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DESIGN AND VALIDATION OF A MODULAR FIXTURE FOR MILLING THIN-RIBBED LINKAGE BRACKETS

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Abstract

Thin-ribbed linkage brackets are difficult to machine because their low local stiffness makes them sensitive to both cutting-induced bending and clamping-induced distortion. This study presents a design-oriented procedure for developing a modular milling fixture for linkage brackets containing a central bore, two cylindrical end bosses, and slender connecting ribs. The procedure integrates functional requirement definition, deterministic location, force-path design, analytical sizing of cutting forces, finite-element verification, prototype manufacture, and proof-of-concept machining trials. The fixture employs a fixed and a movable 45° V-block to support the cylindrical bosses, a central locator to control longitudinal position, a rigid base plate, and relief regions that prevent direct contact with the thin ribs. Soft interface layers are introduced at selected contacts to limit surface damage and reduce local pressure concentration. For the investigated milling condition, the estimated tangential, radial, and axial force components were 300, 195, and 90 N, respectively. Static finite-element results indicated a maximum von Mises stress of approximately 72.55 MPa and a maximum displacement of 1.59×10^{-3} mm under the modeled loading and boundary conditions, remaining below the assumed material yield strength. Prototype trials with aluminum and polymer brackets showed stable seating, unobstructed tool access, and no visible slippage or rib damage. Because the experimental assessment was qualitative and no comprehensive metrological uncertainty study was available, the results should be interpreted as evidence of functional feasibility rather than as complete industrial qualification. The work provides a compact fixture-design framework for deformation-sensitive linkage components and identifies the measurements required for subsequent quantitative validation.

Keywords: *fixture design; thin-walled machining; linkage bracket; V-block; finite-element analysis; milling.*

1. Introduction

Work holding is a primary determinant of machining accuracy because the fixture establishes the workpiece coordinate system, constrains rigid-body motion, and transfers cutting loads to the machine structure. A suitable fixture must therefore satisfy three coupled functions: deterministic location, sufficient resistance to cutting-induced motion, and controlled contact pressure at the workpiece–fixture interfaces. Contemporary fixture research increasingly treats these functions as an integrated design problem, linking setup planning, locator selection, stiffness distribution, and manufacturability within a unified workflow [1–5]. Recent developments have additionally emphasized digital design support, modularity, knowledge reuse, and flexible fixture architectures for parts whose geometry or production volume does not justify a dedicated high-cost solution [6–10].

The fixture-design problem becomes more difficult for thin-walled components because clamping and cutting loads act on a structure with low local bending stiffness. Even when the nominal cutting force is moderate, an unfavorable force path can generate elastic deflection, datum shift, residual deformation, or vibration at ribs and unsupported walls. Recent studies have therefore investigated contour-matching jaws, adaptive multipoint supports, floating clamping, and digital-twin-assisted fixture control to improve contact-force distribution and reduce deformation [11–14]. Intelligent fixture synthesis, virtual clamping models, actuator-supported compensation, and experimental stiffness evaluation further demonstrate that locating accuracy must be considered alongside contact compliance and load transfer within the fixture–workpiece system [15–18]. Flexible and reconfigurable devices provide a useful response to geometric variability, but adaptability is generally obtained at the cost of additional interfaces, moving elements, control complexity, or reduced structural stiffness. Dedicated fixtures developed for

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complex components and part families demonstrate that productivity can be improved when the locating and clamping arrangement is derived directly from the functional geometry and machining sequence [19–23]. Computer-aided fixture synthesis and recent studies of thin-wall milling similarly indicate that fixture configuration, wall compliance, residual stress, and process-induced deformation should be treated as interacting design variables rather than independent considerations [24–28]. Thin-ribbed linkage brackets constitute a representative case in which the workpiece combines robust cylindrical features with slender load-carrying ribs. The central bore and end bosses typically define the component's functional relationships, while the connecting ribs reduce mass but remain highly sensitive to local contact pressure and transverse cutting loads. Reliable fixture sizing consequently requires a defensible estimate of the milling load. Mechanistic, analytical, and physics-informed models relate chip thickness, cutter engagement, tool geometry, runout, and specific force coefficients to the instantaneous or average force components [29–33]. Broader force-modeling studies and experimentally calibrated measurement systems provide complementary means of establishing a realistic load envelope for the workpiece–fixture system [34–38].

