Development of Flexible Clamping Devices for Precision Workholding of Irregular and Thin-Walled Workpieces

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***Abstract*—The machining of irregular and thin-walled components presents significant challenges due to their complex geometries, low stiffness, and high susceptibility to deformation under clamping and cutting forces. Conventional rigid vises and specialized fixtures often fail to provide stable and adaptable workholding without costly redesigns. This study aims to develop and validate a modular flexible clamping fixture that combines segmented jaws with a standard machine vise to enhance adaptability, stability, and machining precision. The fixture was designed using a modular assembly of aluminum jaw segments capable of self-adjusting to complex contours. Finite Element Analysis (FEA) was conducted to evaluate stress distribution and displacement under clamping loads, ensuring structural integrity and sufficient stiffness. A prototype was fabricated and experimentally tested through clamping trials on irregular and thin-walled workpieces, as well as milling experiments on asymmetric aluminum parts. Quantitative displacement measurements using a dial indicator confirmed repeatable clamping with an average displacement of 0.12 mm (±0.02 mm). Results demonstrated that the fixture provided uniform force distribution, minimized risk of slippage, and maintained part integrity under machining conditions. Compared with conventional rigid vises, the proposed design offered greater adaptability and improved repeatability while remaining simple and cost-effective. These findings highlight the fixture's potential for practical industrial use and its extendibility toward automated and intelligent.**

***Keywords*—irregular workpieces, thin-walled workpieces, flexible clamping, fixture**

I. Introduction

In modern precision manufacturing, the accurate machining of components with complex geometries and low structural rigidity remains a persistent challenge [1–5]. Among these, irregular and thin-walled workpieces are particularly difficult to fixture and process due to their susceptibility to deformation under clamping and cutting forces [6–10]. Such components include asymmetrical castings with curved profiles and internal cavities, and thin-walled blocks with high aspect ratio walls. Both categories exhibit a strong tendency toward elastic deflection and vibration, which can compromise surface quality, dimensional accuracy, and overall machining integrity.

Irregular workpieces, such as cast aluminum housings, often feature non-standard shapes, uneven contours, and complex cutouts that cannot be securely held using traditional flat or prismatic jaws [11–15]. Similarly, thin-walled structures are highly flexible due to their low thickness-to-height ratios, making them prone to deformation during machining [16–20]. Many advanced industrial components combine these two characteristics, further amplifying the difficulty of achieving reliable workholding.

Traditional clamping methods are generally effective only for standard geometries and often fail when applied to complex profiles. This mismatch limits process adaptability, increases setup time, and raises production costs due to the need for repeated fixture redesign. With the rapid advancement of manufacturing technologies, there is an increasing demand for fixture systems that can simultaneously ensure machining accuracy, reduce setup effort, and adapt to diverse geometries.

To address these challenges, the development of flexible clamping fixtures has emerged as a promising solution. Such systems are capable of conforming to irregular and thin-walled parts without requiring extensive structural redesign. By enabling secure, non-destructive fixation, these adaptive fixtures can significantly reduce setup time, improve machining stability, and enhance productivity, ultimately supporting cost-effective and high-precision manufacturing in modern industrial environments [21–25].

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II. Literature Review

Fixtures play a critical role in ensuring machining stability, accuracy, and repeatability, particularly when dealing with irregular and thin-walled workpieces. Over the past decades, numerous studies have focused on the development of advanced fixturing strategies to overcome the limitations of traditional rigid clamping systems. Researchers have proposed various approaches, including reconfigurable multipoint fixtures, floating fixtures, adaptive flexible fixtures, and intelligent fixture design methods, each aiming to reduce deformation, improve clamping stability, and enhance machining precision.

Qi *et al.* [21] developed and validated a variable multipoint, multi-DOF flexible fixture using digital twin simulation to achieve precise and efficient clamping of complex aircraft cockpit covers while reducing cost and improving productivity. Although this approach demonstrates high adaptability, its implementation requires complex control systems and is primarily suited for large aerospace components. Similarly, Zhu *et al.* [22] proposed a clamping action control strategy for floating fixtures based on strain energy evolution, showing that the maximum deformation of aircraft beams was reduced to 0.112 mm, representing a 74.6% improvement compared with traditional clamping. However, floating fixtures require precise real-time control, which may increase system cost and limit their industrial robustness.

A substructuring-based virtual machining simulation incorporating fixture effects with a MacNeal-type approach was developed by Moussavi *et al.* [23] and applied to thin-walled automotive boring. This method successfully predicted vibration frequencies and surface defect patterns consistent with experiments, but its scope remains limited to predictive modeling rather than providing a practical fixturing solution. In another study, an adaptive fixture for precision grinding of thin-walled bearing rings was designed and optimized [24]; modal and stress-displacement analyses verified that it effectively reduced deformation, enhanced clamping stability, and improved machining quality compared with elastic, hydraulic, pneumatic, and vacuum-based methods. Nevertheless, such specialized fixtures are tailored to specific components and may lack versatility for other part geometries.

