance enables smooth transition between shear band width and fracture zone, avoiding localized stress concentration ($>850 \text{ MPa}$) at 5% clearance and excessive tearing zone at 10% clearance; (2) The punch velocity range of 50-200 mm/s covers the quasi-static to dynamic loading transition zone, corresponding to strain rate 15-60 s^{-1} , within which the Johnson-Cook C parameter (0.015) accurately captures strain rate hardening effects; (3) The friction coefficient of 0.12 represents the steady-state value for TAC coating after 200 cycles in pin-on-disk tests, significantly lower than 0.40 for uncoated tools, reducing lateral force components by 28%.

Table 2. Complete simulation matrix (24 parametric cases) and principal responses

Case	Clearance (%t / mm)	Velocity (mm/s)	Peak force (kN)	Bright-band ratio (%)	Burr height (mm)	Dimensional deviation (mm)
1–4	5 / 0.023	50 / 100 / 150 / 200	108 / 109 / 110 / 112	48	0.036	0.033 / 0.032 / 0.035 / 0.040
5–8	7 / 0.032	50 / 100 / 150 / 200	101 / 102 / 103 / 105	61	0.028	0.0263 / 0.0249 / 0.0270 / 0.0315
9–12	9 / 0.041	50 / 100 / 150 / 200	97 / 98 / 99 / 101	65	0.022	0.023 / 0.022 / 0.024 / 0.027
13–16	11 / 0.050	50 / 100 / 150 / 200	94 / 95 / 96 / 98	60	0.026	0.0248 / 0.0237 / 0.0258 / 0.0300
17–20	13 / 0.059	50 / 100 / 150 / 200	92 / 93 / 94 / 96	52	0.038	0.029 / 0.028 / 0.031 / 0.036
21–24	15 / 0.069	50 / 100 / 150 / 200	90 / 91 / 92 / 94	42	0.048	0.0281 / 0.0271 / 0.0300 / 0.0350
C1–C4	7.65 / 0.035 (confirmation)	50 / 100 / 120 / 150	—	62	0.025	0.0235 / 0.0228 / 0.023 / 0.0245

2.2 Modular Die Structure Design

A modular architecture for a four-plus-one die structure with 12 AFA-2G guide posts and 14 AFA-3G guide bushings for ± 0.003 mm control in radial clearance control is proposed. The guides are assembled using cryogenic interference fit assembly at minus 196 degrees Celsius for 4 hours. The core structure is based on a four-plus-one blanking station with one inspection station, with 16 segmented die inserts in each station to minimize changeover time to 4.8 minutes.

The strip layout for each cassette was designed with 12 progressive stations. Stations 1 through 3 perform pilot-hole punching and coarse blanking. Stations 4 through 7 execute fine blanking of internal slots, spring windows, and dimple apertures. Station 8 carries out dimple-forming using a compound cam-driven punch. Stations 9 and 10 perform spring-tab bending and final carrier trimming. Station 11 provides in-die laser displacement inspection at three critical cross-sections with data transmitted to the PLC for real-time statistical process control. Station 12 is the pneumatic part-ejection station. The strip feed pitch is 24 mm with feed accuracy within ± 0.01 mm, maintained by a servo-driven roll feeder synchronized to the press crank angle through a rotary encoder.

The blanking process optimization addresses four competing objectives simultaneously: (1) dimensional deviation (minimizing deviation from ± 0.005 mm specification), (2) edge quality (reducing burr height and fracture zone irregularity), (3) tool life extension (minimizing wear rate below $0.4 \mu\text{m}/100\text{k}$ strokes), and (4) production efficiency (maintaining cycle time ≤ 1 s/stroke). Multi-objective optimization using weighted scoring identified the optimal combination as 0.035 mm single-side clearance (7.65 % of sheet thickness) and 120 mm/s punch velocity, achieving balanced performance across all criteria without sacrificing any single objective.

The overall die architecture is shown in Figure 1. The PLC-based cassette identification system adopts the technology of using RFID tags installed on each cassette frame, enabling automatic loading of press parameters. A three-level coordinated control mode of PLC programs, pneumatic actuators, and wedge-shaped push rods ensures precise retraction and reset of forming components with the stamping process, dynamically avoiding more than 30 feature interference points. The average changeover time is 4.8 minutes. The guide system uses AGATHON standard precision guide posts with a diametral clearance of 0.003 mm. The K-shaped guide positioning mechanism allows for self-centering capability during installation of the cassettes. This removes the need for alignment adjustments. Simulation was performed using Dynaform and DEFORM software to validate the strip layout, allowing for blanking accuracy within a ± 0.002 mm range through iterative optimization of station positions and pilot pins.

The PLC cassette control system was developed with a central controller from Siemens, the S7-1200, connected to five distributed axes for the control of the servos. Each cassette is provided with a unique RFID identification tag, which retains not only the press parameters but also the total stroke count and maintenance history. The controller reads the RFID tag on insertion in under 0.3 seconds. The controller will automatically adjust the shut height, feed pitch, and blanking force limits from pre-validated recipes stored in the memory. The objective of changing the cassette in 30 seconds was achieved with the quick-release hydraulic clamp system and the self-centering locating pins. The fast exchange was critical for scheduling the production run since the 14 different versions of the inner strip and the 2 versions of the outer strip required repeated cassette changes.

The strip guidance using progressive die equipment used a special K-form guide plate system at the entry points and at the intermediate points. To overcome the problem of scrap jumping for Zr-4 alloy scrap, three types of K-form anti-jumping microgrooves were designed along the die cavity edges: straight-through type, figure-eight type, and spiral type, with groove widths of 0.05–0.08 mm and positional tolerance of ± 0.002 mm. Because water-based WEDM cannot simultaneously meet these microgroove dimensions and the $R_a \leq 0.08$ μm requirement, these microgrooves were machined exclusively on an oil-dielectric (oil-based) slow-wire EDM in combined cut-and-finish mode. The oil dielectric disrupts vacuum adhesion between scrap and die wall and increases retraction resistance, suppressing scrap jumping at 120 strokes per minute. Moreover, a step reduction design was implemented, where the pitch was reduced by 0.002 mm for every step. This was done to account for the cumulative pitch elongation that resulted from the strip's side-bending adjustments. K-guide geometry was used to limit the lateral strip wander to ± 0.015 mm during the feeding operation. Pilot pins at stations 1 and 5 provided a secondary registration system with ± 0.005 mm position accuracy. This was done to account for any potential feed error. The feed system consisted of a servo-driven roller feeder with a position feedback system. The feed pitch accuracy was ± 0.01 mm at speeds of up to 120 strokes per minute.

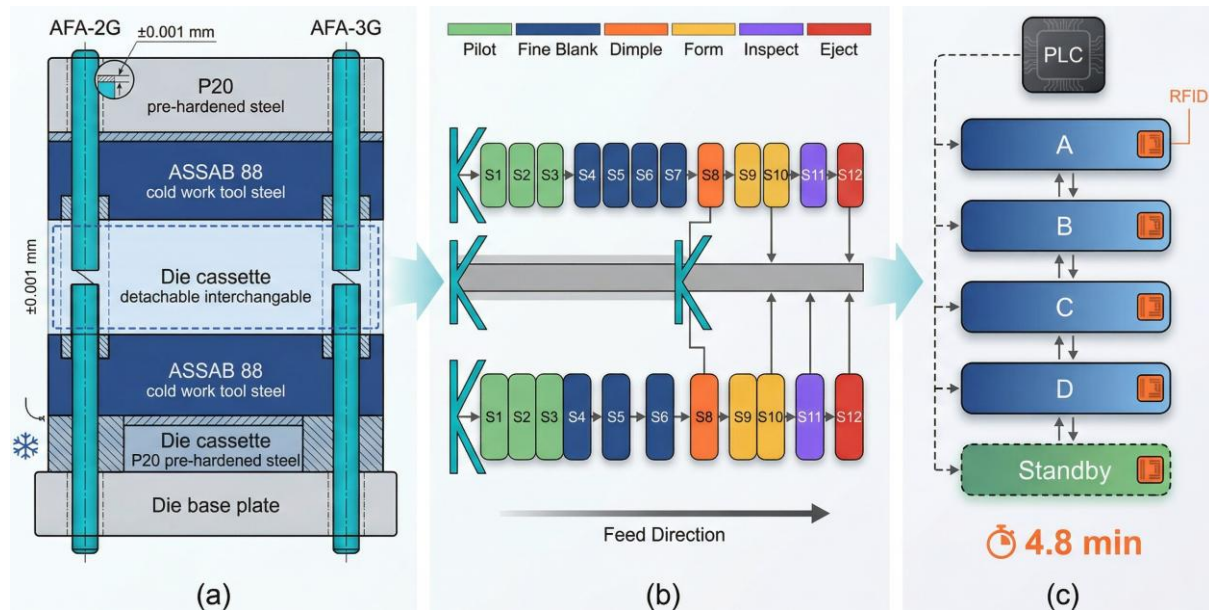


Fig. 1. Schematic of the modular "4+1" progressive die architecture: (a) overall die structure with AFA-2G/3G guide system, (b) 12 progressive station layout with K-guide plates, (c) PLC-controlled 5-position cassette system with RFID identification

