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Article

Experimental Evaluation of a Vertical Lifter Mechanism for a Cover Front Top Injection Mold under Prototype-Level Cyclic Testing

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Abstract

Angular lifter mechanisms are commonly used in injection molds for plastic parts with under-cut geometries; however, their inclined motion path generates lateral-force components that may increase friction, wear tendency, alignment sensitivity, and mold-space requirements. This study experimentally evaluates a vertical lifter mechanism as an alternative undercut-release system for a Cover Front Top injection mold. The investigated mold contained a 120 mm undercut feature re-quiring an 80–120 mm release stroke, while the existing angular lifter operated within an inclina-tion angle range of 3°–15°. A prototype-based experimental approach was conducted through baseline assessment, CAD-based redesign, fabrication, assembly, dry-run validation, staged injec-tion trials, quantitative component inspection, molded-part measurement, and visual defect as-sessment. The proposed vertical lifter reduced the number of mechanism components from 17 to 11, corresponding to a 35.29% reduction compared with the conventional angular lifter configura-tion. Quantitative dimensional inspection was performed on six main vertical lifter components at 124 measured points before testing and after 50, 100, and 200 shots. After 200 shots, all meas-ured points remained within the acceptance criteria, with 0 NG points and a maximum dimension-al change of no more than 0.01 mm. Molded-part evaluation was conducted on 200 parts from cavity A, showing 184 defect-free parts or a product-level defect-free rate of 92.0%. Based on 1015 inspection checkpoints, 998 checkpoints were classified as OK and 17 as NG, resulting in an over-all checkpoint acceptance rate of 98.3%. No dimensional, thickness, or sampled-deformation nonconformities or flash were detected, while minor cosmetic defects consisted of white mark, flowline, shrink mark, and scratch. These results indicate that the vertical lifter provides a more compact and me-chanically stable prototype-level undercut-release solution by reducing component count, main-taining dimensional stability of critical components, and supporting acceptable molded-part qual-ity. Nevertheless, extended-cycle testing and broader cavity validation are still required to confirm long-term industrial durability.

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1. Introduction

Injection molding is widely used to manufacture plastic components with high dimensional repeatability and production efficiency, particularly for parts with complex geometry [1], [2]. In the automotive sector, increasingly rapid vehicle model development intensifies the demand for efficient and reliable mold systems, especially for components such as the Cover Front Top [3]. One of the main challenges in this type of mold lies in the presence of undercut geometry, which cannot be released effectively using a simple ejection system. In industrial mold design, the selection of an undercut-release mechanism depends not only on its ability to release the product, but also on its influence on mold compactness, structural complexity, and machine-capacity requirements. A more compact mechanism can reduce

mold size, enable the use of smaller injection machines, and improve production efficiency while lowering operating cost [4].

Undercut identification and handling have long been recognized as critical aspects of injection-mold design and have been studied through automated recognition and mechanism-design approaches [5], [6]. Core-pulling and lifter systems are especially important for components with internal features and geometries that cannot be released directly along the primary ejection direction [7], [8]. Among these, the angular lifter remains one of the most widely used solutions. However, despite its practical usefulness, the angular lifter has several inherent limitations, including relatively large space requirements, strict motion tolerances, high assembly complexity, and increased maintenance demand caused by wear and stress concentration along inclined contact surfaces during repeated ejection cycles [9]. These limitations can affect not only mechanism durability, but also part-release con-sistency and molded-part surface quality, particularly in automotive plastic components with constrained geometry and demanding dimensional requirements.

Previous studies have indicated that alternative release mechanisms may improve mold efficiency and reduce structural complexity [10]. Nevertheless, much of the reported work remains focused on design methods, geometric optimization, and computer-aided analysis, whereas experimental validation through direct mechanical testing of mold prototypes under actual or near-production operating conditions remains limited [11]. Consequently, although conceptual and simulation-oriented approaches continue to expand, prototype-based studies that directly evaluate the motion stability and operating performance of vertical lifter mechanisms for complex automotive undercut applications remain scarce. This limitation is important because direct mechanical validation is often necessary before a redesigned ejection mechanism can be considered suitable for practical mold implementation.

Injection molds are multidisciplinary engineering systems comprising cavity-core configuration, cooling, venting, and ejection subsystems, all of which must operate reliably under repetitive cyclic loading [12], [13]. Among these subsystems, moving elements such as ejectors, slides, and lifters are particularly critical because their performance depends on the combined effects of mechanical loading, friction, repeated contact, and alignment accuracy [14], [15]. Although computer-aided technologies have significantly improved mold-design efficiency and accuracy, especially for complex structures and higher-volume production, direct validation of subsystem performance remains essential prior to implementation in production tooling [16], [17], [18].

Based on this background, the present study evaluates the mechanical feasibility of a vertical lifter mechanism as an alternative to the conventional angular lifter for a Cover Front Top injection mold. The proposed design was developed to align lifter motion with the primary ejection direction, thereby reducing lateral-force effects, simplifying the mechanism, and improving release stability. Its performance was assessed through a prototype-based experimental approach involving dry-run validation, staged injection trials up to 200 cycles, and post-test mold disassembly to examine motion behavior, molded-part quality, and the condition of critical components after repeated operation [19].

Compared with previous studies that mainly emphasize design methods, automated undercut recognition, or computer-aided design/computer-aided engineering (CAD/CAE)-based mold development, the present study strengthens the experimental validation of a vertical lifter mechanism through quantitative evidence. The novelty of this study lies in combining kinematic comparison, mechanism simplification, component dimensional inspection, and molded-part quality evaluation under prototype-level injection testing. The proposed vertical lifter reduced the number of mechanism components from 17 to 11, while its dimensional stability was evaluated at 124 measured points before testing and after 50, 100, and 200 shots. Molded-part quality was also assessed using 200 inspected parts from cavity A, supported by defect-free rate, checkpoint acceptance rate, dimensional measurement, thickness measurement, sampled deformation assessment, and visual defect classification.

Accordingly, the objective of this study is to develop a vertical lifter design compatible with the Cover Front Top geometry, apply the design to a reused prototype mold, and evaluate its mechanical functionality and motion stability through prototype-level cyclic testing. The study also aims to provide technical recommendations regarding the use of the vertical lifter as a more compact and mechanically stable alternative to the conventional angular lifter in this mold application. Through this approach, the work seeks to contribute practical experimental evidence for the implementation of vertical lifter mechanisms in injection molds where compactness, acceptable part quality, and operational stability are critical design considerations.