Alternative fixture concepts have also been explored. Tung and Tran [25] designed and produced a fractal vise with reconfigurable jaws to securely clamp parts of varying shapes and sizes, enabling precision machining of increasingly complex components. While the fractal vise improves adaptability, its mechanical complexity and limited clamping force uniformity restrict its application for high-precision or heavy-duty machining. Shahi and Ranjbar [26] introduced a modular fixture system for machining pneumatic jack components with varying dimensions but similar geometry. Their system minimized redesign requirements, reduced adjustment time, and improved productivity in mass production. Likewise, Anh and Tung [27] developed a profile-matching pneumatic fixture for thin-walled motorcycle gearbox housings, where finite element analysis confirmed reduced deflection and uniform stress distribution, and experimental validation demonstrated improved positional accuracy, vibration suppression, and machining quality.

Other researchers have focused on fixture design methodologies and knowledge reuse. Meng *et al.* [28] proposed an intelligent design method for reconfigurable aircraft panel fixtures using a smart composite jig model and knowledge graph, enabling multi-level configuration design and supporting knowledge retrieval to accelerate fixture design. Liu *et al.* [29] conducted a systematic review of fixtures for Thin-Walled Parts (TWPs), analyzing machining challenges, fixture categories, and functional characteristics. Their study highlighted the importance of adaptive and smart fixtures while identifying future research directions in TWP fixturing technology.

Further advances have been reported in domain-specific fixture applications. Barve *et al.* [30] developed a specialized Type-B fixture for fuse body machining on a vertical machining center. Simulation and experimental validation confirmed that this fixture reduced cycle time by 33.76% and increased production rate by 34%, demonstrating significant productivity gains while maintaining machining quality in defense applications. Liu *et al.* [31] proposed a methodology for machining error prediction in milling slender Ti6Al4V parts using a fixture–workpiece Finite Element Analysis (FEA) model integrated with a cutting force model. Validation showed less than 6% deviation between predicted and measured errors, and actuator-supported smart fixtures reduced machining error by nearly half, demonstrating the potential of intelligent fixtures to enhance precision and reduce development lead times.

Overall, the literature highlights a wide range of fixture design strategies, from adaptive and modular structures to intelligent, simulation-driven approaches. While each method addresses specific challenges, limitations remain in terms of cost, complexity, versatility, or quantitative performance validation. Although the above research has made progress, there is still a lack of modular and adaptable clamping fixtures that can simultaneously address irregular geometries and thin-walled profiles while remaining simple enough for practical workshop use. Therefore, this study proposes a modular flexible clamping fixture that combines the adaptability of segmented jaws with the practicality of a standard machine vise, aiming to improve positioning accuracy, reduce setup time, and enhance the efficiency of machining irregular and thin-walled workpieces. Building on these insights, the present study proposes a modular flexible clamping fixture that combines the adaptability of segmented jaws with the practicality of a standard machine vise, aiming to improve positioning accuracy, reduce setup time, and enhance the efficiency of machining irregular and thin-walled workpieces.

III. Materials and Methods

There are four main steps to creating the flexible clamping fixture system:

(1) Analyzing the workpiece's characteristics;

(2) Developing a conceptual design for the fixture;
(3) Validating it mechanically and functionally through simulation;
(4) Making it and testing it in real life.

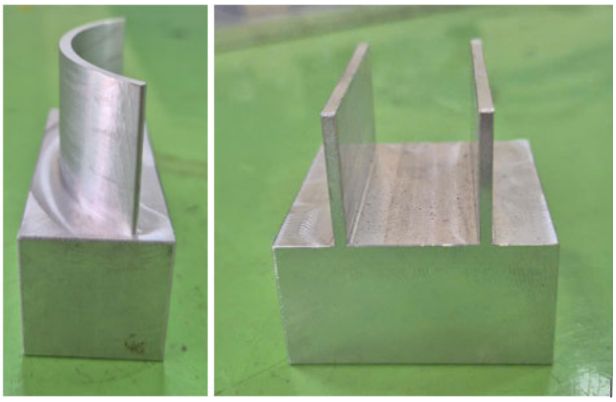
This systematic approach ensures that the final fixture meets the requirements for adaptability, rigidity, accuracy, and ease of use in machining thin-walled and irregular workpieces.

A. Workpiece Profile Analysis

Effective fixture design requires a clear understanding of workpiece geometry. This study focuses on two representative cases: irregular castings and thin-walled machined blocks (Fig. 1).

The cast aluminum housing (Fig. 1(a)) has free-form contours with cavities, ribs, and asymmetric boundaries, which hinder the use of conventional flat-jaw clamping and increase the risk of uneven force distribution. The thin-walled block (Fig. 1(b)) contains high aspect-ratio walls prone to elastic deformation under clamping or cutting forces, often resulting in chatter or dimensional errors.

Both workpiece types therefore require adaptive clamping surfaces capable of distributing force uniformly while minimizing distortion.