For thin-walled milling, the predicted force must be interpreted together with wall compliance, machining strategy, chatter susceptibility, evolving boundary conditions, and residual-stress redistribution. Recent numerical and experimental investigations have examined deformation prediction, residual-stress evolution, dynamic support, and error compensation in flexible structures [39–43]. Reviews of chatter, machining accuracy, allowance planning, and cutting-parameter optimization further show that process selection can reduce the imposed load but cannot compensate for an unsuitable constraint scheme or insufficient fixture stiffness [44–48]. Studies addressing machinability, surface integrity, sustainable machining, milling strategy, and allowance allocation provide additional criteria for selecting practical cutting conditions and defining the fixture design load [49–52].

Although the literature contains advanced fixture concepts and extensive work on thin-wall machining, fewer studies present a compact design procedure that begins with the functional geometry of a thin-ribbed linkage bracket and explicitly connects locating logic, force-path selection, clamp sizing, finite-element verification, and prototype machining. Existing highly adaptable systems are often more complex than required for a bracket dominated by cylindrical bosses, whereas conventional vises do not isolate the ribs from clamping pressure. The resulting design gap is a mechanically simple, modular fixture that leverages the bracket's robustness while preserving tool access and providing an analytically traceable load path.

Accordingly, this study develops and evaluates a modular milling fixture based on opposed 45° V-blocks, a central locating element, replaceable contact liners, and relief zones around the thin ribs. The contribution is design-oriented: the work translates part geometry into functional requirements, establishes the location and clamping scheme, estimates the cutting and clamping loads, verifies the fixture structure using finite-element analysis, and assesses the prototype through machining trials on aluminum and polymer. The study does not claim a universal fixture principle; rather, it demonstrates a systematic and practically implementable design methodology for a defined class of thin-ribbed linkage brackets.

2. Design methodology

2.1. Design requirements and fixture concept

The target component is a linkage bracket comprising a central cylindrical hub, two end bosses, and thin ribs that transfer load between these features. The central bore and end bosses are functionally important because their relative position controls assembly alignment. The ribs reduce mass while preserving in-service stiffness, but their small thickness and relatively long unsupported length make them unsuitable as primary clamping surfaces. Fig. 1. Identifies the principal deformation-sensitive regions.

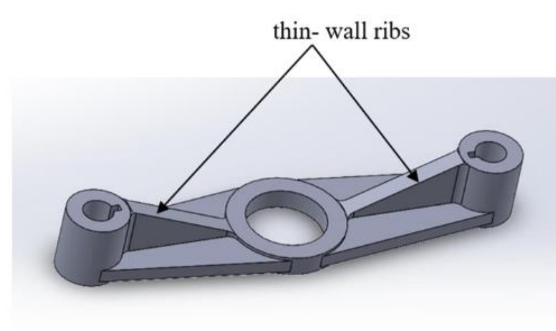

Fig. 1. Representative thin-ribbed linkage bracket and deformation-sensitive rib regions.

From a fixture-design perspective, the component contains three categories of surfaces: functional datums, structurally robust clamping regions, and protected non-contact regions. The cylindrical end bosses are selected as the primary support and clamping features because they have a greater local section modulus than the ribs. The central bore is used for secondary longitudinal location, provided that the locator does not over constrain the workpiece. Rib surfaces are treated as protected zones and are separated from the fixture by relief pockets.

The design process follows a requirement–concept–analysis–prototype–validation sequence. The workpiece geometry, expected machining loads, machine-table interface, setup repeatability, and protection of the thin ribs were translated into the design requirements summarized in Table 1. These requirements guided the selection of the locating scheme and the subsequent analytical and numerical verification.

The fixture is based on a fixed–movable V-block arrangement. A V-block creates two line or narrow-area contacts around a cylindrical boss, thereby providing stable radial support with self-centering behavior. The fixed V-block establishes the primary lateral reference, while the movable V-block applies the closing force and accommodates dimensional variation. A central locator engages the main bore or an associated robust datum to control longitudinal translation. The base plate establishes the vertical datum and reacts to the axial component of the cutting force.

The design intentionally avoids a fully rigid six-point clamp pattern applied to the ribs. Instead, the constraints are concentrated at the bosses and central hub, where local stiffness is higher. This arrangement reduces the probability of clamp-induced rib bending. To avoid redundant constraint, the central locator should provide only the degree of freedom required for longitudinal positioning; a close sliding fit or relieved locator is preferable to a forced interference fit.

