[1.] Tran Thanh TUNG , [2.] Nguyen Thi ANH, [3.] Nguyen Xuan QUYNH, [3.] Tran Vu MINH

DESIGN AND FABRICATION OF A PRECISION MACHINED MECHANICAL LINKAGE ARM FOR STRUCTURAL AND MOTION APPLICATIONS

[1.]Faculty of Engineering Mechanics and Automation, VNU University of Engineering and Technology, Hanoi, VIETNAM
[2.]Faculty of Mechanical Engineering, Thuyloi University, Hanoi, VIETNAM
[3.]School of Mechanical Engineering, Hanoi University of Science and Technology, Hanoi, VIETNAM

Abstract: This study presents the design, CNC based fabrication, and dimensional evaluation of a precision–machined mechanical linkage arm intended for use in structural and motion transmission applications. The component, manufactured from 6061–T6 aluminum alloy, is designed to operate under rotational or oscillatory motion in moderate load conditions, such as robotic manipulators and automated mechanical linkages. Key features include a forked slot for keyed shaft connection, a pinhole for pivoting motion, and a tapered profile to optimize structural rigidity and reduce mass. A combination of CNC milling and wire electrical discharge machining (EDM) was employed to achieve high dimensional accuracy and surface finish, especially for complex internal features such as the keyway. The manufacturing process involved sequential operations including face milling, drilling, boring, reaming, slotting, and EDM keyway cutting. Inspection results confirm that all critical dimensions and geometric tolerances, such as hole diameter, parallelism, perpendicularity, and keyway geometry, conform to the technical drawing specifications. The results validate the effectiveness of the proposed design and machining strategy in producing a functional, lightweight, and structurally reliable mechanical linkage arm suitable for high–performance engineering applications.

Keywords: CNC milling, mechanical linkage, fabrication, manufacturing

INTRODUCTION

In advanced manufacturing, Computer Numerical Control (CNC) milling has become one of the most important processes for producing high-precision and geometrically complex mechanical components [1-6]. As a subtractive manufacturing process, CNC milling removes material from a workpiece through the controlled motion of a rotating multi-point cutting tool following pre-programmed toolpaths generated from CAD/CAM models [7-12]. Owing to its high dimensional accuracy, repeatability, automation capability, and flexibility, CNC milling has been widely adopted in aerospace, automotive, robotics, and industrial automation for the manufacture of functional parts with stringent geometric and surface-quality requirements

Among the many applications of CNC milling, the fabrication of mechanical linkage arms is of particular engineering interest because these components are directly involved in transmitting motion and force between interconnected joints in constrained mechanical systems. A representative mechanical linkage arm considered in this study is shown in Figure 1. The component consists of a circular mounting end, a tapered arm body, and a forked end incorporating a central bore and an internal slot, resulting in a geometry suitable for rotational or oscillatory motion transmission. Such linkage arms are commonly employed in robotic manipulators, motion transmission systems, suspension mechanisms, and automated machinery, where reliable force transfer, accurate alignment, and adequate structural rigidity are required.

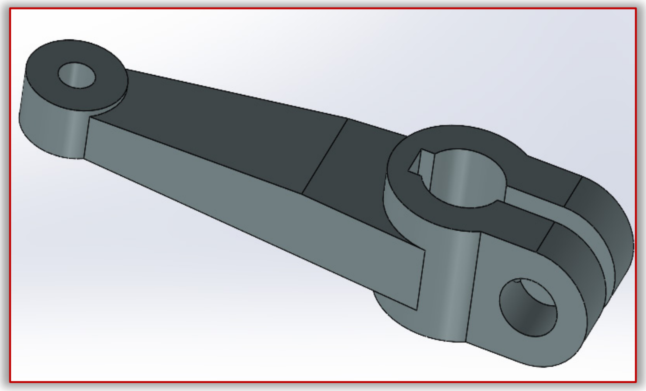

Figure 1. Mechanical linkage arm

Because of their functional role, linkage arms must satisfy several important design requirements, including sufficient stiffness and strength under repeated loading, tight dimensional tolerances for assembly compatibility, and suitable surface quality at contact, bore, and pivot interfaces. In addition, when a component contains a forked region, an internal slot, or a locally reduced cross-section, machining accuracy can become more sensitive to cutting forces, clamping conditions, and local structural compliance. Similar challenges have been widely reported in the machining of thin-walled and rib-stiffened components, where deformation control, fixture design, and process planning strongly influence dimensional accuracy, surface integrity, and machining stability [13-19].