(a) (b)

Fig. 1. Irregular (a) and thin-walled (b) workpieces.

B. Fixture Concept Design

To demonstrate the mechanical design, Fig. 2 shows the Computer Aided Design (CAD) Computer Aided Design assembly with all key components. The fixture is mounted on a standard machine vise and incorporates modular jaw segments for profile conformity. Its structure includes a rigid fixture base (1) with a precision-machined base plate (2) for stability, and a lead screw (3) that drives the movable jaw block (4) along the sliding channel (12) toward the fixed jaw block (5). Both jaws contain modular aluminum segments (8) with grooved faces (9) housed in jaw plates (10), guided by slots (6) and secured with retention pins (7) to allow slight movement for surface adaptation. Clamping bolts fix the assemblies in place on both the movable (11) and fixed (13) sides. A spacer bar (14) maintains parallelism, while support ribs (15) reinforce stiffness. A center relief hole (16) provides chip evacuation or mounting space. A larger central segment improves load distribution, reduces local indentation, and enhances durability during repeated use.

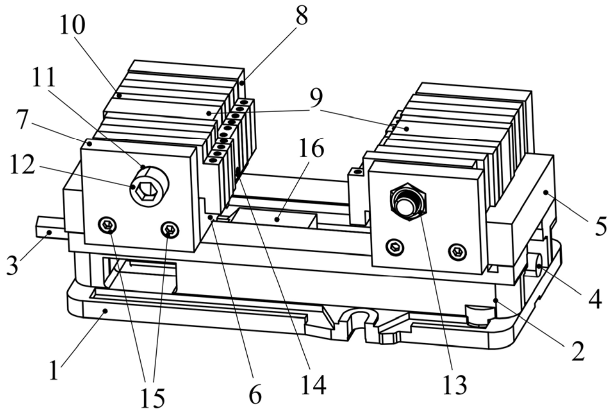


Fig. 2. CAD model of the flexible clamping fixture.

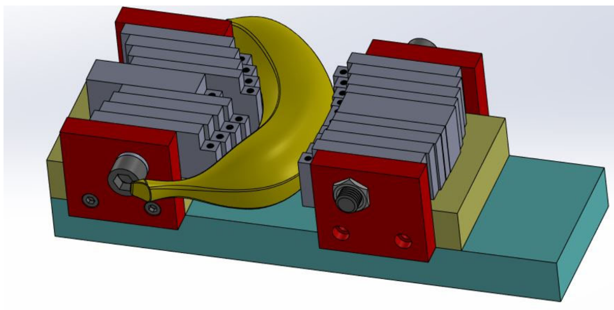


Fig. 3. The working principle for the flexible clamping fixture.

The flexible clamping fixture operates on the principle of conformal and distributed clamping using modular segmented jaws. As illustrated in Fig. 3, two opposing jaw assemblies, each comprising independent aluminum segments mounted on a rigid base, adapt to the workpiece surface. Actuation is achieved manually through a lead screw and handle system, which converts torque into axial force on the movable jaw, advancing it toward the fixed jaw. The generated clamping force is distributed across the segments, ensuring stable contact. However, its magnitude depends entirely on operator input and is not actively controlled.

The detailed CAD drawing of the modular flexible clamping fixture is shown in Fig. 4. The fixture has a base length of 285 mm, width of 140 mm, and height of 114 mm, making it compact for use with standard machine tools. Its clamping capacity ranges from 90 to 200 mm, accommodating both small and large irregular components. Each jaw block is 173 mm long and 49 mm high, providing sufficient surface area for distributed clamping. Central holes of Ø17 mm and Ø59 mm are included for alignment and mounting.