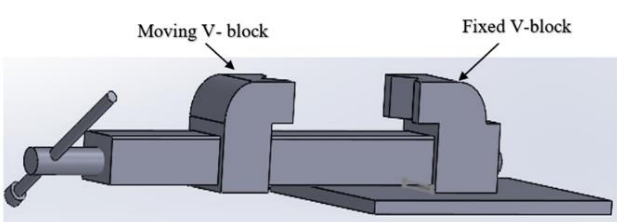

Fig. 2. Fixture concept with fixed and movable 45° V-blocks.

The proposed fixture consists of a ground base plate, a fixed V-block, a screw-driven movable V-block, a central locating element, replaceable contact liners, and local relief features. The base plate transfers the resultant load to the machine table. The fixed V-block provides the principal reference, whereas the movable V-block generates the clamping action. The screw mechanism was selected for the prototype because it is simple, inexpensive, and allows direct observation of the seating process. Pneumatic or hydraulic actuation can be introduced later without changing the fundamental locating architecture.

The 45° contact faces convert the horizontal closing action into two normal reactions around each cylindrical boss. Soft liners can be bonded or mechanically retained on these faces. Their purpose is not to create a compliant global fixture, but to reduce local pressure peaks and prevent aluminum galling or polymer surface marking. Reliefs are machined wherever the rib geometry could otherwise contact the base or jaws. The resulting load path runs from the cutter through the robust hub and bosses, into the V-blocks and base plate, and finally into the machine table.

2.2. Analytical force and clamping model

The analytical sizing step establishes a conservative load envelope before detailed structural analysis. For a two-flute end mill, the feed per tooth is calculated from spindle speed n, table feed v_f, and flute number z:

$$f_z = v_f/(nz) \quad (1)$$

Using n = 2000 rpm, v_f = 1500 mm/min, and z = 2 gives f_z=0.375 mm/tooth. For an illustrative specific cutting-force coefficient k_c=800 N/mm² and axial depth of cut a_p=1 mm, the first-order tangential force estimate is:

$$F_t = k_c a_p f_z \quad (2)$$

The radial and axial components are represented using proportional coefficients C_r and C_a. For the preliminary design, C_r=0.65 and C_a=0.30 were adopted, giving F_t=300 N, F_r=195 N, and F_a=90 N. These values should be treated as sizing assumptions; for final qualification, coefficients should be calibrated using the mechanistic force model and tri-axial dynamometer described in recent work [29, 35].

$$F_r = C_r F_t, \quad F_a = C_a F_t \quad (3)$$

The in-plane resultant to be resisted against sliding is therefore approximately 358 N. A simplified friction-based lower bound on the effective clamping force is:

$$F_c \geq S F_{xy}/\mu_{eff}, \quad F_{xy} = (F_t^2 + F_r^2)^{1/2} \quad (4)$$

where μ_eff is the effective friction coefficient of the contact system, and S is a safety factor accounting for force fluctuation, tooth entry, runout, and uncertainty in the force coefficients. For μ_eff=0.25 and S=1.5, the required effective closing force is approximately 2.15 kN. This value is a conservative design target rather than a measured prototype force. The final clamp setting must also satisfy a pressure constraint at the boss contact:

$$p_{max} = F_N/A_{eff} \leq p_{allow} \quad (5)$$

where F_N is the normal reaction on the V-face, A_eff is the effective contact area, and p_allow is selected from the allowable local stress of the workpiece/liner system. This second inequality is essential because increasing clamping force improves slip resistance, but it can also damage the workpiece. The practical design problem is therefore to find a force window that simultaneously prevents sliding and limits local contact deformation.

2.3. Finite-element and structural performance verification

A static finite-element model was used to verify whether the proposed structure could resist the preliminary design load without yielding or excessive elastic displacement. The model represented the fixture assembly under the selected constraints and applied load. The stress plot is reported in SI pressure units; therefore, the displayed maximum of 72,552,352 N/m² corresponds to approximately 72.55 MPa, not 72.55 Pa. The assumed yield strength shown in the simulation was 160 MPa, giving a nominal static factor of safety of approximately 2.2 with respect to the peak von Mises stress.