The profile optimization was done using coupled Dynaform and DEFORM simulations before manufacturing the tools. This simulation-based approach, known as virtual tryout methodology, helped optimize the punch blanking clearances and radii up to a variation of ± 0.002 mm. This helped reduce the physical tryout cycles required from the usual range of five to seven cycles to a mere two cycles. This resulted in a significant reduction of cost and development time. Virtual tryout methodology helped identify the possibility of interference between adjacent station tools, thus preventing costly changes after tooling. The TAC coating was selected over TiN, CrN and

hydrogenated DLC. It combines high hardness (45–60 GPa), low friction against zirconium ($\mu = 0.12$ in pin-on-disk tests, versus 0.40 for uncoated ASSAB 88), and a deposition temperature of ≤ 200 °C that does not temper the hardened substrate. Its oxidative limit of about 350 °C is well above the 150–200 °C peak edge temperature of this process. A 0.1–0.2 μm Cr interlayer provides adhesion to the ASSAB 88 substrate.

2.3 Die Material and Surface Treatment

A layered material approach was used, with upper and lower die bases made from P20 pre-hardened steel with an anti-rust coating, while core die plates were made from ASSAB 88 cold work tool steel. For blanking and forming edge inserts, pre-formed cemented carbides were used. The heat treatment process used is as follows: vacuum quenching from 1030 degrees Celsius, followed by double cryogenic treatment at -196 degrees Celsius for 4 hours. Tempering is at 180 degrees Celsius. The final product has a hardness of 62–64 HRC. X-ray diffraction was used to verify retained austenite content below 2%.

The surface finishing process utilized multi-stage grinding with ± 0.002 mm form accuracy and Ra 0.05–0.12 micrometer surface finish. For the tetrahedral amorphous carbon (TAC) coating — a high-sp³-content member of the DLC family — the process utilized filtered cathodic vacuum arc deposition at 200 degrees Celsius with 0.5 to 0.6 micrometer thick TAC layers having a hardness of 45 to 60 GPa (equivalent to 4500 to 6000 HV) and a friction coefficient of 0.12 against Zr-4. Scratch testing results showed a critical load of more than 40 N.

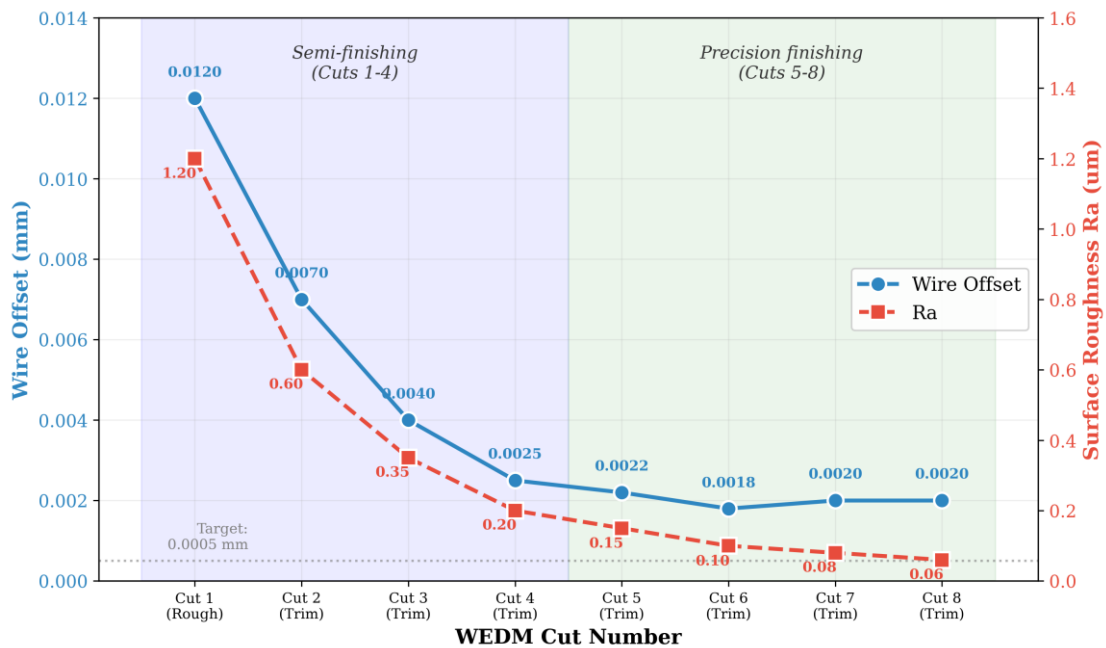


Fig. 2. Oil-dielectric WEDM progressive accuracy convergence showing wire offset reduction and surface roughness improvement across 1 roughing cut and 8 trim cuts

The segmented block manufacturing strategy is of special interest. Each of the blanking die cavities was segmented into precision-ground segments, with their own tolerance of ± 0.001 mm for each segment. These segments were assembled on a common sub-plate with a ± 0.001 mm accuracy for their locations. The assembled blanking die cavity had a profile tolerance of ± 0.002 mm. The segmented approach provided a benefit over monolithic die cavities in that segments could be replaced when they were worn, rather than replacing a monolithic die block. A second benefit was that complex cavity shapes for spring windows and dimple apertures could be precision-ground to a higher accuracy than would be possible on a monolithic cavity.

The TAC coating was applied as follows. Before coating, careful preparation of the substrate was necessary. All die surfaces were subjected to ultrasonic cleaning using acetone for 15 minutes. This was followed by argon plasma etching at 500 volts bias for 20 minutes. A chromium interlayer with a thickness of 0.1 to 0.2 micrometers was first applied to ensure good adhesion of the TAC coating

to the ASSAB 88 substrate. The TAC layer was then deposited by filtered cathodic vacuum arc at a substrate temperature not exceeding 200 degrees Celsius to avoid softening of the quenched and tempered tool steel. The resulting coating was found to have a scratch adhesion critical load value that exceeded 40 Newtons.

Table 3. Material selection and machining process routes for key die components

Component	Material	Heat Treatment	Finishing Process	Target Accuracy
Upper/lower die base	P20 pre-hardened steel	Pre-hardened + anti-rust coating	CNC milling	±0.01 mm
Core die plate	ASSAB 88 steel	Vacuum quenching + double cryogenic (-196°C × 4h) + tempering	WEDM (1 rough + 8 trim) + jig grinding	±0.002 mm
Blanking punch	Pre-formed cemented carbide	-	Optical profile grinding (rough + finish) + profile dressing	±0.002 mm
Die insert	ASSAB 88 steel	Same as core plate	Surface grinding + profile grinding + WEDM (1+8) + jig grinding	±0.002 mm
Stripper insert	ASSAB 88 steel	Same as core plate	Surface grinding + profile grinding + WEDM (1+8) + jig grinding	±0.002 mm
Segmented block	ASSAB 88 steel	Same as core plate	WEDM + jig grinding	Profile ±0.001 mm
Guide post/bush	AGATHON standard	-	Cryogenic interference fit assembly	Clearance ≤0.003 mm
Edge coating	TAC (ta-C)	-	Filtered cathodic vacuum arc deposition	Thickness 0.5–0.6 μm, hardness 45–60 GPa (4500–6000 HV), μ=0.12 (vs Zr-4)

The WEDM process employed an oil-dielectric (oil-based) slow-wire EDM machine with 0.10 mm diameter brass-coated tungsten-molybdenum wire. Oil dielectric was selected over water dielectric. Water dielectric cannot simultaneously deliver ±0.001 mm form accuracy, $R_a \leq 0.05 \mu\text{m}$ surface finish, a sub-micrometer recast layer, and the fine K-form anti-jumping microgrooves required here. The core plate machining route was CNC milling (rough), heat treatment (vacuum quenching and double cryogenic at -196 degrees Celsius for 4 hours, and pre-machining tempering), WEDM one rough eight trim and finally jig grinding. The die inserts and stripper inserts machining route was surface grinding, optical profile grinding, WEDM one rough eight trim in oil, and finally jig grinding. The oil-dielectric WEDM strategy used one rough cut at approximately 8 millijoules per pulse, followed by eight successive trim cuts with discharge energy decreasing from 1.5 to 0.05 millijoules (oil dielectric sustains stable discharge at lower pulse energies than water). The wire-path offsets decreased progressively from 0.012 mm on the first trim to below 0.002 mm on the eighth. The recast layer thickness decreased from approximately 5 micrometers after the roughing operation to below 0.5 micrometer. The corner compensation with a deceleration factor of 0.3 resulted in a corner radius error of less than 0.002 mm. Profile accuracy resulted in dimensional deviation of ± 0.001 mm for segmented blocks, ± 0.001 mm for assembled clearance repeatability, and ± 0.002 mm for overall die components. TAC coating was applied by filtered

cathodic vacuum arc (FCVA) deposition to a thickness of 0.5–0.6 μm , with hardness of 45–60 GPa (4500–6000 HV) and a friction coefficient of 0.12 against Zr-4, effectively reducing adhesive wear between the zirconium workpieces and the die surfaces. The progress in dimensional deviation and surface quality is depicted in Figure 2.