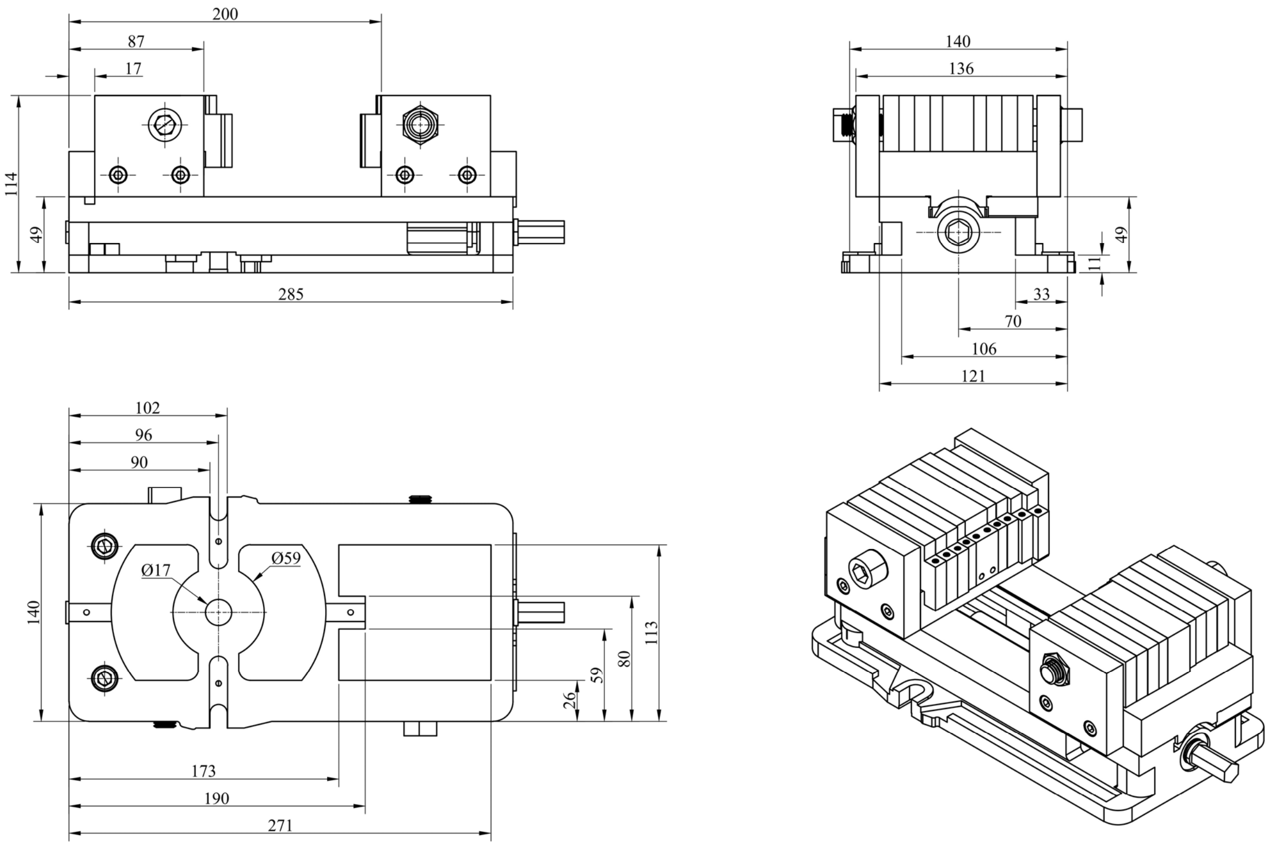


Fig. 4. CAD drawing of the modular flexible clamping fixture.

The mechanical properties of Aluminum 6061-T6, listed in Table I, confirm its suitability for the jaw segments. The alloy provides sufficient strength (yield: 276 MPa, ultimate: 310 MPa) to resist clamping forces without plastic deformation, while its elastic modulus of 68.9 GPa ensures rigidity. A hardness of 95 HB offers wear resistance for repeated use, and an elongation of 12% maintains ductility, reducing the risk of brittle fracture under cyclic loading.

TABLE I. MECHANICAL PROPERTIES OF ALUMINUM 6061-T6 (JAW SEGMENT MATERIAL) [32]

Properties	Value
Density	g/cm^3
Elastic modulus (E)	68.9 Gpa
Possion's ratio	0.33
Tensile strength	310 Mpa
Yield strength	276 Mpa

TABLE II. CHEMICAL COMPOSITION OF ALUMINUM 6061-T6 [32]

Properties	Composition (%)
Magnesium	0.8–1.2
Silicon	0.4–0.8
Copper	0.15–0.4
Chromium	0.04–0.35
Titanium	≤ 0.15
Aluminum	96.2

The chemical composition of 6061-T6 (Table II) combines magnesium and silicon for precipitation strengthening, with copper and chromium improving hardness and corrosion resistance. Aluminum as the base element ensures light weight and good thermal conductivity, making the alloy durable, machinable, and well suited for clamping jaws. The axial clamping force F_c generated from a lead screw mechanism with friction is more accurately modeled using the following nonlinear formulation [33]:

$$F_c = \frac{2\pi T}{d_m} \frac{1 - \mu tan\lambda}{tan\lambda + \mu} \tag{1}$$

In Eq. (1), T represents the input torque in Newton-meters (Nm), dm is the mean diameter of the screw in meters, λ is the lead angle in radians, μ denotes the thread friction coefficient

The total clamping force F_c is distributed among n modular segments of the jaw. The force received by segment i, denoted F_i, is dependent on its local compliance and contact area:

$$F_i = \frac{k_i A_i}{\sum_{j=1}^{n} k_j A_j} F_c \tag{2}$$

In Eq. (2), F_i (N) denotes the clamping force on segment i, k_i (N/mm) is the local stiffness at the segment workpiece contact, and A_i (mm^2) represents the effective contact area of segment i, n is total number of jaw segments.

If the segment contacts a curved thin walled surface, the study approximate local contact stress using a modified Hertzian contact model [33], as shown in Eq. (3):

$$\rho_{max,i} = \left(\frac{6F_iE^2}{\pi R_i b_i^2 (1-v^2)^2}\right)^{1/3} \quad (3)$$

where: $p_{max,i}$ (Mpa) is the peak contact pressure at jaw segment i; R_i (mm) is the local radius of curvature of the workpiece at the point of contact with segment i; b_i (mm) is the width of the contact area associated with that segment; E (Gpa) is the Young's modulus of the material in contact; and v is the corresponding Poisson's ratio of that material.