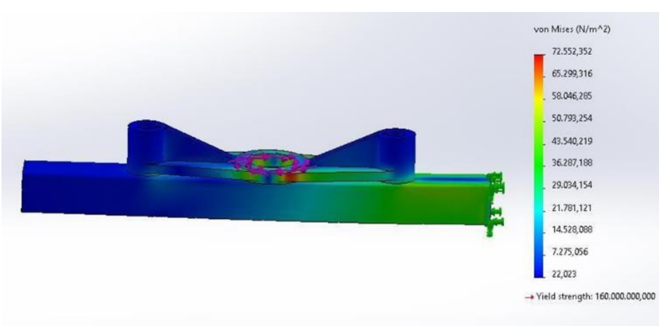

Fig. 3. Static von Mises stress distribution of the fixture model (maximum approximately 72.55 MPa).

The total-displacement plot indicated a maximum value of approximately 1.59 × 10^{-3} mm. The highest displacement occurred away from the fully constrained The prototype was manufactured using conventional machining processes and mounted on the CNC machine table through the base plate. Setup followed a controlled sequence: clean the datum surfaces, place the bracket against the fixed V-block, engage the central locator, advance the movable V-block until both bosses are seated, apply the final screw torque, and verify tool clearance. Aluminum and polymer workpieces were used to examine the fixture's ability to accommodate materials with different stiffness and surface sensitivity.

The available trials were intended as functional demonstrations rather than a statistically designed validation campaign. The recorded evidence supports assessment of seating, accessibility, gross stability, chip evacuation, and visible surface damage. It does not provide sufficient data to quantify positioning repeatability, dimensional capability, surface roughness, or uncertainty. This distinction is maintained throughout the discussion to avoid overstatement.

The prototype achieved the intended mechanical function: the cylindrical bosses were captured between the opposed V-blocks, the central feature provided longitudinal reference, and the ribs remained clear of direct clamping contact. The open-top configuration preserved cutter access to the central region and adjacent planar surfaces. Compared with a conventional flat-jaw vise, the V-block arrangement offers a more direct geometric match to the boss surfaces and reduces sensitivity to minor width variation.

The design also provides a clear force path. In-plane milling loads are reacted by the opposed V-blocks, while the axial component is transmitted into the base. This is preferable to reacting the load through the thin ribs, where the same force would produce a larger bending moment and local displacement. The central locator contributes positional repeatability but should not be used as the principal force-reacting member; otherwise, bore damage or over constraint may occur.

The peak von Mises stress of approximately 72.55 MPa is below the assumed 160 MPa yield strength, indicating that the modeled fixture remains in the elastic range under the applied static load. The corresponding nominal factor of safety is adequate for a prototype assessment, but lower than would be expected if the erroneous unit interpretation of 72.55 Pa were retained. Correct unit conversion is therefore critical: the simulation supports structural feasibility, not an effectively unloaded condition.

The predicted maximum displacement of 1.59 × 10^{-3} mm is negligible relative to typical workshop tolerances. Nevertheless, the absolute value is strongly dependent on boundary conditions and contact definitions. A future model should include bolt pretension, frictional contacts, the actual workpiece, clamp-force variation, and a distributed or moving cutting load. Modal and harmonic analyses would also be required to evaluate chatter susceptibility. Recent studies on flexible workpieces and fixture-supported milling show that static stiffness alone cannot guarantee dynamic stability [25–28, 36–44].

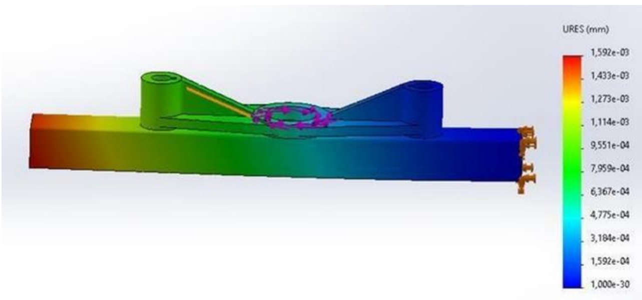

Fig. 4. Static displacement distribution of the fixture model (maximum approximately 1.59×10^{-3} mm).

3. Results and discussion

3.1. Machining performance and material response

During the aluminum trial, the workpiece remained visibly seated while the cutter machined the central region. No gross sliding, rotation, or clamp release was observed. The fixture body and clamping screw remained clear of the tool path, and the open geometry allowed chip evacuation. The use of robust boss surfaces as clamping regions appears appropriate for aluminum, where direct pressure on the ribs could otherwise cause permanent marking or elastic springback.