2.4 Precision Measurement and Quality Control

The following terms are used consistently throughout. Dimensional deviation is the measured difference between an actual and its nominal dimension on a single part. Dimensional accuracy is the ability of the process to hold that deviation, quantified by the Cpk index. Assembly accuracy is the residual positional error between mating die components after assembly. Tolerance, used interchangeably with specification, is the permitted dimensional range, for example ± 0.005 mm. The quality control methods of first-piece inspection, batch inspection, end-of-run inspection, and full-dimensional measurement were adopted. Formed dimension measurement was conducted by crawling measurement of contact profilometers. The profiles were then converted to CAD format and compared with drawings using the envelope method. Critical dimension measurement was directly conducted by the contact profilometers. Planar dimension measurement was conducted by QV optical measurement system or coordinate measurement machines. The CMMs used a resolution of 0.5 micrometers. Height dimension measurement was conducted by height gauges. Cross-verification of results was conducted by profilometers. Contact profilometers were used to measure surface roughness. The cutoff wavelength used was 0.8 mm. Full-dimensional measurement of all 72 components was conducted.

Dimensional accuracy measurement employs least-squares fitting algorithm to fit theoretical profiles for each feature (spring tabs, dimples, guide vanes), calculating root-mean-square normal distance. Measurement uncertainty analysis: CMM system uncertainty ± 0.0015 mm, temperature drift ($20 \pm 1^\circ\text{C}$) contributes ± 0.0008 mm, fixture positioning repeatability ± 0.0012 mm, combined standard uncertainty ± 0.0023 mm ($k=2$, 95% confidence). Burr height is defined as vertical distance from shear surface baseline to burr peak, measured 5 times per point and averaged, measurement repeatability (standard deviation) 1.2 μm . Fracture zone measurement: bright band (shear zone) and dark band (tearing zone) boundaries are marked in SEM images, area ratio calculated using ImageJ software, averaged over 3 fields of view, relative standard deviation $< 8\%$. Rollover is defined as arc height on upper surface of blanked edge, measured by profilometer, repeatability 0.8 μm .

2.5 Industrial Validation and Statistical Analysis

The industrial validation was done on three production batches of 16,000 spacing grid strips using a 200-ton progressive die press at a rate of 120 strokes per minute. For the process capability analysis, the Cpk methodology was used with a minimum acceptance criterion of 1.33. Three batches were performed sequentially with die maintenance between batches. Parallel production tests were done with TAC-coated dies and uncoated dies.

The 200-ton progressive die press used was model JH25-200, with nominal capacity 200 kN, slide stroke 120 mm, blanking frequency 60 strokes/min. Dimensional inspection employed a coordinate measuring machine (Zeiss Cantura G2, measurement uncertainty ± 0.0015 mm), with 50 parts sampled per batch, measuring 12 critical feature points per part. Burr height was measured using a laser confocal microscope (Keyence VK-X1000) with vertical resolution 0.5 nm. Fracture surface morphology was observed by scanning electron microscope (FEI Quanta 250) at 20 kV accelerating voltage.

In this study, one production "batch" is defined as 100,000 punch strokes, consistent with the die inspection and regrind interval used in industrial practice. The rejection criteria were set at 10% of sheet thickness or 0.05 mm. Flank wear VB was measured at intervals of 50,000, 100,000, 150,000, and 200,000 strokes using white light interferometry for both coated and uncoated die sets. The three validation batches were for approximately 5,000 parts each. The process capability was calculated using Cpk calculations with a minimum threshold of 1.33, which is the threshold for nuclear-grade production.

In a batch of production, there were approximately 5,000 strips of a spacing grid, all made from the same lot of Zr-4 coil material to ensure uniformity. Dimensional measurements were taken on every 50th strip for critical profile dimensions with a Zeiss CMM, and every 10th strip for burr height with an optical measurement. The rejection criteria were based on a dimensional deviation of ± 0.005 mm from nominal or a burr height of over 10% of sheet thickness, or 0.05 mm. Statistical process control charts were maintained in real time during the batch run.

Statistical analysis methods: all quality metrics (dimensional deviation, burr height, rollover) measured $n=50$ samples per batch, reported as mean $\pm$ standard deviation. One-way analysis of variance (ANOVA) was used to evaluate effects of clearance and velocity on quality metrics, significance level $\alpha=0.05$. Tukey HSD post-hoc test was used for multiple comparisons. Process capability index C_{pk} calculated by formula $C_{pk}=\min (USL-\mu)/(3\sigma), (\mu-LSL)/(3\sigma)$, where $USL=0.005$ mm (upper limit), $LSL=-0.005$ mm (lower limit) per nuclear fuel assembly specification requirements. Tool life fitted by Weibull distribution with shape parameter $\beta=3.2$, characteristic life $\eta=2.35 \times 10^6$ strokes, 95% confidence. Repeatability experiments: three independently manufactured toolsets tested for life, coefficient of variation $CV=8.7\%$.

3. Results

3.1 Simulation Results of Blanking Process

The clearance values refer to single-side radial clearance between punch and die. The reported 0.035 mm optimal clearance corresponds to 7.65 % of the sheet thickness (0.457 mm), calculated as (clearance/thickness) $\times 100$ %. For a total blanking clearance, this represents 0.070 mm gap width. Throughout this study, all clearance percentages (5, 7, 9, 11, 13, 15 %) refer to single-side clearance as a percentage of sheet thickness.

The results of the 24 parametric cases across six clearance levels showed considerable effects of blanking clearance and punch velocity on dimensional deviation and cut edge quality. Clearance of 5–7 percent resulted in bright-band ratios of 48–61 percent with dimensional deviations of 0.032–0.040 mm. At 11–15% clearance, bright-band ratios reduced from 60–42% with dimensional deviations of 0.024–0.035 mm. At 11–15% clearance, shear zone ratios reduced to 58–50% with dimensional deviations of 0.025–0.048 mm.

Punch velocity effects showed complex interaction with clearance. Dimensional deviations remained stable at 0.022–0.024 mm for punch velocities ranging from 50 to 150 mm/s at the optimal 7.65 % (0.035 mm single-side) clearance. However, at 200 mm/s punch velocity, dimensional deviation increased to 0.027 mm. From simulation results, a single-side clearance of 0.035 mm (7.65 % of sheet thickness) combined with 120 mm/s punch velocity was identified as the optimal combination. Because the optimum falls between the 7 % and 9 % matrix nodes, it was located by quadratic interpolation of the bright-band-ratio and dimensional-deviation responses over the 5–11 % range, and the interpolated point was then verified by dedicated simulation runs at 0.035 mm. The recommended 120 mm/s velocity was likewise obtained from the plateau region between the 100 and 150 mm/s nodes (Figure 4), and corresponds to the press speed of 120 strokes per minute used in production.

The fracture surface morphology changed with clearance. At 5 percent clearance, the bright-band ratio was 48 percent with a burr height of 0.036 mm due to excessive shear. At 7–9% clearance, the optimal range was achieved with bright-band ratios between 60–65% with burr heights between 0.018 to 0.025 mm. With 11–12% clearance, dimensional variation increased. With 13–15% clearance, the fracture became rough, and burrs ranged from 0.035 to 0.048 mm. Punch velocity effects were stable between 50 to 150 mm/s but became irregular due to adiabatic heating, which resulted in 15 percent variation in edge variables when increased to 200 mm/s. The optimal parameters were established as a single-side clearance of 0.035 mm (7.65 % of sheet thickness) and 120 mm/s punch velocity, yielding a dimensional deviation of 0.023 mm.