Recent studies provide several useful perspectives for addressing these issues. A milling technique for mechanical parts with thin-walled ribs demonstrated that an appropriate cutting approach can improve dimensional control in locally compliant geometries [13]. Review studies on low-rigidity components have further clarified the deformation mechanisms involved in machining compliant structures and the corresponding control strategies [14]. A methodical fixture-design approach for thin-walled components showed that suitable support configuration and clamping design are essential for reducing deformation and improving repeatability during milling [15], while a recent review on flexible fixture design likewise highlighted the importance of adaptive support systems for improving machining accuracy in compliant workpieces [16]. In parallel, deformation prediction and numerical modeling have been increasingly used to evaluate the response of low-rigidity parts under machining loads. A cutter-workpiece-engagement-based model was proposed to predict deformation in flank milling of thin-walled parts [17], and a three-dimensional finite element model has also been developed and experimentally validated for force-deflection prediction in thin-wall milling [18]. Moreover, comparative investigation of up- and down-milling strategies confirmed that machining direction can significantly affect force-deflection behavior and the resulting dimensional accuracy of compliant parts [19]. Although the present component is not a classical thin-walled plate, these findings remain relevant because its tapered body and forked end introduce local stiffness variation that must be considered during machining.

Motivated by these considerations, the present study focuses on the design and fabrication of a lightweight yet structurally robust mechanical linkage arm manufactured from 6061-T6 aluminum alloy, a material known for its favorable strength-to-weight ratio, good machinability, and corrosion resistance. The component is intended to operate under rotational or oscillatory motion as a pivoting member in a constrained mechanical assembly. Its design integrates a forked slot for keyed shaft engagement, a precision bore for pin-based mounting, and a tapered profile to reduce mass while preserving structural integrity. Based on these requirements, the study establishes a practical manufacturing route combining CNC milling and wire electrical discharge machining (EDM) to produce the component with the required dimensional accuracy and geometric quality. In this way, the work highlights the relationship between structural design, material selection, machining strategy, and manufacturability in the realization of functional mechanical parts for structural and motion applications.

DESIGN CONSIDERATIONS

The mechanical component shown in the Figure 1 as a linkage arm designed to transmit force and rotational motion between two mechanical joints. Its geometry, featuring a forked end with a central bore and keyway slot, allows it to securely interface with a rotating shaft or axle, facilitating constrained angular movement. The opposite end includes a single circular hole, intended for pin or bolt mounting, enabling pivoting around a fixed axis. The tapered body of the arm provides a structural balance between rigidity and weight reduction, ensuring the component can withstand bending and torsional loads under moderate mechanical stress. This type of linkage is commonly employed in applications such as robotic joints, vehicle suspensions, or industrial mechanisms where precise force transmission, alignment, and durability are essential.

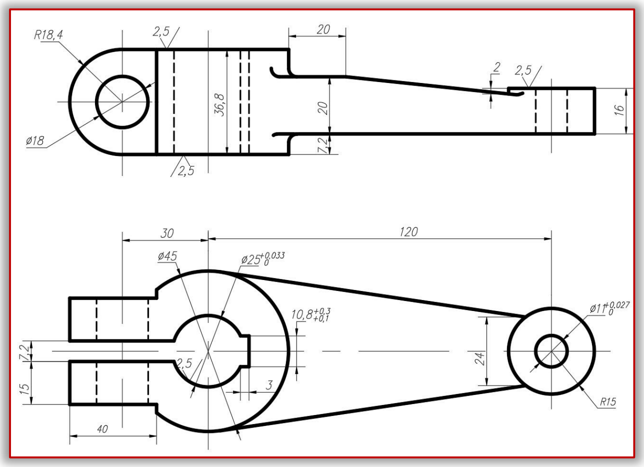

Figure 2. Technical drawing of the mechanical component

The mechanical component shown in the Figure 2 is a precision machined linkage arm designed to transfer rotational motion and mechanical force between two pivoting points in a constrained mechanism. The forked end with a central bore (Ø25 mm) and keyway enables a secure, torque-transmitting connection to a mating shaft or joint, while the opposite end features a smaller through hole (Ø11.8 mm) intended for pin or bolt mounting to a secondary structure or linkage. The tapered profile of the arm not only reduces material usage and overall weight but also helps maintain structural stiffness along its length. This geometry supports bending and torsional loads effectively during oscillating or cyclic motion. The arm is suitable for applications requiring precise alignment, repeatable movement, and lightweight performance, such as in robotic systems, automotive suspensions, or mechanical linkages in automated machinery.