2. Methods

This study employed an experimental, prototype-based approach to evaluate the feasibility of a vertical lifter mechanism as an alternative to the conventional angular lifter in a Cover Front Top injection mold with undercut geometry. The investigation commenced with a systematic assessment of the existing mold configuration and the corresponding product CAD model, developed using Unigraphics (UG). The mold under study is a two-cavity system designed for the Cover Front Top component.

The undercut feature was identified at a single location at the end of the product, with a depth of 120 mm. Based on this geometry, the primary ejection direction was defined, and the required release stroke was determined within the range of 80–120 mm to ensure complete disengagement from the undercut region. The conventional angular lifter, operating within an inclination angle range of 3°–15°, was used as the baseline design. This baseline configuration served as the reference for modification and subsequent performance evaluation of the proposed vertical lifter mechanism, particularly in terms of kinematic behavior, installation feasibility, and operational reliability.

Based on this baseline assessment, the vertical lifter mechanism was developed through a CAD-based redesign of the local ejection region using UG NX version 10, since accurate CAD representation is essential for translating design intent into manufacturable mold components [16], [20]. The redesign considered the lifter motion path, release stroke, interaction with the ejector system, and compatibility with the existing mold base. The main design objective was to align the lifter motion with the primary ejection direction to reduce the lateral-force component associated with the inclined motion of the angular lifter. The modification was implemented locally in the lifter region without altering the main mold base structure; therefore, the existing mold base was reused as prototype tooling with minimal structural modification. The critical components were selected according to their functional roles in motion transmission, guiding accuracy, and wear resistance. Shaft 3 was manufactured from SKH51 with a hardness of 58–60 Rockwell C hardness (HRC), while the cam finger was produced from SKS3 with a hardness of approximately 58 HRC. Shaft 2, Guide Bush 1, and Guide Bush 2 were manufactured from SUJ-2 with a hardness of approximately 58 HRC. Supporting elements, including the bolt joint, lock nut, and locking plate, were used to maintain component positioning and assembly stability during cyclic operation. The components were fabricated using milling, electrical discharge machining (EDM), and polishing processes. Precision fits for shaft-and-hole interfaces followed H6/H7 tolerance classes, while other functional dimensions were controlled within approximately ±0.05 to ±0.10 mm, depending on the component size and functional requirement. Polishing was applied to the sliding and contact surfaces to improve surface smoothness and reduce friction during repeated motion. Initial fitting and alignment were then carried out to verify proper interaction among the moving components before testing.

The configuration of the redesigned vertical lifter and its integration into the modified mold region are illustrated in Figure 1. The mechanism consists primarily of the lifter head, lifter rod, lifter shoe, and lifter base, which work together to release the undercut region of the Cover Front Top during the ejection sequence. The figure also indicates the primary ejection direction and the release stroke considered in the mechanism design.

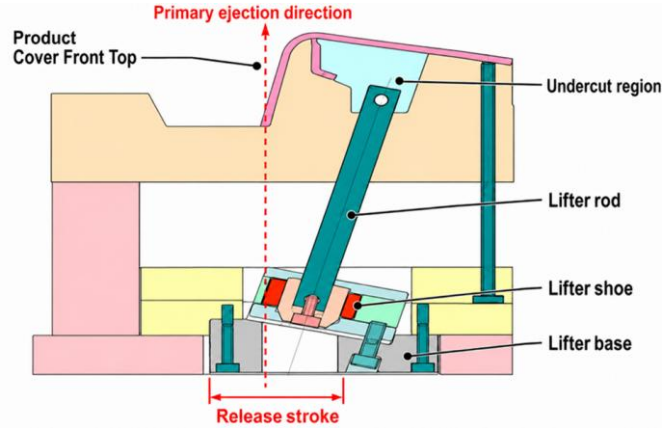


Figure 1. Sectional configuration of the redesigned vertical lifter mechanism in the Cover Front Top mold, showing the main modified components, undercut region, primary ejection direction, and release stroke.

After assembly, the mechanism was first subjected to a dry-run test using a mechanical simulation machine operated in semi-auto mode without polymer injection. The dry-run test was conducted at an operating speed of 30–40 mm/s for 5–20 cycles, depending on the adjustment required to achieve proper alignment. This stage was intended to verify the motion functionality of the mechanism without the influence of melt pressure and thermal loading. The evaluation focused on motion stability, align-ment, friction behavior, and synchronization among the lifter rod, cam finger, and limiter during repeated operation. Stable motion was defined as smooth and repeatable lifter movement along the intended path without visible interruption, jamming, or abnormal contact. Misalignment was defined as any visible positional deviation of the moving components from their intended motion path, while loss of synchronization was identified when the relative movement among the lifter rod, cam finger, and limiter became irregular or inconsistent during operation. If irregular motion, abnormal contact, or positional deviation was observed, local adjustment was performed before continuing to the injection trials.

Following dry-run validation, the prototype mold was tested under injection molding conditions representative of production practice for similar parts. Acrylonitrile butadiene styrene (ABS), Lotte PT-0180H, supplied by Lotte Chemical, was used as the molding material. The trials were conducted using a Toshiba 450-ton hydraulic injection molding machine. The barrel temperature was set within 240–260 °C, while the mold temperature was maintained at 45–50 °C. The injection pressure was controlled at 75–80 MPa, with a holding pressure of 65–70 MPa. The injection speed was set at 30–40 mm/s, and the screw speed was maintained at 15 rpm. The injection time was 10 s, consisting of a filling time of 3.1 s and a holding time of 7.9 s, while the charging time was 4.5 s. Injection trials were conducted in stages of 50, 100, and 200 cycles to evaluate mechanism functionality, motion stability, and early-stage performance under repeated operation. In this study, the 200-cycle trial was treated as a prototype-level cyclic validation rather than a full lifecycle durability test. At the end of each stage, the process was paused for interim observation of lifter behavior and molded-part quality.