The photographic evidence cannot, however, establish micron-level positional accuracy. A complete assessment should measure the central-bore position, boss-to-bore distance, rib thickness, surface flatness, and surface roughness before and after repeated setups. At least 10–30 repeated clamp–machine–release cycles would be desirable for estimating repeatability and process capability. Clamp force or screw torque should also be recorded because manual tightening is a major source of variation.

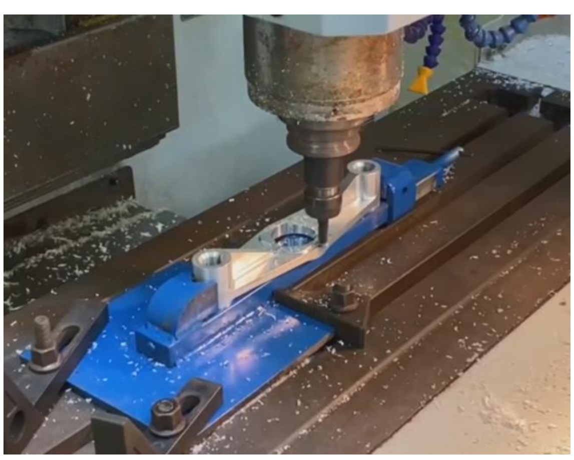

Fig. 5. Proof-of-concept milling trial with an aluminum linkage bracket.

Fig. 6. Proof-of-concept milling trial with a polymer linkage bracket.

The polymer trial demonstrated that the same fixture architecture can hold a lower-stiffness, more surface-sensitive workpiece. No visible slippage or severe indentation was apparent in the available image. This result supports the value of replaceable soft liners and distributed V-block contact. It also highlights the need for material-specific clamp settings: a force suitable for aluminum may be excessive for a polymer, while a force safe for polymer may be insufficient to resist aggressive aluminium milling.

For polymer parts, thermal effects and time-dependent deformation should be considered. The contact pressure may relax during a prolonged cut, and cutting heat can alter stiffness or dimensional stability. Future tests should therefore monitor clamp force over time and, where appropriate, compare dry, air-blast, and minimum-quantity lubrication conditions.

3.2. Comparative discussion, limitations, and validation requirements

The proposed fixture occupies a practical middle ground between dedicated rigid fixtures and highly reconfigurable or actively controlled systems. Fractal and segmented-jaw vises offer broader geometric adaptability but introduce more moving interfaces and potentially lower stiffness [9, 10]. Digital-twin, floating-support, and robot-assisted systems can actively reduce deformation, but their sensors, actuators, and control architecture increase cost and implementation complexity [12–18]. Profile-matching pneumatic fixtures provide strong production repeatability for a fixed geometry, but require greater manufacturing investment [11]. The present V-block concept is less universal, yet it is mechanically transparent, low-cost, and well-matched to linkage brackets with cylindrical bosses.

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The main novelty is therefore not the isolated use of a V-block, which is established practice, but the systematic integration of robust-feature clamping, rib relief, analytical load sizing, corrected FEA interpretation, and explicit proof-of-concept validation for a thin-ribbed linkage geometry. This positioning is more defensible than claiming a universally new fixture principle.

The results should be interpreted within the limits of the present prototype study. The cutting-force coefficients were adopted for preliminary sizing rather than calibrated for the exact tool–workpiece combination, and the manual clamping force was not measured directly. Moreover, the finite-element model was static and did not include bolt preload, complete frictional contact, progressive material removal, or dynamic excitation. The machining trials, therefore, provide qualitative evidence of seating, accessibility, and gross stability, but they do not yet establish statistical repeatability, process capability, or the full claimed size range. These limitations do not invalidate the design concept; they define the additional evidence required before industrial qualification.

A quantitative validation campaign should therefore combine measured cutting loads, instrumented clamping, repeated setup tests, dimensional metrology, and surface-quality assessment. The tri-axial force history should first be recorded with a calibrated dynamometer and compared with the mechanistic estimate [29, 35]. The clamp force should then be related to the tightening torque using a load washer or a force sensor. Repeated clamp–machine–release cycles should be used to evaluate datum shift, bore position, boss spacing, rib thickness, flatness, and surface roughness, with a conventional vise tested under identical conditions as a benchmark. Reporting the mean, standard deviation, confidence interval, measurement capability, and process-capability indices would convert the present proof of feasibility into a statistically supported fixture qualification. The recommended validation matrix is summarized in Table 3.

Table 1. Functional requirements, design responses, and verification criteria.