The fabrication of the mechanical linkage arm requires careful consideration of its technological properties to ensure high precision, structural integrity, and cost effective production. The component's geometry, which includes a forked end with a central bore and keyway, a tapered body, and a secondary mounting hole, demands accurate machining to achieve tight tolerances and maintain functional alignment.

The use of aluminum alloy 6061–T6 offers several manufacturing advantages, including excellent machinability, good corrosion resistance, and a favorable strength to weight ratio, making it suitable for applications involving dynamic loading. From a manufacturing standpoint, the part is well suited for CNC milling processes, particularly with 3–axis machines. Operations such as face milling, slotting, contour profiling, and boring can be employed to produce the necessary features. Special attention must be given to workpiece fixturing, especially during the machining of the fork and internal slot, to maintain dimensional stability and prevent deflection.

Tolerance–critical features, such as the Ø25 mm and Ø11.8 mm holes, may require reaming or precision boring to achieve the required surface finish and fit. Overall, the product exhibits a balanced combination of structural design and manufacturability, enabling efficient production while meeting the mechanical performance requirements of linkage applications.

MANUFACTURING PROCESS

The fabrication process of the mechanical linkage arm is structured to ensure both geometric precision and surface quality through a sequential and methodical approach. Initially, face machining is carried out on the primary surfaces using milling operations, which provide flatness and establish reference planes for subsequent steps. The remaining face is then also machined by milling to achieve the final part thickness and ensure dimensional consistency.

Hole machining is performed at multiple stages, depending on the functional requirements of each hole. For the precision bore intended for shaft mounting, a combination of boring and reaming is employed to achieve tight tolerances and a smooth surface finish. Additional holes are machined through a sequence of drilling, boring, and reaming, where appropriate, to maintain alignment and dimensional accuracy. For less critical holes, drilling alone is sufficient.

Groove machining, such as the slot between the forked arms, is executed by milling, ensuring accurate width and depth while maintaining edge definition. Lastly, the keyway feature, which requires high precision and fine finish, is produced using the wire-cut electrical discharge machining (EDM) method, offering superior accuracy for internal slots and avoiding tool-induced stress or deformation. This fabrication strategy ensures that the component meets all functional and geometric requirements efficiently, making it suitable for high-performance mechanical applications.

Roughing Operation: End Milling

The roughing phase of the surface pocket operation is carried out using a D10.4 mm flat end mill, as shown in the Figure 3. This process is intended to rapidly remove the bulk material from the top surface of the workpiece, forming the general geometry before finishing passes. The machining parameters used in the roughing operation of the linkage arm are carefully selected to ensure efficient material removal while maintaining stability and tool life.

A flat end mill with a diameter of 10.4 mm is employed for the operation, suitable for generating flat surfaces and rough pocket features. The spindle speed is set to 4200 revolutions per minute (rpm), combined with a feed rate of 4000 mm/min, indicating a high-speed cutting strategy optimized for materials like aluminum, which are known for their excellent machinability.

The axial depth of cut per pass is 0.3 mm, a relatively shallow value chosen to minimize cutting forces and reduce the risk of tool deflection or vibration, especially when machining tapered or unsupported regions of the part. This setup allows for stable roughing without compromising dimensional integrity.