The evaluation focused on three aspects: motion behavior of the mechanism, molded-part quality, and the post-test condition of critical components. The inspection was conducted visually at several stages, namely before dry-run testing, after mechanical dry-run checking, after 50 and 100 injection cycles, and after completion of the 200-cycle trial. Photographic documentation was taken to record the condition of the vertical lifter assembly before testing, after mechanical checking, and after 200 injection cycles, with a scale bar added to support visual comparison. During dry-run and injection trials, the mechanism was observed for motion smoothness, visible misalignment, abnormal friction, jamming, abnormal contact, and movement consistency during mold opening and ejection. Molded parts were inspected visually, particularly in the undercut region, for flash, scratches, white marks, and release-related deformation. After completion of 200 injection cycles, the mold was disassembled, and the lifter rod, cam finger, limiter, and associated sliding interfaces were visually examined for visible wear, deformation, abnormal contact marks, cracking, or other signs of mechanical degradation.

The performance of the proposed vertical lifter was qualitatively compared with the original angular lifter based on design configuration, component arrangement, motion path, assembly structure, and observations obtained during prototype testing. The comparison was not based on direct side-by-side injection testing under identical production conditions or statistical analysis of prior production records, but on engineering judgment supported by design drawings, manufacturing data, kinematic characteristics, and prototype observations. The QCDSM (quality, cost, delivery, safety, and maintainability) items were therefore defined using specific observation bases. Quality was assessed using molded-part visual defect classification and quantitative inspection results, including defect-free rate, checkpoint acceptance rate, dimensional measurement, thickness measurement, sampled deformation assessment, and visual defect distribution. Cost was interpreted from the absence of visible component damage, replacement, or corrective rework during the 200-cycle prototype trial, rather than from detailed economic calculation. Delivery or productivity was evaluated from the continuity of operation during the 50-, 100-, and 200-cycle trials without jamming, abnormal interruption, or functional failure. Safety was assessed from the absence of abnormal motion, unintended collision, jamming, or visible mechanical failure during mold opening and ejection. Maintainability and setup efficiency were evaluated from the accessibility of the lifter assembly during inspection and disassembly, the simplified component arrangement, and the reduced need for lateral adjustment. Accordingly, the QCDSM results should be

interpreted as a qualitative prototype-level evaluation supported by design-based engineering judgment and experimental observation, rather than as full-scale production validation.

2.1. Quantitative dimensional inspection of vertical lifter components

Dimensional inspection of the main vertical lifter components was conducted before testing and after 50, 100, and 200 shots to evaluate early-stage dimensional stability. Six components were inspected, namely Shaft L3/lifter rod, Slide L3/cam finger-related component, Insert Lifter 3, Slide Holder L3, Slide Rail L3, and Guide L3. A total of 124 measured points were evaluated across critical guiding, sliding, contact, and positioning features.

Dimensional change was calculated by comparing each measured value at a given inspection stage with its baseline value before testing, as expressed in (1):

$$\Delta x_i = \left| x_{i,t} - x_{i,0} \right| \tag{1}$$

where Δx_i is the dimensional change at the *i*-th measurement point, $x_{i,t}$ is the measured value after a given number of shots, and $x_{i,0}$ is the initial measured value before testing. The maximum dimensional change was determined using (2):

$$\Delta x_{max} = max\ \Delta x_i \tag{2}$$

Each measured point was classified as acceptable (OK) or nonconforming/not good (NG) based on the allowable tolerance in the component inspection sheet. The results were summarized using the number of measured points, OK points, NG points, OK rate, NG rate, and maximum dimensional change.

2.2. Quantitative inspection of molded parts

Molded-part quality was evaluated using 200 parts obtained from cavity A, corresponding to one inspected part for each shot during the 200-shot prototype-level trial. Cavity B was excluded to maintain consistency of sampling and interpretation. Visual inspection was performed on all 200 molded parts for five defect criteria, namely flash, white mark, flowline, shrink mark, and scratch. In addition to the full visual inspection, five molded parts were selected for dimensional, thickness, and deformation measurements. These samples were collected at the 10th, 50th, 100th, 150th, and 200th shots to represent different stages of the prototype-level cyclic trial. Dimensional measurements were performed using a digital caliper, while thickness measurements were conducted using a thickness gauge. Deformation was evaluated using a three-dimensional (3D) scanning system. The measurement results were classified as OK or NG according to the dimensional and tolerance requirements specified in the applicable product engineering drawing.

The product-level defect-free rate and NG rate were calculated using (3) and (4):

$$DRF = \left(\frac{N_{DF}}{N_T}\right) x\ 100\% \tag{3}$$

$$NGR = \left(\frac{N_{NG}}{N_T}\right) x\ 100\% \tag{4}$$

where *DFR* is the defect-free rate, *NGR* is the product-level NG rate, N_{DF} is the number of defect-free parts, N_{NG} is the number of parts containing at least one detected defect, and N_T is the total number of inspected parts. Checkpoint-based inspection was also applied by treating each evaluated inspection item as an individual checkpoint. For the checkpoint-based evaluation, the five visual defect criteria were assessed on all 200 molded parts, resulting in 1,000 visual inspection checkpoints (200 parts × 5 criteria). The dimensional, thickness, and deformation evaluations contributed an additional 15 metrology checkpoints (5 sampled parts × 3 measurement categories). Therefore, a total of 1,015 inspection checkpoints were evaluated during the prototype-level trial. The checkpoint acceptance rate and checkpoint NG rate were calculated using (5) and (6):

$$CAR = \left(\frac{C_{OK}}{C_T}\right) x\ 100\% \tag{5}$$

$$CNGR = 100\% - CAR \tag{6}$$

where CAR is the checkpoint acceptance rate, $CNGR$ is the checkpoint NG rate, C_{OK} is the number of OK checkpoints, and C_T is the total number of inspection checkpoints.

3. Results and Discussion

The conventional angular lifter used in the existing Cover Front Top mold provides the required undercut-release function, but its inclined motion path introduces a lateral-force component relative to the primary ejection direction. Figure 2(a) shows the location of the angular lifter within the existing mold configuration, with the relevant mechanism highlighted by the dashed box. The corresponding enlarged view is presented in Figure 2(b), showing the main angular-lifter components, including the lifter head, retaining pin, lifter rod, lifter guide, lifter shoe, and lifter shoe base. This arrangement enables undercut release through an inclined motion path; however, because the applied ejection load is not fully aligned with the primary ejection axis, lateral-force components may occur at the sliding inter-faces, increasing friction, contact stress, wear tendency, and sensitivity to misalignment [16], [21].