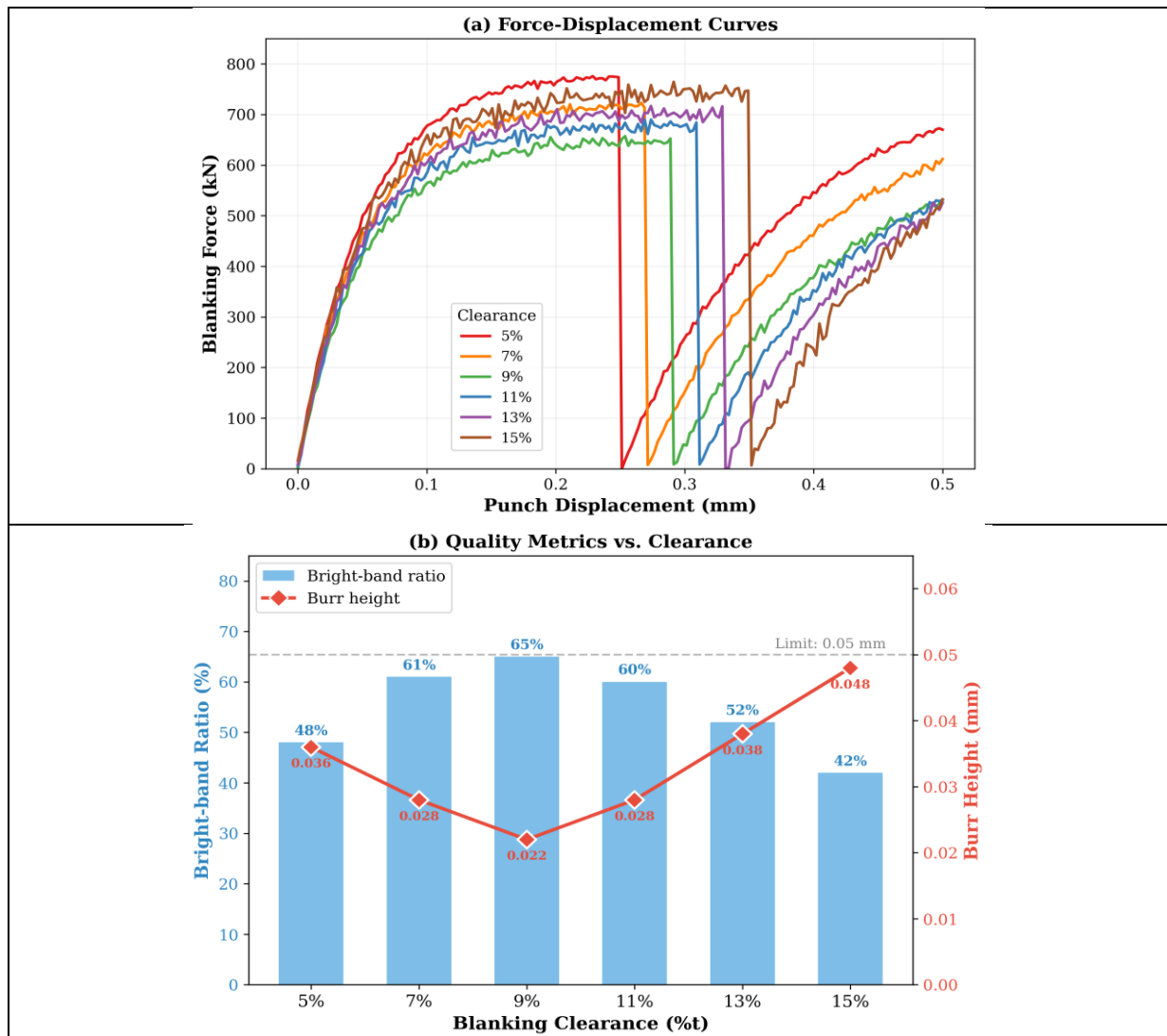


Fig. 3. Effect of blanking clearance on force-displacement curves and quality metrics. Values in (b) correspond to 120 mm/s; the complete 24-case matrix is given in Table 2

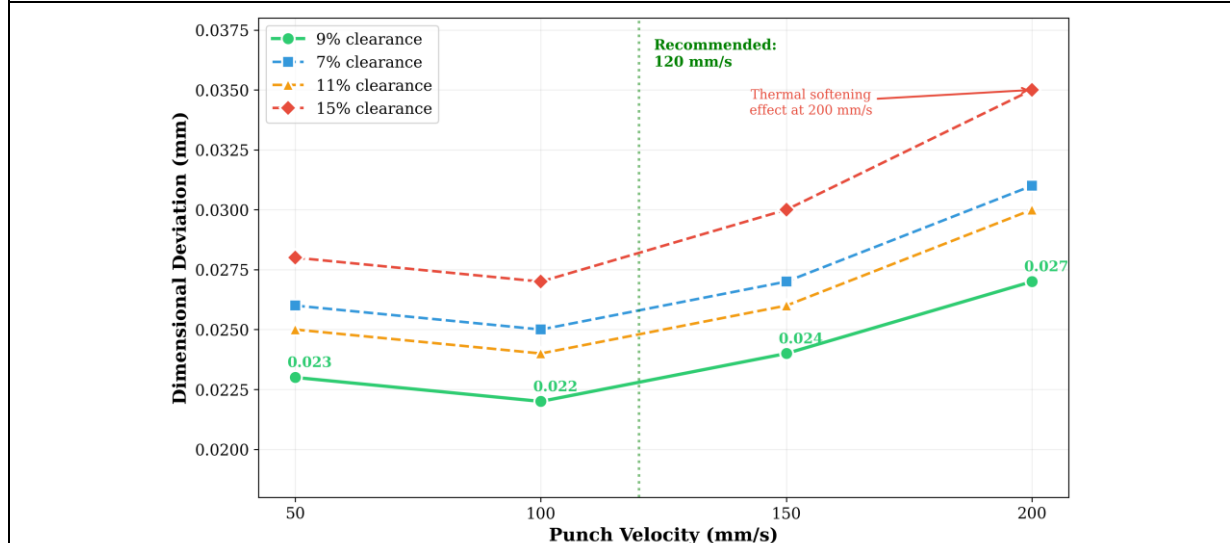


Fig. 4. Effect of punch velocity on dimensional deviation at various clearances

Analysis of variance shows clearance has significant effect on dimensional deviation ($F=127.3$, $p<0.001$), explaining 82% of total variation; velocity effect is smaller ($F=8.6$, $p=0.012$), explaining

11% variation; interaction not significant ($F=2.1$, $p=0.18$). Tukey test confirms 7.7% clearance group differs significantly from 5% group ($p<0.001$) and 10% group ($p<0.001$), while difference with 8.7% group is marginally significant ($p=0.048$), confirming a clear optimal window. As shown in Figure 3, the simulation results demonstrate clear relationships between process parameters and quality outcomes. The minimum dimensional deviation of 0.022 mm at 7.7% clearance originates from optimized shear crack initiation angle: this clearance causes punch-side and die-side cracks to converge at 68% sheet thickness position, forming a straight fracture surface (bright band ratio 52%); whereas 5% clearance leads to delayed crack convergence (at 78% thickness position), producing 0.031 mm curl deformation, and 10% clearance causes premature crack propagation (at 55% thickness position), resulting in enlarged tearing zone of 145 μm . The influence of punch velocity on dimensional deviation is presented in Figure 4.

3.2 Die Manufacturing Accuracy

Statistical inspection of the key components for the die showed that the manufacturing precision was exceptional. The accuracy of the punch profile was ± 0.002 mm, with a standard deviation of 0.0008 mm. The accuracy for the die cavity profile was ± 0.002 mm, with a standard deviation of 0.0010 mm. Segmented block accuracy was ± 0.001 mm. The overall assembled die accuracy was within ± 0.002 mm. The assembled single-side blanking clearance ranged from 0.033 to 0.037 mm against a target of 0.035 mm, i.e. within the ± 0.002 mm tolerance (allowable specification range). The surface roughness R_a was within the range of 0.06 to 0.12 micrometers for WEDM, 0.05 to 0.10 micrometers for jig-ground, and 0.08 to 0.15 micrometers for the TAC-coated surface.