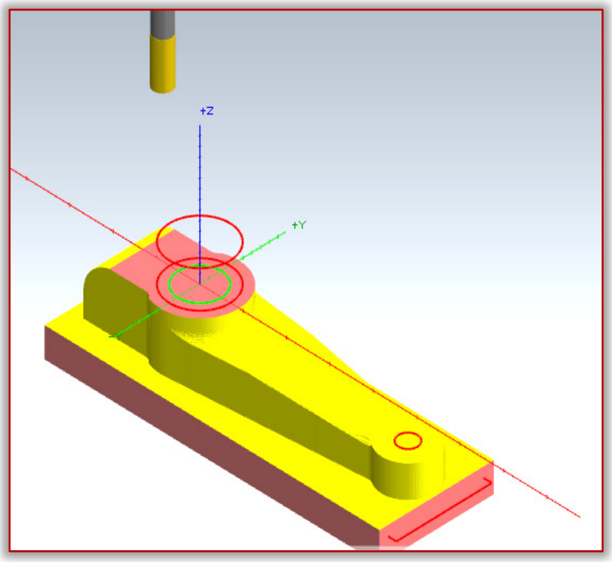

Figure 3. Roughing face mill

The rough milling of the Ø11 mm hole

In the rough machining stage for creating the Ø11 mm hole, a D6 mm flat end mill with a corner radius of 0.5 mm (D6r0.5) is utilized. This tool size is appropriate for progressively enlarging the hole through contour milling, especially when a traditional drill is not applied initially or when a non-circular profile needs to be roughed. The spindle speed is set to 6000 rpm, which, when paired with a feed rate of 2000 mm/min, results in moderate-to-high cutting speeds well suited for aluminum or similarly soft materials. This combination ensures efficient chip removal and stable engagement between the cutter and the material. The axial depth of cut per pass is 0.3 mm, a conservative choice that helps to minimize radial deflection and maintain tool life during repetitive passes, especially when dealing with internal features where rigidity and chip evacuation may be limited.

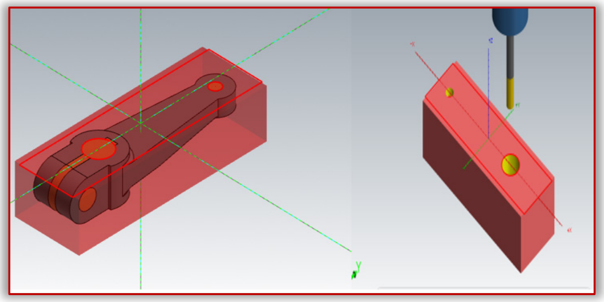

Figure 4. The rough machining stage for creating the Ø11 mm hole

Finishing Operation: End Milling

The finishing of the planar surface is performed using a D6 mm flat end mill with a corner radius of 0.5 mm (D6r0.5), selected to achieve a fine surface finish while minimizing sharp edge wear and tool-induced stress. The spindle speed is set at 6000 rpm, and the feed rate is maintained at 2000 mm/min, which are optimal values for high-speed finishing in aluminum and similar non-ferrous materials. With an axial depth of cut of 0.3 mm, the operation is designed to remove a thin layer of material left from the roughing process, ensuring a high-quality surface finish with improved dimensional accuracy.

The small depth of cut allows for reduced cutting forces, better control of tool deflection, and lower surface roughness (Ra), which are critical for functional contact surfaces or aesthetic requirements.

The use of a tool with a slight corner radius also helps eliminate micro burr formation and improves the fatigue resistance of the machined surface. Overall, this finishing strategy enables the production of a smooth, dimensionally precise flat surface suitable for assembly or as a reference datum for subsequent operations.

Cutting a keyway using a wire EDM machine

The Figure 5 illustrates the keyway cutting process being carried out on a wire electrical discharge machining (EDM) machine. In this operation, a thin, continuously moving wire electrode typically made of brass or molybdenum—generates a series of electrical discharges to erode the material along the programmed path, thereby producing a highly accurate internal slot (keyway) in the mechanical linkage arm.

This method is particularly suitable for hard to machine internal features, such as precision keyways, which require tight tolerances, sharp corners, and high-quality surface finishes.

Figure 5.The keyway cutting process

The keyway cutting operation on the mechanical linkage arm is executed using a wire electrical discharge machining (EDM) process, employing a 0.18 mm molybdenum wire as the cutting electrode.

Molybdenum is chosen for its high tensile strength, excellent wear resistance, and ability to maintain precision over long machining cycles. The process operates at a cutting speed of 200 mm/min, which is suitable for producing fine, accurate internal features in conductive materials such as aluminum alloys.

RESULTS AND DISCUSSION

The Figure 6 shows the completed mechanical linkage arm, which has undergone a full sequence of precision machining operations, including milling, drilling, boring, and wire EDM.