The practical implication of these limitations may include scratches, breakage, bending, higher maintenance demand, and less stable molded-part quality during production-oriented mold operation. In addition to mechanical reliability concerns, the angular lifter also imposes limitations on mold design efficiency. Because the mechanism relies on multiple interacting components arranged along an inclined axis, additional lateral clearance is required within the mold structure, which increases mold dimensions and reduces layout flexibility. The greater number of interacting parts also increases assembly complexity and makes the system more sensitive to positional error and contact-surface degradation during repeated use. From an industrial standpoint, these characteristics may contribute to higher maintenance demand, reduced service life, and less stable molded-part quality in high-cycle production environments. Accordingly, although the angular lifter is functionally capable of releasing undercut features, it presents inherent kinematic and structural drawbacks that justify the development of a more stable and compact alternative.

To address the kinematic and structural limitations of the conventional angular lifter, the proposed lifter mechanism was developed to provide a more controlled undercut-release motion while reducing unnecessary lateral space and mechanism complexity. The kinematic basis of the redesigned mechanism is illustrated in Figure 3.

As shown in Figure 3(a), the release motion is governed by the geometric relationship among the release stroke *(x)*, ejection stroke *(z)*, and lifter angle *(θ)*. The inclined geometric relationship converts the imposed ejection movement into the displacement required to disengage the molded undercut. Figure 3(b) further illustrates this kinematic relationship through sectional representations at incremental release-stroke positions of x = 0, 10, and 20 mm, showing the progressive displacement of the lifter mechanism as the ejection movement

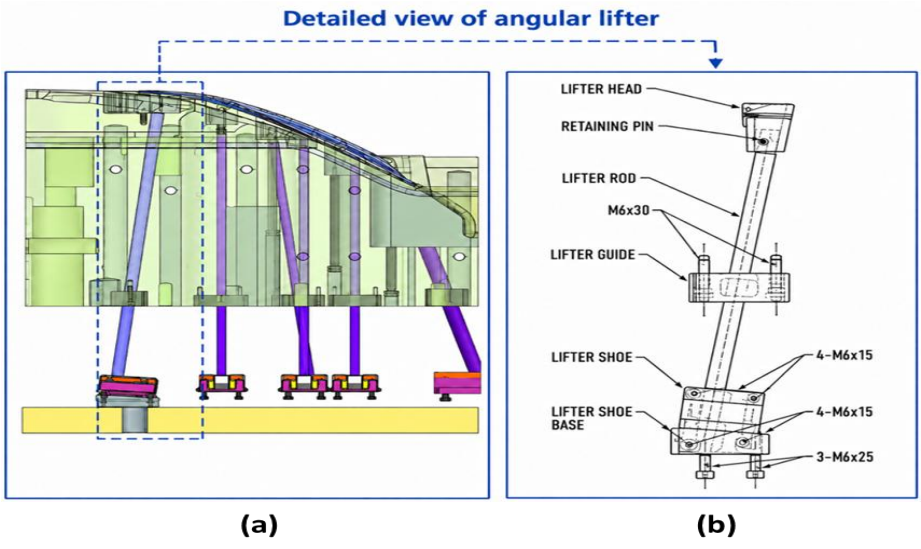


Figure 2. Conventional angular lifter configuration in the Cover Front Top mold: (a) mold cross-section showing the location of the angular lifter highlighted by the dashed box; and (b) enlarged detailed view of the angular lifter assembly showing the lifter head, retaining pin, lifter rod, lifter guide, lifter shoe, and lifter shoe base.

increases. Such control of the lifter motion path is important for maintaining consistent undercut release and reducing sensitivity to interference or misalignment during operation [22].

The geometric relationship shown in Figure 3 is translated into the sequential operating motion of the proposed mechanism, as illustrated in Figure 4.

Figure 4 shows the sequential operation of the proposed lifter mechanism from the stationary condition to the full release position. At the initial stage, the mechanism remains in its stationary position. As the driving rod moves vertically upward, the motion is transmitted through the connecting elements to the lifter head. Progressive rod movements of 10, 20, and 30 mm gradually displace the lifter head along its designed release path. At a vertical rod movement of 45 mm, the mechanism reaches the full release position, providing sufficient disengagement from the undercut region. During the return stage, the driving rod moves downward and the mechanism follows the reverse guided path until it returns to its initial position for the subsequent molding cycle. This guided motion is intended to maintain consistent component interaction and synchronization during repeated operation.

The inset in Figure 4 identifies the principal friction-contact surface involved in transmitting the release motion. Controlled interaction at this interface is important because

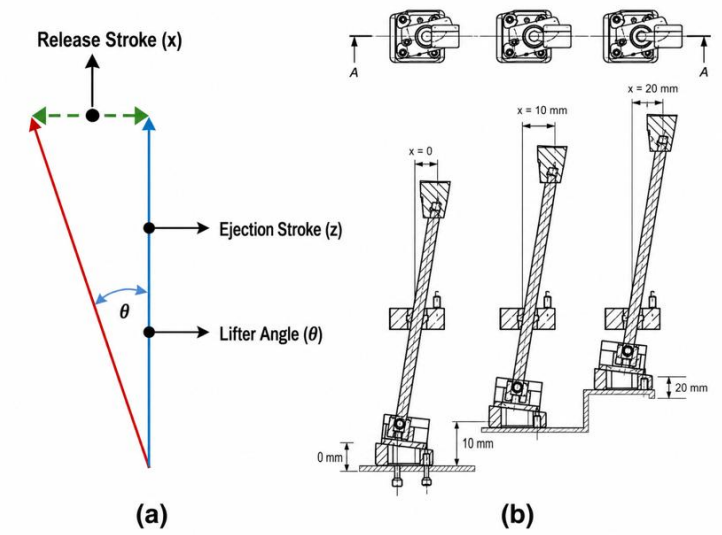


Figure 3. Kinematic basis of the proposed lifter mechanism: (a) relationship among release stroke (x), ejection stroke (z), and lifter angle (θ); and (b) sectional representation of the mechanism at incremental release-stroke positions (x = 0, 10, and 20 mm).

