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Design and Development of a Universal Magnetic Portable Jig: A Modular Approach for Versatile Clamping Applications

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ABSTRACT

Clamping systems play a crucial role in manufacturing by ensuring precision, stability, and repeatability during machining and assembly operations. However, traditional systems often lack adaptability, portability, and ease of use, particularly for diverse workpiece geometries and dynamic applications. Addressing these limitations, this study aims to develop a Universal Magnetic Portable Jig that provides a versatile and user-friendly clamping solution tailored for educational, DIY, and small-scale industrial contexts. The research utilized advanced manufacturing techniques, including 3D printing, CNC machining, and MIG welding, to create a modular jig with a magnetic base and interchangeable attachments. Comprehensive testing and DFMA analysis were conducted to validate its performance, revealing significant findings. The Vise for Cylindrical Shapes achieved a DFA Index of 112.97, showcasing high efficiency and simplicity, while other attachments, like the Dial Test Indicator Holder, highlighted areas for optimization. Identified limitations, such as reliance on ferromagnetic surfaces and size constraints, provide pathways for further enhancement. This study demonstrates that the Universal Magnetic Portable Jig effectively bridges gaps in traditional clamping systems by offering enhanced adaptability and operational flexibility. The principal results confirm its ability to improve productivity and usability across various applications. Future research will explore scalability for larger workpieces and non-magnetic materials, automation features, and further optimization. The findings establish a strong foundation for innovative clamping solutions in modern manufacturing environments.

1. Introduction

Using jigs and fixtures has enhanced manufacturing precision and efficiency, especially in machining, drilling, and assembly operations. These essential tools facilitate the stability and

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accuracy of workpieces, ensuring repeatability and minimizing human error [1]. Historically, the integration of Computer-Aided Design (CAD) and Computer-Aided Fixture Design (CAFD) revolutionized the field, enabling the creation of customized and task-specific fixtures tailored to diverse industrial needs [2-4]. These advancements laid the foundation for achieving enhanced productivity and quality in manufacturing processes.

In recent years, the evolution of manufacturing techniques has further propelled innovations in jig and fixture design. Among these, additive manufacturing technologies such as Fused Deposition Modelling (FDM) have emerged as transformative tools, enabling rapid prototyping and fabrication of bespoke jigs [5-7]. The flexibility and cost-effectiveness of FDM, particularly when using materials like Polylactic Acid (PLA) and Acrylonitrile Butadiene Styrene (ABS), have made it a preferred choice in educational, Do-It-Yourself (DIY) and small-scale industrial contexts [8,9]. Research has consistently demonstrated that optimizing FDM parameters can yield mechanically robust and functionally comparable alternatives to traditional metal fixtures, broadening their applicability in various domains [10,11].

A pivotal innovation in modern jig systems is the incorporation of magnetism. Magnetic jigs offer significant advantages, including swift setup and repositioning, especially for workpieces with complex geometries such as cylindrical or angled shapes. Neodymium magnets, renowned for their strength and stability, have been extensively employed to enhance clamping reliability in industrial and precision measurement applications [12-15]. These advancements have addressed critical challenges in conventional clamping methods, particularly in scenarios requiring high accuracy and adaptability [16]. Ergonomic considerations have also gained prominence in the design of jigs and fixtures. Modern designs prioritize operator safety and ease of use, aligning with Design for Manufacturing and Assembly (DFMA) principles. By reducing part counts and streamlining assembly processes, DFMA enhances the usability of jigs and optimizes their manufacturing efficiency [17-19]. Such ergonomic and adaptive designs have been shown to reduce operator fatigue and improve workflow, underscoring their importance in high-volume and precision-focused production environments [20,21].

Despite these advancements, conventional jigs and fixtures often face limitations regarding adaptability and portability. These constraints pose significant challenges for educators, hobbyists, and small-scale manufacturers working with diverse materials and geometries [22-24]. The development of universal magnetic portable jigs offers a promising solution combining modularity, flexibility, and advanced manufacturing techniques. These systems integrate multiple attachments designed for specific clamping tasks, providing versatile solutions to accommodate cylindrical, rectangular, and angled workpieces [25,26].