The component demonstrates high dimensional accuracy, especially evident in the alignment and uniformity of the forked arms and the circular bores. Dimensional inspection of the finished mechanical linkage arm confirms that all critical geometric and tolerance requirements have been met in accordance with the technical drawing.

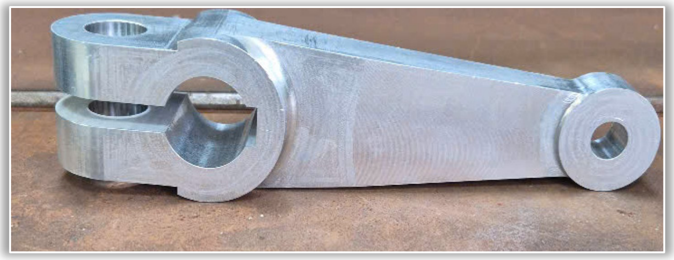

Figure 6. The completed mechanical linkage arm

The diameters of the machined holes are within the allowable tolerances, ensuring proper fit with mating components. Thickness measurements at the 15 mm, 20 mm, and 16 mm surfaces match the nominal dimensions specified in the design, confirming consistent material removal and accurate depth control during machining.

The parallelism between the two primary fork holes was measured at 0.04 mm, which falls within the permissible range defined by the technical specifications for the claw-shaped geometry.

Similarly, the non-perpendicularity between the hole centerline and the reference end faces was measured at 0.06 mm, also complying with the design's functional requirements. Furthermore, the parallelism of the end faces relative to the central bore axis was verified to be within acceptable limits, ensuring uniform bearing and load distribution during assembly.

Finally, the keyway dimensions precisely conform to the drawing specifications, indicating successful execution of the wire EDM process. These inspection results collectively confirm that the finished component satisfies all critical design and functional criteria, validating the effectiveness of both the machining process and quality control measures applied.

While this study successfully demonstrated the design and fabrication of a precision mechanical linkage arm, several limitations should be acknowledged. First, the research was limited to the production of a single prototype, and therefore, scalability and repeatability in mass production were not evaluated.

Second, although dimensional accuracy and geometric tolerances were verified through physical inspection, no mechanical testing (e.g., tensile, fatigue, or load-bearing analysis) was performed to experimentally validate the structural performance under actual service conditions.

Third, the study focused exclusively on machining processes using CNC milling and wire EDM without incorporating post-processing techniques such as surface finishing, anodizing, or heat treatment, which may affect long-term durability.

Additionally, thermal effects, tool wear, and machining-induced residual stresses were not monitored, which could influence the dimensional stability and fatigue life of the part in extended use. Lastly, the dynamic behavior of the linkage arm in an operational assembly was not explored, leaving questions about its real-world motion characteristics and integration performance unaddressed.

CONCLUSION

This study successfully demonstrated the design and fabrication of a precision-machined mechanical linkage arm using CNC milling and wire EDM technologies. The component, made from 6061-T6 aluminum alloy, was developed with a focus on structural integrity, dimensional accuracy, and manufacturability. Through a carefully planned sequence of machining operations including face milling, drilling, reaming, and keyway cutting the final product achieved all critical geometric specifications, including hole diameters, parallelism, and surface quality. The use of wire EDM for the keyway enabled the production of complex internal features with high precision and minimal mechanical stress. Dimensional inspection of the completed part confirmed that the design requirements and tolerances were fully met, validating the effectiveness of the selected machining strategy and process parameters. This work highlights the potential of combining digital design, CNC based fabrication, and high precision inspection as a robust workflow for producing mechanical components for structural and motion applications.

Although the fabrication process yielded a successful prototype, several areas remain for future investigation. First, structural performance analysis, such as Finite Element Analysis (FEA) under real loading conditions, could be conducted to validate the component's mechanical reliability and optimize material usage.

Second, implementing surface treatment processes such as anodizing could be explored to improve wear resistance and extend the service life of the component in harsh environments.

Third, further refinement of the machining strategy, including toolpath optimization and tool wear monitoring, may help enhance production efficiency for batch manufacturing. Lastly, integrating this linkage arm into a functional robotic or mechanical assembly and conducting system level testing would provide insights into its long-term performance, fatigue behavior, and assembly compatibility.