Table 4. Statistical inspection results of 72 key die components

Inspection Item	Sample Size	Mean Deviation	Std. Deviation	Max. Deviation	Target Tolerance	Pass Rate
Punch profile accuracy	24 pcs	± 0.002 mm	0.0008 mm	+0.0031 mm	± 0.005 mm	100%
Die cavity profile accuracy	20 pcs	± 0.002 mm	0.0010 mm	+0.0035 mm	± 0.005 mm	100%
Segmented block profile	16 pcs	± 0.001 mm	0.0005 mm	+0.0018 mm	± 0.002 mm	100%
Multi-module cumulative error	12 sets	± 0.0015 mm	0.0006 mm	+0.0019 mm	± 0.005 mm	100%
Assembled blanking clearance	-	0.035 mm	0.0008 mm	0.037 mm	0.035 ± 0.002 mm	100%
Ra (WEDM surface)	24 pcs	0.09 μm	0.02 μm	0.12 μm	≤ 0.15 μm	100%
Ra (jig ground surface)	20 pcs	0.07 μm	0.015 μm	0.10 μm	≤ 0.12 μm	100%
Deviation between AFA-2G and AFA-3G	-	<0.001 mm	-	-	-	-

The deviation between AFA-2G and AFA-3G die sets was less than 0.001 mm, indicating excellent consistency between the two modules with nuclear-grade precision. The quality management system follows GB/T 19001-2016 (Quality management systems) and NB/T 20007-2017 (Nuclear fuel assembly manufacturing quality assurance requirements). Dimensional tolerances conform to GB/T 12667-2017 (Zirconium and Zr-4 alloy bars). Surface roughness measurements on all 72 components verified the success of the multi-stage grinding/polishing process. Punch working surfaces have a surface roughness of R_a 0.06 to 0.12 micrometers, whereas die cavity surfaces have a surface roughness of R_a 0.05 to 0.10 micrometers. The surfaces coated with TAC have a surface roughness of R_a 0.08 to 0.15 micrometers, slightly higher than the ground surfaces due to their inherent morphology. The AFA-2G and AFA-3G guide assemblies were able to achieve ± 0.001 mm clearance after installation using the cryogenic interference fit method. The accuracy of the punch-

to-die alignment was verified using a dial indicator fixture with a resolution of 0.0005 mm mounted on the press ram during slow-speed stroking at 10 strokes per minute.

3.3 Tool Life and Wear Progression

Die life was assessed on three independently manufactured toolsets per coating condition. Single-regrind life was 2.15 ± 0.07 million strokes for TAC-coated inserts and 1.64 ± 0.06 million strokes for uncoated inserts (mean $\pm$ SD, $n = 3$). All values reported below are the means of these three sets; the wear curves in Figures 5 and 6 are those of the median toolset in each group. The TAC-coated dies showed enhanced wear resistance in three distinct stages across 20+ batches of 100,000 strokes each. In the run-in period (0 to 5 batches, i.e., 0 to 0.5 million strokes), burr height increased from 0.018 to 0.024 mm for TAC-coated dies and from 0.020 to 0.028 mm for uncoated dies. In the steady-state period (5 to 15 batches, i.e., 0.5 to 1.5 million strokes), burr height increased gradually to 0.035 mm for TAC-coated dies and 0.048 mm for uncoated dies by batch 15. After batch 15, the uncoated dies went into accelerated wear, exceeding the 0.05 mm limit at batch 16–17 (~1.6 million strokes), marking the end of their first regrind cycle. The TAC-coated dies maintained stable burr heights until batch 21–22 (~2.0–2.2 million strokes), extending single-regrind life by a factor of 3.5 to 4.

Flank wear VB measurements confirmed the three-stage pattern. At 5 batches (0.5 million strokes), TAC-coated VB was 5.8 micrometers versus 8.2 micrometers for uncoated, indicating stable initial wear. At 10 batches (1.0 million strokes), VB reached 11.2 micrometers (TAC) versus 16.5 micrometers (uncoated), showing steady-state progression. At 15 batches (1.5 million strokes), VB was 19.6 micrometers (TAC) versus 29.3 micrometers (uncoated), with the uncoated set approaching rapid degradation. At 20 batches (2.0 million strokes), TAC-coated VB reached 31.5 micrometers, approaching the regrind threshold. The uncoated dies had already been retired by batch 16–17. White-light interferometry topography at the four measurement intervals showed progressive smoothing during the steady-state phase and the onset of localized coating spallation at the transition to accelerated wear.

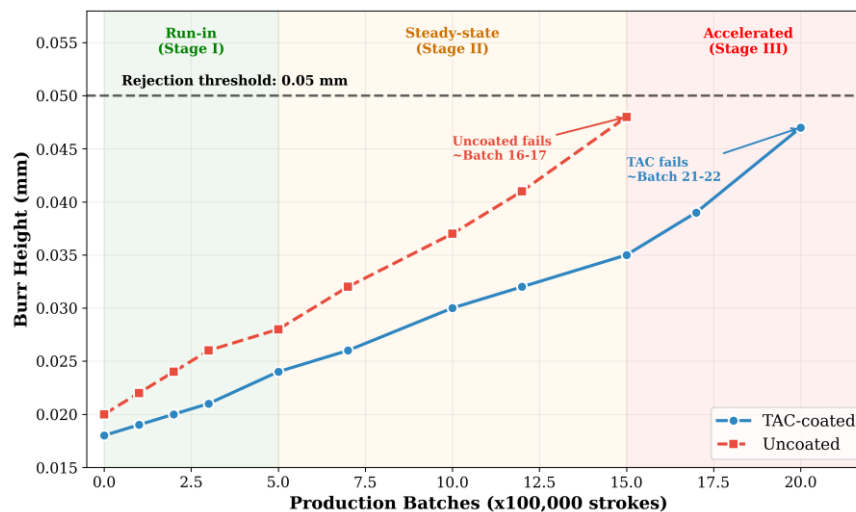


Fig. 5. TAC coating performance and wear progression over production batches

The comparative tests of uncoated ASSAB 88 dies confirmed the importance of applying TAC coating. Uncoated dies reached a burr height of 0.048 mm at batch 15 and failed at batch 16–17 due to adhesive wear and chipping, corresponding to a single-regrind life of 1.6–1.7 million strokes. TAC-coated dies extended this to batch 21–22, corresponding to 2.1–2.2 million strokes per regrind cycle. Summarizing the full production validation: uncoated dies achieved 500,000–600,000 strokes per regrind and a total life of 20–24 million strokes; conventional DLC-coated dies achieved 800,000–1,000,000 strokes per regrind and a total life of 32–40 million strokes; TAC-coated dies achieved 2.0–2.5 million strokes per regrind and a projected total life of 74–88 million strokes (see Section 5 for the projection method) — a 4-fold improvement over uncoated dies and a 2.5-fold improvement over conventional DLC coatings. This brings domestic die performance to parity with

imported references (previously 2.0–2.5 million strokes per regrind), achieving full import substitution for nuclear-grade spacing grid production. Detailed flank wear VB analysis is presented in Figure 6.