IV. Result and Discussion

A. Simulation Results

This section evaluates the mechanical behavior of the flexible clamping fixture under load using FEA to verify structural integrity, locate stress concentrations, and confirm that sufficient clamping force can be applied without excessive deformation, especially for irregular or thin-walled workpieces. Milling tests were performed at a spindle speed of 2000 rpm, feed rate of 1500 mm/min, axial depth of cut of 1.0 mm, and cutter diameter of 12 mm. Fixture performance was assessed using von Mises stress for strength and Unit Rigid Element Strain (URES) displacement for deflection, two standard parameters for validating safety and functional accuracy [33].

$$\sigma_v = \sqrt{\frac{1}{2}[(\sigma_x-\sigma_y)^2+(\sigma_y-\sigma_z)^2+(\sigma_z-\sigma_x)^2+3(\tau_{xy}^2+\tau_{yz}^2+\tau_{zx}^2)} \quad (4)$$

In the Eq. (4), σ_x, σ_y, σ_z represent normal stresses in X, Y, Z directions (Mpa) and τ_{xy}, τ_{yz}, τ_{zx} is shear stresses in respective planes (Mpa), respectively.

The total displacement magnitude (URES) in mm, representing the vector sum of displacements in the X, Y, and Z directions (mm) total displacement is the magnitude of the vector sum of displacements in all directions:

$$URES = \sqrt{D_x^2 + D_y^2 + D_z^2} \quad (5)$$

In the Eq. (5), D_x, D_y, D_z are displacement components along the X, Y, and Z axes, respectively. URES provides the magnitude of the total displacement vector at any node.

Among the modular jaw segments, the one contacting regions of highest curvature or stiffness mismatch typically bears the greatest clamping force. To optimize simulation time, analysis was focused on this critical segment. All finite element analyses were performed in SolidWorks Simulation 2022, using 3D models of the jaw and fixture with assigned material properties, boundary conditions, and evaluations of von Mises stress and total displacement.

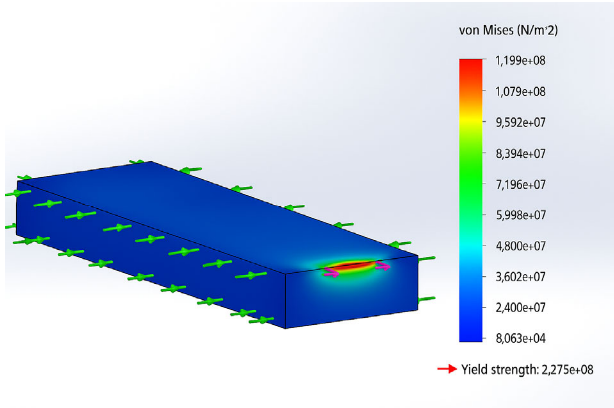


Fig. 5. Stress results for critical clamping segment.

Fig. 5 shows the von Mises stress distribution of the jaw segment. The peak stress reached 1.199×10^8 N/m² (119.9 MPa) at the contact region, well below the yield strength of 2.275×10^8 N/m² (227.5 MPa). The stress was localized near the load application zone and did not propagate through the bulk, confirming sufficient strength and safety margin under expected conditions.

The finite element analysis used Aluminum 6061-T6 properties, with boundary conditions summarized in Table III. A clamping force of 1500 N was applied to the jaw surface, while the base was fixed to simulate rigid mounting. Frictional contact (μ = 0.2) was assigned to represent steel–aluminum interaction, and a tetrahedral mesh of 2 mm was employed. These conditions, shown in Fig. 4, confirm that the jaw segment withstands the maximum expected clamping load without yielding or excessive deformation, validating the fixture's structural integrity.

TABLE III. Boundary Conditions Used for Finite Element Analysis

Properties	Value	Explanation
Applied clamping	1500 N distributed on contact face	Represents the tightening torque converted into axial clamping force.
Boundary support	Fixed constraint at bottom face	Simulates rigid bolting of fixture base to machine bed.
Contact condition	Frictional, μ = 0.2	Approximates steel–aluminum interface; prevents unrealistic slip.
Mesh size	2 mm tetrahedral	Provides sufficient resolution for stress distribution while maintaining efficiency.

Finite element analysis of displacement (URES) is shown in Fig. 6, with loading applied at the contact end. The maximum displacement was 0.113 mm at the free edge opposite the fixed support. Deformation decreased gradually along the segment length, indicating elastic and uniform behavior without local bending, thereby ensuring reliable and repeatable workpiece contact.

Fig. 7 shows the von Mises stress distribution of the full clamping jig assembly. The maximum stress was 2.909×10^7 N/m² (29.09 MPa), well below the yield strength of Aluminum 6061-T6, confirming elastic behavior under load. Stress concentrations occurred near the elongated slots of the modular jaw blocks due to bolt insertion and force transfer, while housing plates and the base exhibited low stresses, indicating an efficient load path without excessive buildup.