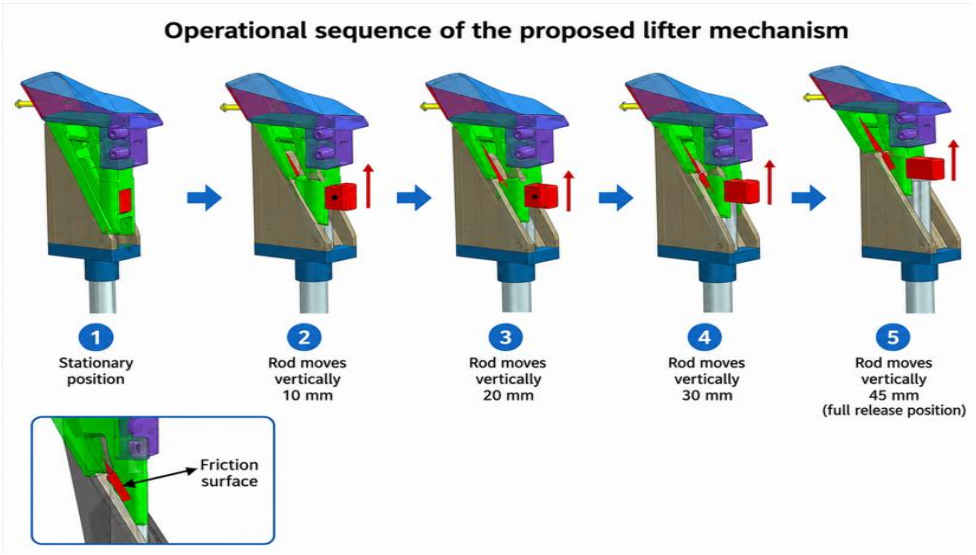


Figure 4. Operational sequence of the proposed lifter mechanism during ejection, showing the stationary position and progressive vertical rod movements of 10, 20, 30, and 45 mm up to the full release position; the inset highlights the friction-contact surface within the mechanism.

Table 1. Quantitative comparison between the conventional angular lifter and the proposed vertical lifter mechanisms.

Evaluation Criteria	Angular Lifter	Vertical Lifter	Technical Interpretation (Basis of Evaluation)
Number of mechanism components	17	11	The vertical lifter reduced the component count by 35.29%, resulting in a simpler mechanism layout.
Lifter angle range considered	3°–15°	15°–30°	The angular lifter relies on an inclined motion path, while the vertical lifter was configured to support a more compact release motion.
Ejection/drive stroke range, *s*	80–120 mm	40–50 mm	The vertical lifter required a shorter stroke range to support the undercut-release motion.
Maximum calculated displacement	32.15 mm	28.87 mm	Calculated using $d = s \tan \theta$; the vertical lifter provided sufficient release displacement within a shorter stroke range.
Mold-space requirement	Higher lateral clearance	More compact layout	The vertical lifter reduces the need for lateral clearance inside the mold structure.
Prototype validation	Baseline reference	200-shot trial	The proposed vertical lifter was validated under prototype-level injection testing.

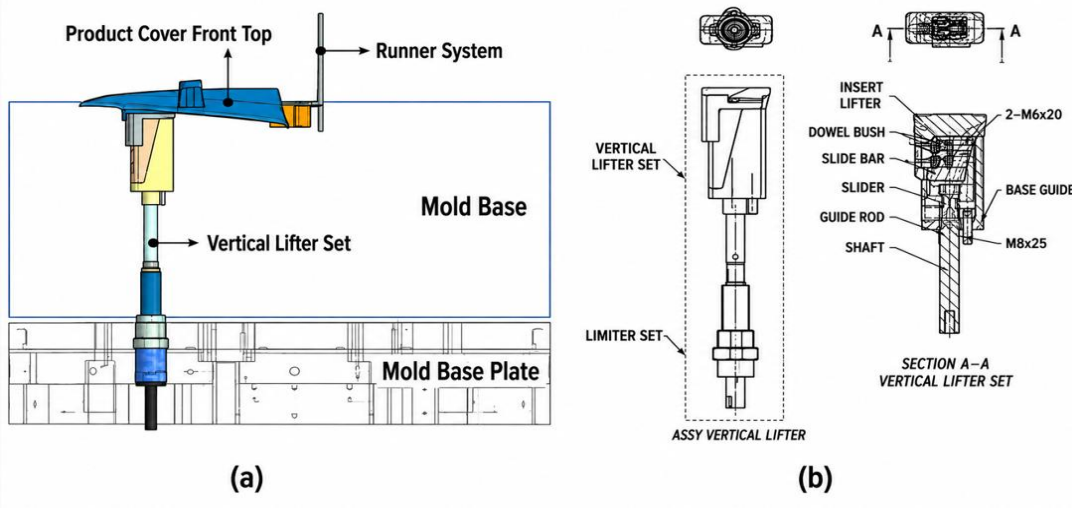


Figure 2. Proposed vertical lifter design and implementation in the prototype mold: (a) mold-level integration of the vertical lifter set beneath the Cover Front Top and runner system; and (b) assembly and sectional representation of the vertical lifter showing the insert lifter, dowel bush, slide bar, slider, guide rod, shaft, base guide, and limiter set.

repeated sliding contact can contribute to frictional resistance and affect demolding behavior and motion stability. The proposed mechanism therefore maintains a guided contact path to reduce friction-related disturbance and support repeatable movement during cyclic operation. In addition to the motion characteristics illustrated in Figures 3 and Figures 4, the redesigned mechanism also offers an advantage in mold-layout efficiency. The conventional angular lifter requires additional lateral clearance to accommodate its inclined motion and associated components, whereas the proposed configuration reduces the space required for the undercut-release mechanism and enables a more compact mold arrangement [4]. The redesigned mechanism also reduced the number of mechanism components from 17 to 11, corresponding to a 35.29% reduction. These kinematic and structural differences provide the engineering rationale for the quantitative comparison summarized in Table 1 and for the subsequent prototype-level experimental validation.

To provide a quantitative basis for the comparison, the calculated displacement was estimated using $d = s \tan \theta$, where d is the calculated displacement, s is the lifter stroke, and θ is the lifter angle. The comparison between the conventional angular lifter and the proposed vertical lifter is summarized in Table 1.

The proposed vertical lifter was then implemented in the Cover Front Top mold through a localized modification strategy, as shown in Figure 5. In Figure 5(a), the prototype mold

configuration demonstrates that the redesigned mechanism was integrated specifically into the undercut-release region without altering the primary mold base. This is important from a practical standpoint because it indicates that the concept can be introduced into an existing mold architecture with minimal structural modification. The component-level and sectional arrangement is shown in Figure 5(b), where the lifter rod, cam finger, limiter, cavity, core, and ejector system are aligned to support a predominantly axial motion path. Compared with the original angular-lifter configuration, this arrangement reduced the number of mechanism components from 17 to 11, corresponding to a 35.29% component-count reduction. The simplified arrangement also reduced the number of interacting motion interfaces and lowered alignment sensitivity during repeated operation. Therefore, the implemented configuration confirms both the kinematic suitability and the practical feasibility of the vertical lifter for prototype-level validation.