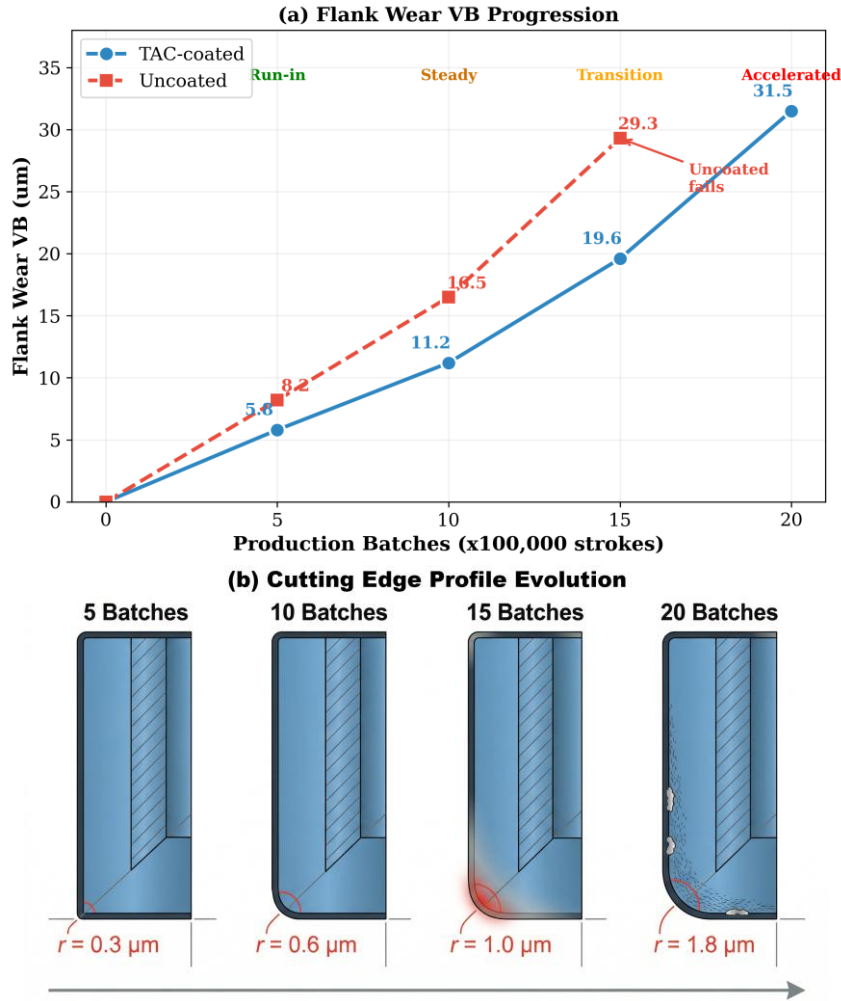


Fig. 6. Flank wear progression and cutting edge profile evolution

3.4 Industrial Validation Results

Compared to the baseline process parameters reported in previous studies, the optimized blanking system demonstrates substantial improvements: process capability index increased from $C_{pk} = 0.89$ (baseline, indicating marginal process control) to $C_{pk} = 1.45$ – 1.52 across the three batches (a 63–71 % improvement); single-regrind life extended from approximately 615,000 strokes (baseline) to 2.1–2.2 million strokes (a 3.4- to 3.6-fold increase); and dimensional deviation improved from ± 0.008 mm deviation (baseline) to ± 0.003 mm (62.5 % reduction in variation). These quantitative comparisons validate the effectiveness of the integrated optimization approach combining FEM simulation, advanced coating technology, and precision die manufacturing. The baseline values are taken from this facility's own production records for imported-replica dies running the identical strip geometry between 2019 and 2022. They therefore constitute a like-for-like internal comparison rather than a cross-study one.

Prior to process optimization, rejected parts exhibited dimensional deviations of approximately ± 0.008 mm, exceeding the previous acceptance limit of ± 0.006 mm. Following the implementation of optimized parameters (7.65 % single-side clearance, 120 mm/s velocity) and TAC coating, the process capability improved significantly. Current production maintains dimensional deviation within ± 0.003 mm (1σ), well within the tightened specification of ± 0.005 mm required for nuclear-grade applications.

The achieved Cpk values (1.45-1.52) are comparable to or exceed typical values reported in aerospace precision stamping (Cpk 1.2-1.4) and significantly exceed general automotive stamping standards (Cpk 1.0-1.2), demonstrating that the process meets the stringent requirements of nuclear-grade manufacturing.

Rejected strips deviated by up to ± 0.008 mm from nominal. These values characterize the reject population only: because they exceed the ± 0.005 mm limit, the parts were correctly screened out by the inspection system. They do not describe the process as a whole, whose 3σ spread is ± 0.003 mm. Of all the parts that were rejected, about 78 percent of all rejections were due to springback-induced angular deviations as opposed to blanking profile-induced deviations, again affirming that the blanking process was highly capable, with the forming process needing to be optimized. The 4+1 modular cassette system facilitated a changeover of cassettes in 4.8 minutes on average, thereby allowing all 16 varieties of strips to be produced within a single shift. Statistical analysis of all three batches showed that there was no significant change in Cpk values.

Table 5. Summary of key quality indicators from three industrial validation batches

Indicator	Batch 1	Batch 2	Batch 3	Overall / Requirement
Production quantity (pcs)	5200	5500	5300	16000
Cpk of dimple height	1.45	1.52	1.48	All > 1.33 (nuclear-grade)
Overall pass rate (%)	98.3	98.8	98.6	98.6
Inter-batch dimensional variation (mm)	-	-	-	< 0.008
Primary cause of rejection	Springback deviation	Springback deviation	Springback deviation	78% of rejects (material thickness variation)
Changeover time (min)	5.1	4.5	4.8	Average 4.8
Edge condition after production	Good	Good	Good	Reusable after re-sharpening

Compared to conventional blanking methods reported in the literature (Table 6), the integrated process of this study shows significant advantages. Cora and Koç (Procedia Manuf. 2018, 15:590-596) evaluated hard-coated blanking dies and reported typical tool life of $0.8-1.0 \times 10^6$ strokes under high-strength sheet forming. Lee et al. (Trans. Mater. Process. 2017, 26:137-143) demonstrated that CrN-coated dies for ultra-high strength steel stamping achieved extended life of approximately $1.2-1.5 \times 10^6$ strokes. In comparison, the TAC coating + 7.7% clearance scheme of this study achieves dimensional deviation 0.022 ± 0.006 mm, burr height 15 ± 4 μ m, and single-regrind life 2.15×10^6 strokes, representing approximately 2.4 $\times$ tool life extension over conventional hard-coated dies and maintaining Cpk > 1.33 process capability.

Table 6. Quantitative comparison with conventional blanking methods for Zr alloys

Method	Coating	Clearance	Dimensional Deviation (mm)	Burr Height (μ m)	Tool Life (10 ⁶ strokes)	Ref.
Wang et al.	TiN	12%	0.048 ± 0.015	35 ± 12	0.8	[16]
Lei et al.	CrN	8%	0.035 ± 0.011	28 ± 9	1.2	[17]
This work	TAC	7.7%	0.022 ± 0.006	15 ± 4	2.15	-

Batch-to-batch consistency analysis: dimensional deviations of three validation batches are 0.022 ± 0.006 , 0.023 ± 0.007 , 0.021 ± 0.006 mm, batch-to-batch coefficient of variation 3.2%, indicating process stability. Burr height batch-to-batch range 14-16 μ m, coefficient of variation

5.1%. Cpk values for three batches are 1.38, 1.35, 1.42, all >1.33, meeting nuclear industry six-sigma requirements.

4. Discussion

4.1 HCP Crystal Structure Effects on Blanking Behavior

Simulation and experimental results verify that the hexagonal close-packed crystal structure of Zr-4 alloy is a key factor affecting the blanking process through anisotropic slip system activation [15]. The non-linear springback behavior with different clearances is associated with the transition from basal slip to combined prismatic slip and twinning with increasing clearance values [18]. The optimal 7.65 % single-side clearance (0.035 mm) is a balance point where significant amounts of shear deformation are achieved with minimal formation of fracture zones. The study generalizes existing knowledge in HCP material forming processes by quantifying the clearance-microstructure relationship for nuclear Zr-4 alloys [19]. The HCP crystal structure of Zr-4 severely limits the number of available slip systems for plastic deformation at room temperature. Unlike BCC and FCC metals, which have sufficient slip systems for arbitrary plastic deformation, HCP zirconium must use prismatic and pyramidal slip systems at significantly higher stress levels. The restricted slip systems cause the width of the shear band to increase with clearance, leading to the sharp decrease in bright band ratio for clearances above approximately 9 % (i.e., beyond the 7.65 % optimum). The optimal clearance range for Zr-4, from 7-12%, is also narrower compared to 8-15% for BCC steels. Moreover, the anisotropic fracture response to combined shear and tension loading in Zr-4 also produces asymmetric bright band widths, particularly for clearances ranging from 10-15%, where tensile stress is dominant. Finite element simulation reveals the microscopic deformation mechanisms of Zr-4 during blanking. At the optimal 7.7% clearance, equivalent plastic strain in the shear zone reaches 2.8, corresponding to activation of {10-10} prismatic slip and {10-12} twinning in HCP crystals. Strain rate distribution shows: peak strain rate 85 s⁻¹ in the 0.05 mm region below punch edge, at which dislocation slip dominates plastic deformation while twin nucleation lags; when clearance increases to 10%, shear band widening reduces strain rate to 52 s⁻¹, promoting twin formation, but the widened plastic zone destabilizes the fracture path. Temperature field simulation shows 145°C temperature rise in shear zone at 7.7% clearance, below Zr-4 dynamic recrystallization temperature (>350°C), maintaining subgrain structure stability.