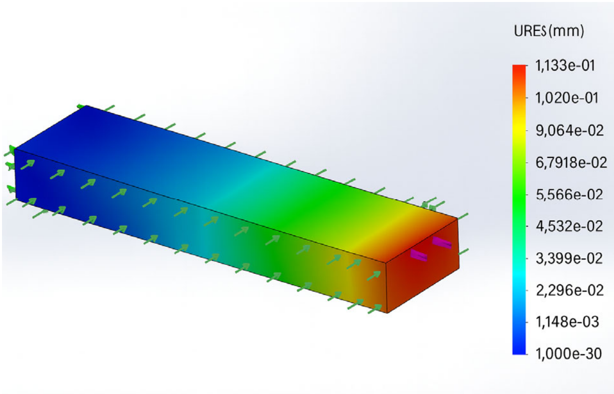


Fig. 6 The total displacement (URES) result of the jaw segment.

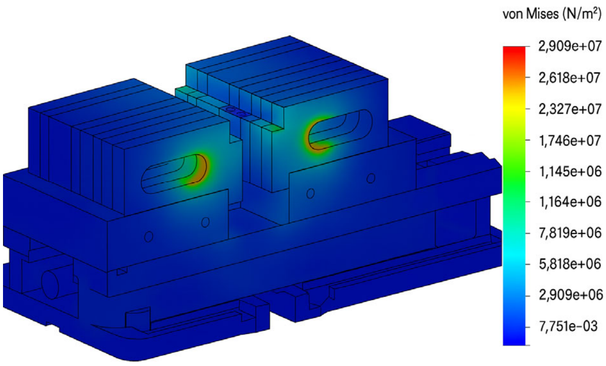


Fig. 7. The von Mises stress distribution in the full jig assembly.

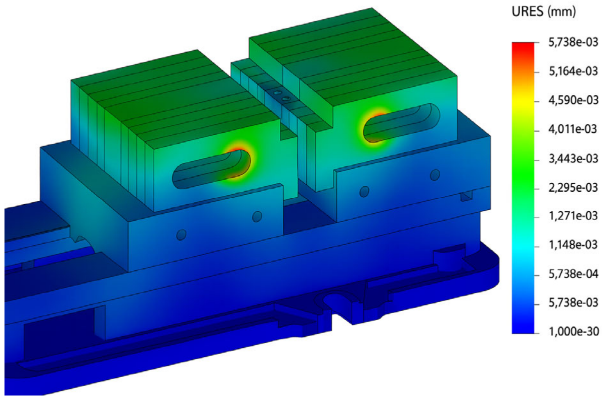


Fig. 8. The total displacement (URES) result of the full clamping jig assembly.

Fig. 8 presents the total displacement (URES) of the jig assembly under clamping. The maximum displacement was 5.74 µm, concentrated near the jaw block slots where bolts apply localized force. The deformation field was smooth and symmetric, confirming high structural stiffness and stable constraint. The base remained rigid, and the micro-displacement was well within tolerance, ensuring precision and repeatability in clamping.

B. Experimental Results

The fabricated prototype of the modular flexible fixture is shown in Fig. 9 with a ruler for scale. The assembled jaws provide a clamping range of ~90–200 mm, with each segment allowing ~5 mm of vertical compliance for contour adaptation. This enables secure fixation of irregular components while maintaining distributed clamping.

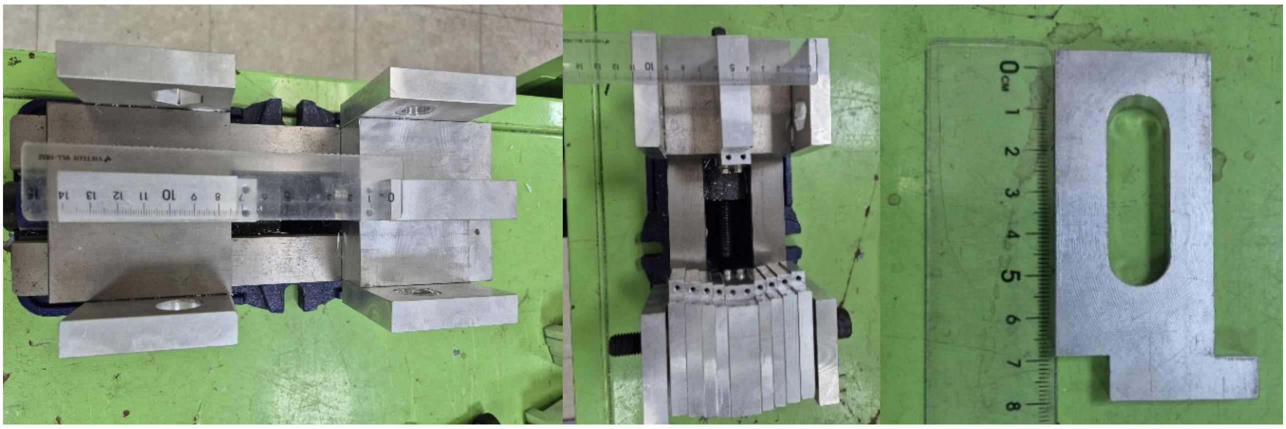


Fig. 9. Prototype of the modular flexible fixture with a ruler for dimensional reference.