Requirement	Design response	Verification method	Acceptance basis
Deterministic location	Boss support plus central longitudinal locator	Constraint and assembly review	No uncontrolled rigid-body motion
Low rib loading	Relief pockets beneath/around ribs	CAD interference review	No direct clamp contact on thin ribs
Resistance to milling loads	Opposed fixed and movable 45° V-blocks	Force analysis and FEA	No sliding; stress below yield
Tool accessibility	Open-top architecture and low-profile supports	Tool-path clearance review	No collision within intended operations
Surface protection	Replaceable polymer/soft liners	Visual inspection after clamping	No visible indentation or galling
Adaptability	Movable V-block and elongated base arrangement	Setup trials	Accommodates the intended bracket-length range
Manufacturability	Machined prismatic parts and standard screw actuation	Process review	Fabricable with conventional workshop equipment
Repeatability	Hard datum surfaces and controlled clamping sequence	Repeated setup measurement (future work)	Statistically demonstrated positional consistency

Table 2. Preliminary machining parameters and cutting-force estimates.

Parameter	Value	Role in preliminary sizing
Spindle speed, n	2000 rpm	Defines tooth-passing rate
Table feed, v_f	1500 mm/min	Determines chip load
Number of flutes, z	2	Used in feed-per-tooth calculation
Axial depth, a_p	1 mm	Defines engaged chip area
Specific force, k_c	800 N/mm²	Illustrative coefficient for aluminum sizing
Tangential force, Ft	300 N	Dominant cutting component
Radial force, Fr	195 N	Primary lateral destabilizing component
Axial force, Fa	90 N	Reacted mainly by base support

Table 3. Recommended validation matrix for industrial qualification.

Validation item	Instrument/method	Primary response	Minimum evidence
Clamp-force calibration	Load cell or instrumented bolt	Force vs. torque	Calibration curve and uncertainty
Repeated location	Dial indicator or CMM	Datum displacement	≥10 repeated setups
Machined geometry	CMM/3D scanning	Bore position, flatness, rib thickness	Mean, SD, comparison with tolerance
Surface integrity	Contact profilometer and visual inspection	Ra/Rz, indentation, galling	Multiple traces per surface
Dynamic behavior	Accelerometer/microphone/force signal	Dominant frequency and chatter indicator	Time/frequency-domain analysis
Benchmarking	Conventional vise vs. proposed fixture	Accuracy, setup time, roughness	Matched cutting conditions

4. Conclusions

This study presents a modular fixture for milling thin-ribbed linkage brackets by combining opposed 45° V-blocks, a central locating element, replaceable contact liners, and deliberate relief around the ribs. The design was derived from the functional geometry of the workpiece and from the requirement to transfer machining loads through the cylindrical bosses and central hub rather than through the compliant ribs. The resulting methodology integrates requirement definition, constraint logic, force-path selection, analytical load sizing, finite-element verification, and prototype machining into a coherent engineering design process. Under the preliminary cutting condition, the estimated tangential, radial, and axial forces were 300, 195, and 90 N, respectively, indicating that the fixture must provide a kilonewton-scale effective clamping action while maintaining contact pressure below the allowable level of the workpiece–liner system. Finite-element verification gave a maximum von Mises stress of approximately 72.55 MPa and a maximum displacement of approximately 1.59×10^{-3} mm, thereby supporting the structural feasibility of the prototype under static loading under the assumed boundary conditions. Proof-of-concept machining trials on aluminum and polymer workpieces further confirmed functional seating, tool accessibility, chip clearance, and the absence of visible gross slippage or rib damage. These trials should nevertheless be regarded as proof-of-concept evidence because the clamping force, dynamic response, dimensional repeatability, and surface integrity were not quantified statistically. The principal contribution is therefore a practical and traceable fixture-design strategy for a defined class of thin-ribbed linkage brackets. Future qualification should integrate measured force histories, instrumented clamping, contact-aware dynamic simulation, repeated metrology, surface-roughness evaluation, and benchmarking against a conventional vise.

Declarations

i. Funding: The authors should insert the applicable funding statement before submission.
ii. Conflicts of interest: The authors declare no conflict of interest.
iii. Data availability: The data supporting the findings should be made available by the corresponding author upon reasonable request, subject to institutional policy.

Author contributions: Conceptualization, design, analysis, experimentation, writing, and supervision statements should be completed in accordance with the target journal taxonomy.

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