The mechanical behavior of the proposed system was first examined through dry-run testing without polymer injection, followed by injection-based cyclic trials under production-representative conditions, as summarized in Figure 6. In Figure 6(a), the dry-run setup was used to assess the motion functionality of the mechanism independently of melt pressure and thermal effects. During the initial stage of dry-run operation, minor deviations were observed and corrected through preliminary fitting and adjustment of the cam finger and limiter positions. After this stabilization step, the mechanism operated with smooth and repeatable motion, with no visible jamming, loss of synchronization, or abnormal motion-path deviation. The subsequent injection-based trial is shown in Figure 6(b), where the prototype mold was operated progressively at 50, 100, and 200 shots under the specified ABS molding condition. In the present study, the 200-shot test was interpreted as prototype-level cyclic validation or initial durability screening, rather than full industrial lifecycle testing. Within this tested range, the vertical lifter remained operationally stable, and no abnormal interruption of the molding sequence was observed after the initial fitting stage. The observed behavior is consistent with the earlier kinematic rationale, where reduction of lateral-force effects is expected to improve motion stability and reduce friction-related disturbance under repeated operation [22], [12].

The quality of the molded parts was then evaluated, with particular emphasis on the undercut region where release-related damage would most likely appear if the lifter motion were unstable or if excessive friction occurred during demolding. Representative molded parts are presented in Figure 7. The overall part appearance from the front side is shown in Figure 7(a), while the reverse side is shown in Figure 7(b). The critical undercut region is enlarged in Figure 7(c). These visual observations were supported by quantitative inspection of 200 molded parts obtained from cavity A after the 200-shot prototype-level trial.

Visual inspection of all 200 molded parts showed that 184 parts were defect-free, corresponding to a product-level defect-free rate of 92.0%, while 16 parts contained at least one detected visual defect, corresponding to a product-level NG rate of 8.0%. For the checkpoint-based evaluation, a total of 1,015 checkpoints were assessed, comprising 1,000 visual checkpoints from the five defect criteria evaluated on all 200 parts and 15 metrology checkpoints from dimensional, thickness, and deformation measurements conducted on the five sampled

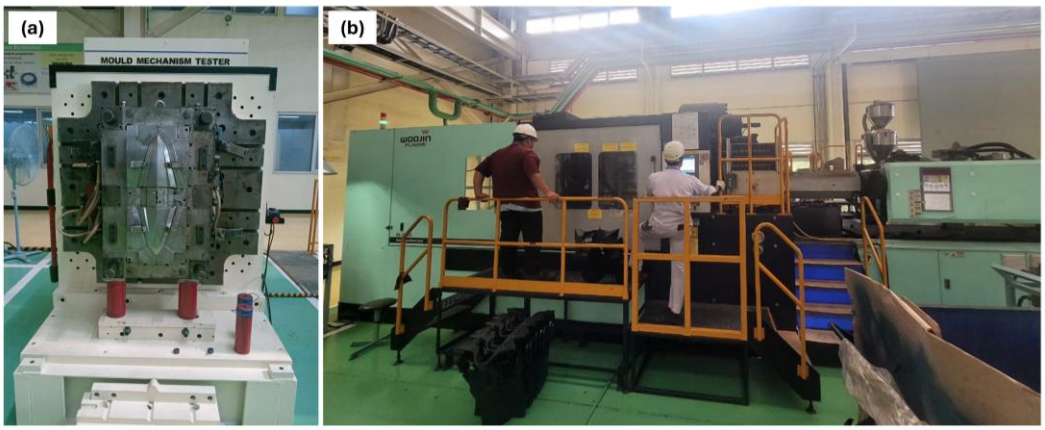


Figure 3. Prototype-level cyclic validation of the vertical lifter mechanism: (a) dry-run test using a mechanical simulation machine without polymer injection to evaluate motion stability and component synchronization; and (b) injection-based cyclic trial conducted up to 200 cycles under production-representative conditions.

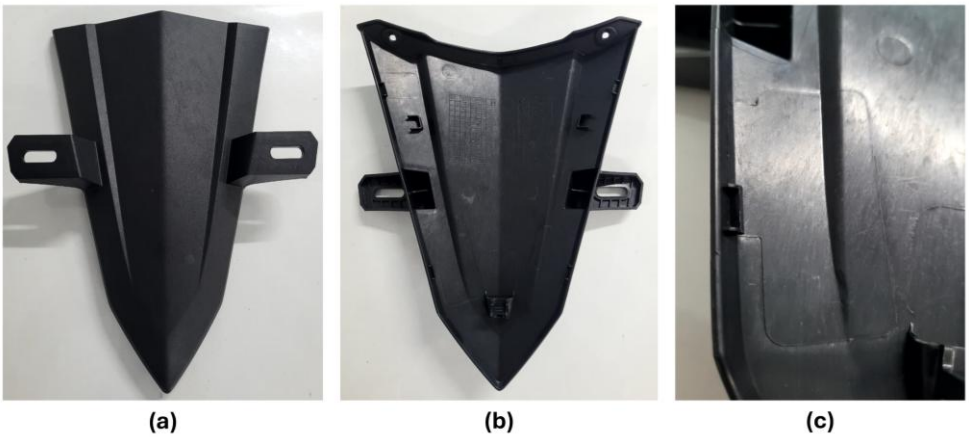


Figure 4. Representative molded parts obtained after 200 injection shots using the vertical lifter mechanism: (a) front view; (b) back view; and (c) detailed view of the undercut region. Product quality was evaluated through visual inspection of 200 parts from cavity A, supplemented by metrology measurements on five sampled parts.

parts. Of these check-points, 998 were classified as OK and 17 as NG, resulting in an overall checkpoint acceptance rate of 98.3% and a checkpoint NG rate of 1.7%. All 15 metrology checkpoints were classified as OK; therefore, no dimensional, thickness, or sampled deformation NG was detected. The 17 NG checkpoints were entirely associated with minor visual defects consisting of white mark, flowline, shrink mark, and scratch. The difference between 16 NG parts and 17 NG visual checkpoints occurred because one molded part exhibited more than one visual defect criterion.