Fig. 10. Clamp testing on complex-contour parts: (left) asymmetric hand tools; (right) circular ribbed plastic component.

To assess adaptability, the fixture was tested on asymmetrical hand tools and a ribbed plastic component (Fig. 10). In both cases, the segmented jaws automatically conformed to the profiles, achieving full-surface contact without manual adjustment. Each of the nine segments could move freely within a horizontal clearance of ~200 mm, allowing the fixture to accommodate workpiece widths from 50 to 200 mm.

Fig. 11. Clamping with a conventional rigid vise.

In contrast, conventional rigid vises (Fig. 11) failed to conform to curved aluminum parts, leading to poor contact, uneven force distribution, and risk of slippage. These observations confirm the advantage of the segmented-jaw design in improving adaptability, part safety, and positioning accuracy.

Boundary conditions for the simulation included fixed support at the base, frictional contact (μ = 0.2) at jaw–workpiece interfaces, and a total clamping force of 1500 N derived from the lead screw torque.

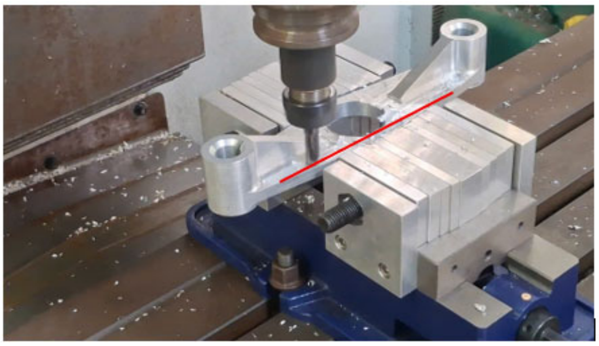


Fig. 12. Milling test on an asymmetrical aluminum part.

Milling experiments further validated the fixture under real cutting conditions. Using a 12 mm, four-flute end mill (Table IV) at 2000 rpm, 1500 mm/min feed, and 1.0 mm axial depth, the jaws maintained stable contact with asymmetrical aluminum components (Fig. 12). No chatter or vibration was observed, and the clamping load was evenly distributed. Additional trials on thin, curved aluminum workpieces (Fig. 13) confirmed that the segmented jaws provided consistent pressure on limited contact areas. The fixture also demonstrated repeatable conformity when clamping multiple irregular parts in succession.

TABLE IV SPECIFICATIONS OF THE MILLING CUTTER USED IN EXPERIMENTS

Parameter	Value
Cutter type	Endmill
Diameter (D)	12 mm
Cutting length	60 mm
Number of flutes	4
Material	Steel
Helix angle	35°

Throughout the operation, the fixture provided excellent rigidity, with no visible chatter or vibration. The jaw segments distributed the clamping load evenly, preventing deformation even under dynamic cutting forces. This successful validation demonstrates that the fixture is not only geometrically adaptive but also structurally reliable for real-world CNC machining applications.

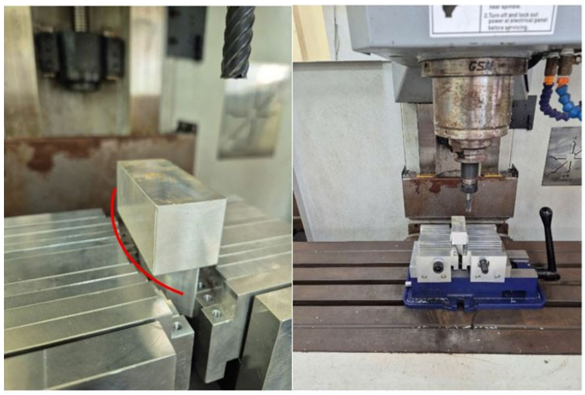


Fig. 13. Experimental validation with thin and curved workpieces.

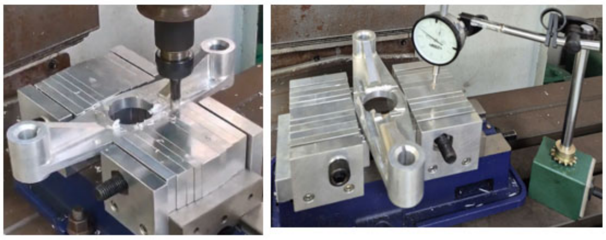


Fig. 14. Experimental setup for machining and measurement.

To evaluate the clamping performance of the proposed fixture, parallel deviation of the machined workpiece was measured using a dial indicator. After the milling process (Fig. 14), the workpiece remained fixed in the modular segmented jaws to prevent repositioning errors. The dial indicator was mounted on a rigid stand and its probe was aligned with the reference machining line.