These directions would contribute to a more comprehensive understanding of the linkage arm's application potential and enable its deployment in a wider range of high precision mechanical systems.

References

[1] Patil, A. S., Sunnapwar, V. K., Bhole, K. S., Ray, M. P., & More, Y. S. (2022). Effective cooling methods for Ti6Al4V CNC milling: a review. Advances in Materials and Processing Technologies, 9(2), 457–506.

[2] [2]. Meher, J., et al. (2022). Recent research development of CNC based milling machining conditions: A comprehensive review. Materials Today: Proceedings, 62, 3983–3989.

[3] [3]. Soori, M., & Arezoo, B. (2023). Dimensional, geometrical, thermal and tool deflection errors compensation in 5–axis CNC milling operations. Australian Journal of Mechanical Engineering, 22(5), 935–949.

[4] [4]. Wang, W., et al. (2023). A state–of–the–art review on robotic milling of complex parts with high efficiency and precision. Robotics and Computer–Integrated Manufacturing, 79, 102436.

[5] [5]. Chan, T. C., Li, J. D., Farooq, U., et al. (2024). Improving machining accuracy of complex precision turning–milling machine tools. The International Journal of Advanced Manufacturing Technology, 131, 211–227

[6] [6]. Kučera, D., Linkeová, I., & Stejskal, M. (2023). The influence of CAD model continuity on accuracy and productivity of CNC machining. The

International Journal of Advanced Manufacturing Technology, 124, 1115–1128

[7] [7]. Petrakov, Y., Korenkov, V., & Myhovych, A. (2022). Technology for programming contour milling on a CNC machine. Eastern–European Journal of Enterprise Technologies, 2(1(116)), 55–61.

[8] [8]. Wang, Z., Wang, X., Liu, X., et al. (2021). Principle and application of the ball end mill tool radius compensation for NURBS curve swept surfaces based on 3–axis CNC milling machines. International Journal of Precision Engineering and Manufacturing, 22, 1517–1526.

[9] Zhao, J., & Chang, Z. (2022). A new approach of modelling bottom edge cutting in 4–axis rough milling of complex parts and its application on feed rate optimization. Micromachines, 13, 2071.

[10] [10]. Mohamed Said, S. H., & Abu Mansor, M. S. (2022). A study on post processor for 5–axis CNC milling via CAD/CAM system. In Intelligent Manufacturing and Mechatronics. Springer, Singapore.

[11] [11]. Yan, X. (2022). Research and application of CNC machining method based on CAD/CAM/Robot integration. Advances in Multimedia, 2022, 5397369

[12] Dharmawardhana, M., Ratnaweera, A., & Oancea, G. (2021). STEP–NC compliant intelligent CNC milling machine with an open architecture controller. Applied Sciences, 11, 6223.

[13] Nguyen Thi Anh, Nguyen Xuan Quynh, & Tran Thanh Tung. (2025). A Milling Technique for the Fabrication of Mechanical Parts with Thin–Walled Ribs. Engineering, Technology & Applied Science Research, 15(4), 24815–24819

[14] Sun, H., et al. (2025). A review of the deformation mechanism and control of low–rigidity thin–walled components in machining. Journal of Manufacturing Processes.

[15] Nguyen Thi Anh, & Tran Thanh Tung. (2025). Methodical approach to fixture design in the milling of thin–walled mechanical components. Results in Engineering, 27, 106518

[16] Wu, D., Zheng, Y., Liang, J., & Wang, H. (2025). Flexible fixture designs and accuracy improvements for the adaptive machining of near–net–shaped blades. Journal of Manufacturing Processes, 143, 188–204.

[17] Lin, M., Wang, C., Yue, T., Guo, G., Guan, W., & Shen, B. (2024). Deformation prediction in flank milling of thin–walled parts based on cutter–workpiece engagement. Journal of Manufacturing Processes, 115, 375–386

[18] Nguyen Thi Anh, & Tran Thanh Tung. (2025). Development and validation of finite element model of milling thin–walled part. Applications in Engineering Science, 25, 100285.

[19] Nguyen Thi Anh, & Tran Thanh Tung. (2026). Finite element and experimental investigation of up– and down–milling in thin–wall machining. Progress in Engineering Science, 3(1), 100209.

ISSN: 2067–3809