These results indicate that the proposed vertical lifter did not generate critical undercut-release defects during the 200-shot prototype-level trial. The absence of flash and measurable dimensional, thickness, or deformation NG suggests that the vertical lifter maintained acceptable release behavior in the critical undercut region. However, the presence of minor cosmetic defects indicates that further process-parameter optimization may still be required to improve molded-part surface quality. The complete quantitative inspection results are summarized in Table 2.4

Table 2. Quantitative inspection results of molded parts after 200 injection shots from cavity A.

Inspection parameter	Result	Percentage	Interpretation
Total inspected parts	200 pcs	100%	Parts from cavity A only
Defect-free parts	184 pcs	92.0%	Parts without detected NG criteria
NG parts	16 pcs	8.0%	Parts with at least one detected NG criterion
Total inspection checkpoints	1015	100%	Part-level and checkpoint-level inspection
OK checkpoints	998	98.3%	Accepted checkpoints
NG checkpoints	17	1.7%	Rejected checkpoints
Flash	0 pcs	0.0%	No flash detected
White mark	4 pcs	2.0%	Minor cosmetic defect
Flowline	5 pcs	2.5%	Minor cosmetic defect
Shrink mark	6 pcs	3.0%	Minor cosmetic defect
Scratch	2 pcs	1.0%	Minor cosmetic defect
Dimensional sample acceptance	5/5 OK	100%	No dimensional NG detected
Thickness sample acceptance	5/5 OK	100%	No thickness NG detected

Note: Visual defect inspection was performed on all 200 molded parts from cavity A. Dimensional, thickness, and deformation measurements were conducted on five parts sampled at the 10th, 50th, 100th, 150th, and 200th shots. Dimensional measurements were performed using a digital caliper, thickness measurements using a thickness gauge, and deformation assessment using a 3D scanning system. Acceptance was determined according to the applicable product engineering drawing. The total of 1,015 checkpoints comprised 1,000 visual checkpoints and 15 metrology checkpoints.

The quantitative inspection results show that the proposed vertical lifter supported acceptable molded-part quality during the 200-shot prototype-level trial. The product-level defect-free rate reached 92.0%, while the checkpoint acceptance rate reached 98.3%. No flash, dimensional NG, thickness NG, or sampled deformation NG was detected. The NG items were limited to minor cosmetic defects, mainly shrink mark, flowline, white mark, and scratch. Therefore, the observed defects did not indicate critical undercut-release failure, although further process-parameter optimization is still required to reduce cosmetic defects.

As shown in Figure 8, the detected NG items were dominated by minor cosmetic defects. Shrink mark showed the highest occurrence with 6 cases or 3.0%, followed by flowline with 5 cases or 2.5%, white mark with 4 cases or 2.0%, and scratch with 2 cases or 1.0%. No flash was detected in any of the 200 inspected parts. This result indicates that the proposed vertical lifter did not generate critical release-related defects in the undercut region during the 200-

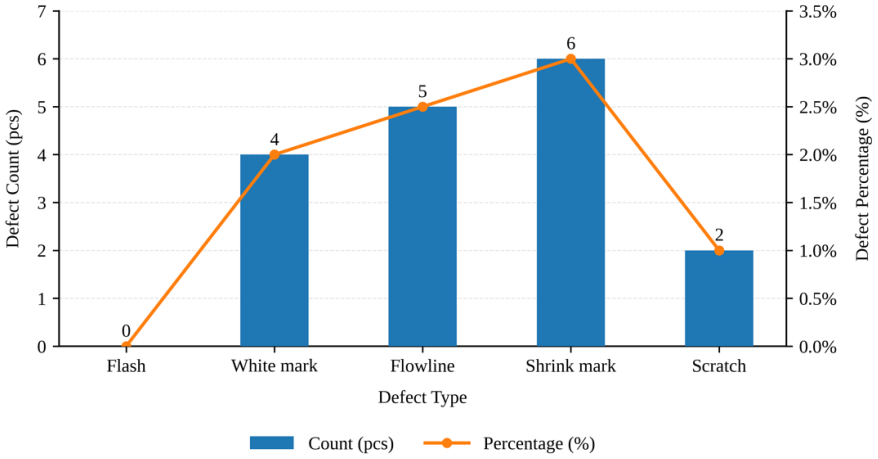
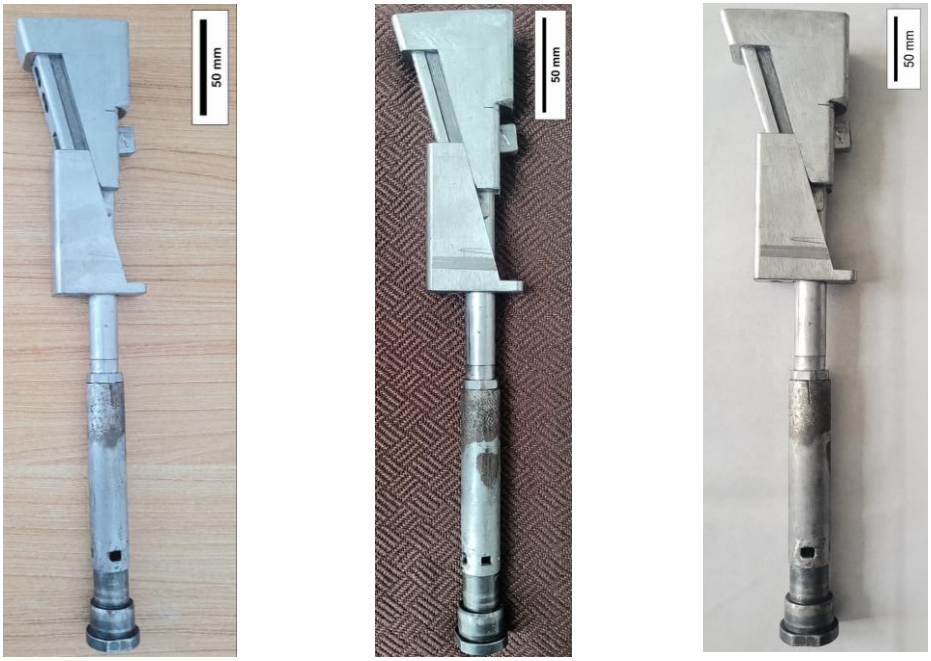


Figure 5. Distribution of molded-part defects after 200 injection shots from cavity A. No flash was detected, while the observed NG items were limited to minor cosmetic defects consisting of white mark, flowline, shrink mark, and scratch.