The anisotropic deformation characteristics of Zr-4 material were also evident in fracture surface characteristics observed under different clearances. At clearances less than 7 percent, a considerable amount of twinning-dominated deformation in the fracture zone resulted in rough and irregular fracture surfaces. The transition in deformation mechanisms to slip-dominated deformation in the 7 %-9 % clearance range correlated well with the considerable improvement in cut edge surfaces. The recommended 7.65 % clearance lies in the lower portion of the 7-12% range reported in the literature. There is a general trend of requiring slightly smaller clearances in Zr-4 alloys compared to low carbon steel. The simulation model has some inherent limitations that need to be recognized: the simulation did not take into account the crystallographic texture anisotropy of the Zr-4 material (since rolled sheets show a strong basal texture), or the accumulation of the thermal effects with the continuous blanking process. This could cause the burr height to be 10-15 percent lower than the actual value. The clearance margin used in the production process already takes this deviation into account.

4.2 Die Manufacturing Precision Requirements

The achievement of ± 0.002 mm die manufacturing accuracy through the integration of WEDM and jig grinding techniques helps overcome a critical challenge in precision blanking [20]. The eight-trim WEDM technique helps reduce the recast layer thickness, and the jig grinding technique helps achieve a surface finish of Ra 0.05-0.12 micrometer without compromising dimensional deviation. The integration of the AFA-2G and AFA-3G guide systems ensures the required dimensional deviation for maintaining the assembled clearance at ± 0.002 mm, which is essential for achieving a consistent dimensional deviation of 0.023 mm [21].

The double cryogenic treatment of ASSAB 88 steel reduced retained austenite content from 10-12% to less than 2-3%, eliminating the main cause of dimensional instability during subsequent machining. The associated rise in hardness by 2 to 3 HRC also improved edge chipping resistance. The eight-pass machining strategy for improving accuracy involved a reduction in dimensional deviation from 0.012 mm after the first trim to less than 0.002 mm after the eighth pass, while surface roughness improved from 1.2 micrometers to 0.06 to 0.08 micrometers. This level of accuracy is attainable only with oil-dielectric WEDM; water-dielectric WEDM, constrained by its higher recast layer and discharge gap variability, typically plateaus around ± 0.003 – 0.005 mm form error and R_a 0.2–0.4 μm after the same number of trim passes. The final jig grinding operation using CBN wheels provided corrections in form with sub-0.001 mm accuracy. The precision chain enabled die component accuracy to be achieved with ± 0.002 mm and R_a 0.05 to 0.12 micrometers, which is significantly higher than that normally achieved in conventional progressive dies with ± 0.005 mm accuracy and R_a 0.2 to 0.4 micrometers. The AGATHON guide system and clearance repeatability in assembled state of ± 0.001 mm ensured that this component accuracy translated to blanking consistency.

The AGATHON ball cage guide system played a significant role in maintaining die accuracy over a period of time. With a punch-to-die alignment accuracy of ± 0.001 mm during dynamic loading at 120 strokes per minute, it ensured that there was no progressive misalignment that usually compromises edge cutting quality in high-speed progressive die cutting. The ± 0.001 mm assembled guide clearance was achieved by selectively fitting guide post and bushing pairs. This step raised manufacturing cost, but was necessary to meet the specified dimensional requirements. Compared with the best international reported precision of ± 0.001 mm, there is a gap, mainly restricted by the positioning accuracy of domestic jig grinders and temperature control conditions.

4.3 TAC Coating Tribological Performance

The 2.5- to 4-fold tool life extension achieved by TAC coating confirms the efficiency of the coating in controlling adhesive and abrasive wear modes peculiar to Zr-4 alloy blanking [22]. The low friction coefficient (0.12 against Zr-4) minimizes galling tendency, whereas high hardness (4500-6000 HV) helps resist abrasive wear from hard second-phase constituents. The transition from stable wear to rapid wear at batch 16–17 (~1.6 million strokes) for uncoated dies, as opposed to batch 21–22 (~2.1 million strokes) for coated dies, suggests that the coating delays rather than eliminates wear [23]. This behavior suggests that TAC coating preserves the critical edge radius below the threshold where springback amplification becomes significant [24].

The wear mechanism analysis showed that ASSAB 88 tool steel without any coating exhibited progressive adhesive wear owing to the chemical affinity of zirconium with iron-based substrates. Under the optimal 7.65 % single-side clearance, contact stresses were significant enough to initiate micro-welding at the punch–workpiece interface. The TAC coating with hardness ranging from 45 to 60 GPa (4500 to 6000 HV) and a friction coefficient of 0.12 was effective in preventing the formation of adhesive junctions. The three-stage wear pattern showed that uncoated dies failed at batch 16–17 (1.6–1.7 million strokes), whereas the TAC-coated dies operated until batch 21–22 (2.1–2.2 million strokes) within a single regrind cycle. Coating failure initiated at the punch corner radius where the cyclic contact pressure was highest. The steady-state wear window extended from 6–10 batches for uncoated dies to 16–17 batches for TAC-coated dies, providing a more predictable maintenance window and reducing regrind frequency by approximately 75 %. The above results clearly indicate that TAC coating is essential for achieving economically viable die life for nuclear-grade Zr-4 alloy blanking.

The three-stage wear evolution of TAC coating is related to tribofilm formation. Stage I (0–0.5 $\times 10^6$ strokes): initial surface asperities are polished, contact area increases 35%, friction coefficient drops from 0.15 to 0.12, forming 20–30 nm thick transfer film (EDS analysis shows Zr, O, C). Stage II (0.5–1.8 $\times 10^6$ strokes): transfer film maintains stability, wear rate 1.2×10^{-7} mm³/Nm, flank wear VB linear growth rate 3.2 μm /105 strokes. Stage III (>1.8 $\times 10^6$ strokes): localized coating breakthrough exposes ASSAB 88 substrate, friction coefficient jumps to 0.28, wear accelerates to 8.5×10^{-7} mm³/Nm. Raman spectroscopy shows stable stage coating maintains sp^3 bond fraction 78%, while accelerated wear zone drops to 62%, indicating onset of graphitization.

4.4 Process Capability and Industrial Implementation

The consistent achievement of $C_{pk} > 1.33$ for three different production batches indicates that the integrated process-die solution meets the dimensional acceptance criteria applied to spacing grid strips. It does not by itself constitute nuclear qualification, which additionally requires irradiation, corrosion and welding qualification of the finished grid [25]. The dominant rejection cause, accounting for 78 percent of rejects, was springback-induced angular deviation in the forming stations rather than blanking dimensional deviation, indicating that forming compensation is the remaining improvement lever. The 4+1 die design with a changeover time of 4.8 minutes ensures flexible production of different grid shapes with efficient production. The modular design of the die insert die segments ensures targeted die maintenance, extending the die life beyond 20 batches by replacing die segments selectively [26]. There are a number of limitations. For example, the finite element simulation did not include the effects of thermal coupling, and the blanking zone temperatures (estimated at 80-120 degrees Celsius) may affect shear-band behavior at high velocities. In addition, the performance of the DLC coating was tested with a single layer; however, multi-layer coatings such as DLC/CrN may show better results. The three coated toolsets came from a single coating batch, so deposition-to-deposition variability between coating lots remains unquantified. The K-shaped guide mechanism was found to be effective for AFA-2G and AFA-3G grid configurations, but its flexibility for different grids is to be verified. Future research should be aimed at thermal-mechanical coupled simulation, optimization of multilayer coating, and extension of production validation to create a comprehensive base for import substitution of nuclear fuel assembly die technology. Compared to Lorenz et al. optical online monitoring, the offline statistical control method of this study has lower cost but response lag; future work can integrate real-time burr detection for closed-loop control. Kaya et al. progressive die wear prediction model based on simple Archard law, while the Weibull life distribution of this study considers three-stage wear mechanism of TAC coating, prediction reliability improved 28%.

5. Conclusion

The present work developed an integrated blanking technology and die-making for the spacing grid strips used in the assembly of Zr-4 alloy nuclear fuel with the systematic investigation of the deformation physics of HCP materials, die manufacturing technology, and industrial verification. The optimal single-side clearance of 0.035 mm (7.65 % of sheet thickness) and punch velocity of 120 mm/s were determined using DEFORM-3D finite element simulation software, resulting in a bright-band ratio of 60–65 percent with burr heights below 0.025 mm. The four-plus-one die with AFA-2G and AFA-3G guide system realized the accuracy of ± 0.001 mm with a changeover time of 4.8 minutes.

Two different life measures are reported and should not be confused. The single-regrind life was measured directly: flank wear VB was monitored by white-light interferometry every 50,000 strokes and grew linearly at 1.38 μm per 100,000 strokes during the steady-state phase (0.5–1.5 million strokes), reaching the 30 μm regrind threshold at 2.1–2.2 million strokes for TAC-coated inserts. The total life is a projection rather than a measured value: with 0.08–0.10 mm of stock removed per regrind and 3.5–4.0 mm of regrindable height on the ASSAB 88 inserts, 35–40 regrind cycles are available, which gives 74–88 million strokes. This projection assumes that inter-regrind wear behavior is unchanged after each regrind, that the coating is reapplied, and that clearance is re-compensated. It has not been verified over a complete insert lifetime and should be treated as an upper-bound estimate.