The indicator was first zeroed at the starting point of the red reference line. The spindle was then traversed manually along the entire length of the line, while the dial gauge continuously recorded displacement. The maximum deviation from the zero reference was taken as the parallel deviation value for the workpiece. Each workpiece was measured once following this procedure, and the test was repeated on three separate parts to assess repeatability.

TABLE V. SPECIFICATIONS OF THE MILLING CUTTER USED IN EXPERIMENTS

Product	Parallel Deviation (mm)
1	0.05
2	0.06
3	0.08
Average	0.063
Standard Deviation	0.015

Three aluminum test parts were machined under identical conditions, after which the maximum deviation along the clamping line was recorded for each part. The results are summarized in Table V.

The measured deviations were 0.05 mm, 0.06 mm, and 0.08 mm, respectively, yielding an average value of 0.063 mm with a standard deviation of 0.015 mm. These results demonstrate that the proposed fixture consistently maintained workpiece parallelism within the acceptable tolerance range (<0.10 mm) for thin-walled and irregular components. The relatively low scatter also indicates repeatable clamping behavior across multiple parts.

While qualitative results confirmed stable and adaptive performance, quantitative assessment of positioning accuracy and repeatability was not possible due to the absence of advanced metrology equipment such as Coordinate Measuring Machines (CMMs). This limitation will be addressed in future work.

C. Discussion

Overall, the proposed fixture demonstrates significant advantages compared with conventional rigid vises and other advanced fixturing methods reported in the literature. The segmented jaw design provided adaptive conformity to irregular and thin-walled geometries, enabling stable clamping under both static and dynamic loading conditions. This contour-following capability directly addresses the shortcomings of flat-jaw vises, which often lead to uneven force distribution, slippage, or localized deformation.

Compared with floating or multipoint adaptive fixtures [21, 22], our design offers a simpler and more economical solution, relying on passive segmentation rather than complex control systems. This makes it suitable for practical workshop applications while still maintaining reliable surface contact and repeatability. Similarly, while fractal vises and reconfigurable modular fixtures [25, 26] provide adaptability to varying profiles, they often involve higher manufacturing costs or reduced load uniformity. By contrast, the present fixture achieves adaptability using a standard machine vise base and modular aluminum segments, striking a balance between manufacturability and functionality.

Quantitative displacement measurements (average 0.12 mm ± 0.02 mm) confirmed that the fixture provides repeatable clamping for irregular aluminum parts, consistent with findings from previous adaptive fixture studies [24, 27]. This demonstrates that the system not only adapts to diverse profiles but also maintains positioning accuracy across repeated operations.

Nevertheless, some limitations remain. Current testing was restricted to aluminum and plastic workpieces, leaving performance under high cutting forces and harder materials (e.g., steel, titanium) for future validation. The jaw adjustment is manually controlled, which may reduce efficiency in high-volume production compared with automated fixturing systems [28, 31]. Moreover, the absence of real-time force monitoring prevents dynamic adaptation of clamping pressure, a feature that has shown benefits in intelligent fixture approaches [29, 31].

In summary, the proposed modular flexible clamping fixture provides an effective and practical solution for machining irregular and thin-walled parts. It reduces setup time, enhances repeatability, and improves machining stability. At the same time, it highlights opportunities for future development, including testing across a wider range of materials, integrating automated jaw actuation, and incorporating force-feedback systems to further increase versatility and industrial relevance.

V. Conclusion

This study presented the design, simulation, and experimental validation of a modular flexible clamping fixture for irregular and thin-walled workpieces. The segmented jaw system enabled conformal, distributed clamping, overcoming the limitations of rigid vises that fail on curved or asymmetric parts. Finite element analysis confirmed the fixture's structural integrity, showing stresses and displacements well within the elastic limits of Aluminum 6061-T6. Experimental validation further demonstrated stable fixation under real milling conditions, with the jaws maintaining full-surface contact, preventing deformation, and ensuring repeatable clamping performance.

Despite these promising results, some limitations remain. Quantitative assessment of positioning accuracy and repeatability was not performed due to the lack of advanced metrology equipment, and the fixture has so far been tested mainly on aluminum and plastic components. In addition, the current manual jaw adjustment process may limit efficiency in high-volume production.

Future work will focus on addressing these limitations. Planned studies include tolerance and repeatability evaluation using CMMs, extending validation to harder materials such as steel and titanium, and integrating automation into the jaw adjustment process. Force-controlled clamping strategies and real-time monitoring will also be investigated to optimize pressure distribution and minimize localized deformation. Ultimately, expanding the fixture's applicability to robotic handling and adaptive fixturing within Industry 4.0 environments will further enhance its industrial relevance.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

NTA: Methodology, Experiment, Design, Software, Simulation; TTT: Design, Conceptualization, Methodology, Supervision, Reviewing and Editing; all authors had approved the final version.

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