(a) (b) (c)

Figure 6. Visual documentation of the vertical lifter assembly during prototype-level evaluation: (a) initial condition before dry-run testing; (b) condition after dry-run testing; and (c) post-test condition after 200 injection shots, showing the retained integrity of the lifter rod, cam finger, limiter, and associated contact interfaces.

Table 3. Quantitative dimensional inspection results of vertical lifter components before testing and after 50, 100, and 200 shots.

No.	Main component	Measured points	Inspection stage	OK points after 200 shots	NG points after 200 shots	Maximum dimensional change after 200 shots	Result
1	Shaft L3 / lifter rod	10	Before test, 50, 100, 200 shots	10	0	≤0.01 mm	OK
2	Slide L3 / cam finger-related component	32	Before test, 50, 100, 200 shots	32	0	≤0.01 mm	OK
3	Insert Lifter 3	12	Before test, 50, 100, 200 shots	12	0	≤0.01 mm	OK
4	Slide Holder L3	20	Before test, 50, 100, 200 shots	20	0	≤0.01 mm	OK
5	Slide Rail L3	28	Before test, 50, 100, 200 shots	28	0	≤0.01 mm	OK
6	Guide L3	22	Before test, 50, 100, 200 shots	22	0	≤0.01 mm	OK
Total		124	Before test, 50, 100, 200 shots	124	0	≤0.01 mm	OK

shot prototype-level trial. The remaining cosmetic defects may be more closely related to molding parameters, material flow, holding pressure, cooling behavior, or local surface conditions.

The vertical lifter assembly was also evaluated after the prototype-level injection trial to examine whether repeated operation affected the condition of the main mechanism components. Figure 9 shows the visual documentation of the lifter assembly before dry-run testing, after dry-run testing, and after 200 injection shots. Visual inspection indicated that the lifter rod, cam finger, limiter, and associ-ated contact interfaces remained intact after testing, with no visible cracking, abnormal contact marks, or functional damage. However, to strengthen the evaluation beyond visual observation, dimensional inspection was also conducted on the main vertical lifter components before testing and after 50, 100, and 200 shots. The corresponding dimensional inspection results are summarized in Table 3.

The dimensional inspection results confirm that all 124 measured points remained within the acceptance criteria after 200 shots. No NG measurement point was detected, and the maximum dimensional change was no more than 0.01 mm. Considering that the functional dimensions of the fabricated components were controlled within approximately ±0.05 to ±0.10 mm, the observed dimensional change was relatively small. This result indicates that the vertical lifter components maintained early-stage dimensional stability within the tested range and that the visual post-test observation was supported by quantitative dimensional evidence.

To strengthen the QCDSM interpretation, quantitative indicators were added to the prototype-level evaluation. From the Quality aspect, molded-part inspection showed 184 defect-free parts out of 200 inspected parts, corresponding to a 92.0% defect-free rate, with a checkpoint acceptance rate of 98.3%. No flash, dimensional NG, thickness NG, or sampled deformation NG was detected. From the Cost/component condition aspect, dimensional inspection of the vertical lifter components showed that all 124 measured points remained within the acceptance criteria after 200 shots, with no nonconforming measurement points and a maximum dimensional change of no more than 0.01 mm. From the Delivery/productivity and Safety/reliability aspects, the mechanism completed staged testing at 50, 100, and 200 shots without observed jamming, abnormal motion, loss of synchronization, or functional interruption after initial fitting. From the Maintainability aspect, the mechanism component count was reduced from 17 to 11 components, corresponding to a 35.29% reduction compared with the conventional angular lifter.

Taken together, these findings extend previous studies that have predominantly addressed undercut-release mechanisms from design, geometric, or computer-aided perspectives by providing direct prototype-level experimental evidence under injection-molding conditions. The scientific contribution of the present study therefore lies in integrating mechanism redesign with cyclic operational validation, component-level dimensional assessment,

and molded-part quality evaluation within a single experimental framework. This approach provides a more comprehensive basis for assessing the practical feasibility of vertical lifter mechanisms before longer-term industrial validation.

4. Conclusions

This study demonstrated the prototype-level feasibility of a vertical lifter mechanism as an alternative to the conventional angular lifter for a Cover Front Top injection mold with undercut geometry. The proposed mechanism reduced the number of components from 17 to 11, corresponding to a 35.29% reduction, and maintained stable operation during staged testing at 50, 100, and 200 shots without observed jamming, abnormal motion, loss of synchronization, or functional interruption after initial fitting. Quantitative inspection confirmed the early-stage stability of the vertical lifter. All 124 measured points on the main components remained within the acceptance criteria after 200 shots, with 0 NG points and a maximum dimensional change of no more than 0.01 mm. Molded-part inspection of 200 parts from cavity A showed a 92.0% product-level defect-free rate and a 98.3% checkpoint acceptance rate. No flash, dimensional NG, thickness NG, or sampled deformation NG was detected, while the remaining NG items were limited to minor cosmetic defects. In this study, the proposed vertical lifter provides a compact and mechanically stable undercut-release alternative by reducing component count, maintaining component dimensional stability, and supporting acceptable molded-part quality under prototype-level testing. However, this study was limited to 200 shots and products from cavity A only. Extended-cycle testing, broader cavity validation, wear-depth measurement, surface-roughness evaluation, and process-parameter optimization are still required to confirm long-term industrial durability.

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Declaration of Generative AI and AI-Assisted Technologies in the Writing Process

During the preparation of this manuscript, the authors used ChatGPT (OpenAI), QuillBot, and Grammarly for limited language assistance and visual refinement. All AI-assisted outputs were reviewed and verified by the authors, who take full responsibility for the final content of the manuscript.

Nomenclature / List of Abbreviations

ABS	Acrylonitrile butadiene styrene
CAD	Computer-aided design
CAE	Computer-aided engineering
CAR	Checkpoint acceptance rate
CNGR	Checkpoint NG rate
DFR	Defect-free rate
EDM	Electrical discharge machining
HRC	Rockwell C hardness
NGR	Product-level NG rate
QCDSM	Quality, cost, delivery, safety, and maintainability

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