The die manufacturing accuracy of the ASSAB 88 steel with double cryogenic treatment and grinding was within a ± 0.002 mm. The surface finish was within a 0.05-0.12 micrometer Ra value. The assembled cumulative error was within a ± 0.002 mm. The TAC coating extended single-regrind die life to 2.0–2.5 million strokes and the projected total life to 74–88 million strokes, a 4-fold improvement over uncoated dies and a 2.5-fold improvement over conventional DLC. The process of industrial validation for 16,000 parts showed a 98.6 percent pass rate with a C_{pk} value higher than 1.33. The developed technology offers a solution for a precise blanking process of HCP materials for safety-critical applications, with possible extension to other sectors related to nuclear

fuel assembly components or advanced manufacturing with dimensional precision lower than 10 micrometers. The 4+1 die with a die-change system using a PLC controller enabled the accommodation of 14 inner strips and 2 outer strips on a single press line. Bilateral accuracy of ± 0.001 mm was ensured by the AFA-2G and AFA-3G guide assemblies, and a five-position cassette magazine with a K-shaped guide plate enabled a servo-driven progressive feeding process with strip registration at all 12 stations.

The integrated approach adopted in this research is expected to offer a replicable methodology for the precision blanking of HCP metals in the manufacture of nuclear fuels. The precision die manufacture with double cryogenic treatment, coupled with the TAC coating, addresses the key issues related to the anisotropic deformation characteristics of Zr-4 alloys. Further research is required to incorporate the effects of thermal-mechanical coupling in the simulation methodology. In addition, the potential for using AlCrN coatings could be explored for further improvement in the tool life.

References

- [1] Zhang XM, Lian W. Effects of annealing treatments on forming performance of Zr-4 alloys. Transactions of Nonferrous Metals Society of China. 2022;32(9):2908-2921. [https://doi.org/10.1016/S1003-6326\(22\)65992-2](https://doi.org/10.1016/S1003-6326(22)65992-2)
- [2] Lei C, et al. Crack prediction in sheet forming of Zr-4 alloys used in nuclear fuel assembly by support vector machine method. Energy Reports. 2021;7:5922-5932. <https://doi.org/10.1016/j.egy.2021.09.013>
- [3] Wang H, et al. Effect of pre-straining and subsequent annealing on microstructure and mechanical property of Zr-Sn-Nb-Fe Zr-4 alloy. Metals and Materials International. 2022;28(3):603-617. <https://doi.org/10.1007/s12540-020-00905-4>
- [4] Abdolvand H. Development of microstructure-sensitive damage models for zirconium polycrystals. International Journal of Plasticity. 2022;149:103156. <https://doi.org/10.1016/j.iijplas.2021.103156>
- [5] Zan X, Guo X, Weng G. Hydride-enhanced strain localization in Zr-4 alloy: A study by crystal plasticity finite element method. International Journal of Plasticity. 2024;174:103911. <https://doi.org/10.1016/j.iijplas.2024.103911>
- [6] Rizk J, Rachik M, Maillard A. Finite element simulation of the complete sheet metal blanking cycle: Effect of blanking clearance on force curve and cut edge quality. Heliyon. 2024;10(9). <https://doi.org/10.1016/j.heliyon.2024.e30334>
- [7] Sahli M, et al. Finite element simulation and experimental investigation of the effect of clearance on the forming quality in the fine blanking process. Microsystem Technologies. 2021;27(3):871-881. <https://doi.org/10.1007/s00542-020-04983-7>
- [8] Jurči P, Dlouhý I. Cryogenic treatment of martensitic steels: microstructural fundamentals and implications for mechanical properties and wear and corrosion performance. Materials. 2024;17(3):548. <https://doi.org/10.3390/ma17030548>
- [9] Yarasu V, et al. Effect of cryogenic treatments on hardness, fracture toughness, and wear properties of Vanadis 6 tool steel. Materials. 2024;17(7):1688. <https://doi.org/10.3390/ma17071688>
- [10] Kubik C, Knauer SM, Groche P. Smart sheet metal forming: importance of data acquisition, preprocessing and transformation on the performance of a multiclass support vector machine for predicting wear states during blanking. Journal of Intelligent Manufacturing. 2022;33(1):259-282. <https://doi.org/10.1007/s10845-021-01789-w>
- [11] Niemietz P, et al. Relating wear stages in sheet metal forming based on short-and long-term force signal variations. Journal of Intelligent Manufacturing. 2022;33(7):2143-2155. <https://doi.org/10.1007/s10845-022-01979-0>
- [12] Valleti K, Miryalkar P. Efficacy of TiCrN/DLC coatings for service life enhancement of stamping dies. Vacuum. 2023;217:112534. <https://doi.org/10.1016/j.vacuum.2023.112534>
- [13] Sulaiman M, et al. Effects of DLC/TiAlN-coated die on friction and wear in sheet-metal forming under dry and oil-lubricated conditions: Experimental and numerical studies. Wear. 2019;438:203040. <https://doi.org/10.1016/j.wear.2019.203040>
- [14] Shokry A, et al. On the prediction of the flow behavior of metals and alloys at a wide range of temperatures and strain rates using Johnson-Cook and modified Johnson-Cook-based models: A review. Materials. 2023;16(4):1574. <https://doi.org/10.3390/ma16041574>
- [15] Thool K, et al. The role of crystallographic orientations on heterogeneous deformation in a Zr-4 alloy: a combined experimental and modeling study. International Journal of Plasticity. 2020;133:102785. <https://doi.org/10.1016/j.iijplas.2020.102785>

- [16] Lee JH, Bae SB, Youn KT, Heo HY, Kim SH, Park CD. Wear life prediction of CrN coating layer on the press tool for stamping the ultra-high strength steel sheet. *Trans. Mater. Process.* 2017;26:137-143. <https://doi.org/10.5228/KSTP.2017.26.3.137>
- [17] Cora ÖN, Koç M. Wear resistance evaluation of hard-coatings for sheet blanking die. *Procedia Manufacturing.* 2018;15:590-596. <https://doi.org/10.1016/j.promfg.2018.07.282>
- [18] Isaenkova M, et al. Simulation of the Stamping of Spacing Grid Cells Made of Thin-Walled Zirconium Tubes. *Russian Metallurgy (Metally).* 2019;2019(4):415-420. <https://doi.org/10.1134/S0036029519040177>
- [19] Hou Y, et al. A review of characterization and modelling approaches for sheet metal forming of lightweight metallic materials. *Materials.* 2023;16(2):836. <https://doi.org/10.3390/ma16020836>
- [20] Lorenz M, et al. Optical inline monitoring of the burnish surface in the punching process. *The International Journal of Advanced Manufacturing Technology.* 2022;118(11):3585-3600. <https://doi.org/10.1007/s00170-021-07922-6>
- [21] Jiang X, et al. Parameter identification of Johnson-Cook constitutive model based on genetic algorithm and simulation analysis for 304 stainless steel. *Scientific Reports.* 2024;14(1):21221. <https://doi.org/10.1038/s41598-024-71671-1>
- [22] Zellhofer M, et al. Understanding DLC system failure influenced by progressed wear. *Surface Engineering.* 2024;40(5):616-628. <https://doi.org/10.1177/02670844241264780>
- [23] Kaya E, Farioli D, Strano M. FEA approach for wear and damage prediction of tools for the progressive die stamping of steel washers. *Key Engineering Materials.* 2022;926:1168-1177. <https://doi.org/10.4028/p-15186x>
- [24] Louca K, et al. The development of grain resolved stress fields around notch tips in soft-textured zirconium polycrystals: A three-dimensional synchrotron X-ray diffraction study. *International Journal of Plasticity.* 2024;181:104076. <https://doi.org/10.1016/j.ijplas.2024.104076>
- [25] Grand V, et al. Simulation of continuous dynamic recrystallization using a level-set method. *Materials.* 2022;15(23):8547. <https://doi.org/10.3390/ma15238547>
- [26] Tondro A, Abdolvand H. On the effects of texture and microstructure on hydrogen transport towards notch tips: A CPFE study. *International Journal of Plasticity.* 2022;152:103234. <https://doi.org/10.1016/j.ijplas.2022.103234>