This study explores the design, fabrication, and validation of a universal magnetic portable jig tailored to the needs of dynamic environments. Leveraging advanced technologies such as 3D printing, Computer Numerical Control (CNC) machining, and Metal Inert Gas (MIG) welding, the proposed jig features a modular architecture with specialized attachments, enabling users to perform a wide range of tasks efficiently [27]. Rigorous testing and DFMA analysis were employed to evaluate the jig’s assembly efficiency, usability, and performance, focusing on addressing existing market gaps for versatile, portable clamping solutions [28,29]. The findings contribute valuable insights into optimizing manufacturing tools for small-scale and educational applications, highlighting the potential of modular jig designs to enhance productivity and innovation [30].

Clamping tools, such as jigs and fixtures, are essential in manufacturing processes to ensure precision, repeatability, and stability during machining and assembly operations. Traditional clamping systems, although reliable, often fail to meet the dynamic requirements of small-scale manufacturers, educators, and DIY enthusiasts who work with varied workpiece geometries and materials. Recent advancements in design and manufacturing techniques have paved the way for modular and magnetic solutions, offering versatility and efficiency. Despite these innovations, gaps persist in delivering affordable, portable, and highly adaptable clamping systems for broader applications.

This study addresses these gaps by developing a Universal Magnetic Portable Jig that integrates modular design with advanced manufacturing techniques. The significance of this study lies in its potential to fill the market void for versatile, portable clamping solutions tailored to diverse user needs. By leveraging neodymium magnets for clamping force and modular attachments for adaptability, the jig offers a modern solution to longstanding challenges in the field. This research aims to design, fabricate, and validate a multifunctional jig system that enhances productivity and operational flexibility across educational, DIY, and industrial settings.

2. Methodology

The design of the universal magnetic portable jig incorporates several mechanisms to ensure its effectiveness and versatility. Material selection played a critical role in optimizing both performance and cost-effectiveness. The magnetic base uses neodymium magnets, renowned for their exceptional magnetic strength and stability. These magnets provide a robust clamping force, allowing secure adhesion to metallic surfaces even under high-torque or vibration conditions. The housing of the base, fabricated using ABS filament through additive manufacturing, offers lightweight and flexible characteristics, while structural components made of high-grade steel ensure durability and mechanical integrity.

This combination of materials balances structural strength, weight, and manufacturing efficiency, making the jig suitable for various applications. Meticulous design features further enhanced the clamping force and stability of the magnetic jig. The magnetic base was milled to achieve a flat surface, maximizing the workpiece contact area and ensuring stable adhesion. A modular locking mechanism was integrated into the base, enabling quick and secure swapping of attachments tailored to specific tasks, such as holding cylindrical, rectangular, or angled workpieces.

Additionally, fine adjustment screws and grooved clamping surfaces were incorporated to prevent slippage and accommodate diverse geometries, thereby improving operational accuracy. To distribute loads effectively and minimize stress concentrations, reinforced structural ribs and strategically positioned fasteners were incorporated into the base design. These features ensure that the jig can support heavier workpieces without compromising stability.

Furthermore, a ferromagnetic backing layer was included to enhance the magnetic interaction between the base and the attachments, ensuring secure and reliable operation across varying conditions. The result is a highly stable and adaptable jig capable of addressing the needs of DIY enthusiasts, educators, and small-scale manufacturers alike. This study followed a structured methodology to design, fabricate, and validate the universal magnetic portable jig. The methodology is segmented into five stages: design concept, exploded view, machining and fabrication process, final product assembly, and testing and validation.

2.1 Design Concept

Figures 1 and 2 depict the development stages of the universal magnetic portable jig, transitioning from initial conceptual sketches to detailed 3D models. This jig design comprises six primary components: a magnetic base and five specialized attachments, each tailored to address specific clamping requirements for diverse workpiece geometries, including cylindrical, rectangular, and angled shapes. The magnetic base forms the system's foundation, serving a dual role as the structural support for the attachments and the primary clamping mechanism. Its ferromagnetic bottom surface ensures secure adhesion to metallic surfaces, providing stability during operation. The upper section of the base incorporates a modular interface, allowing for quick and secure attachment of various tools. This modularity enhances the system's versatility, making it suitable for dynamic applications across DIY, educational, and small-scale manufacturing contexts.

Figure 1 illustrates the initial design sketches, which visually outline the arrangement and intended functionality of the jig's components. Each attachment is strategically designed to hold cylindrical objects, enable angular positioning, or support precision measurement tools like dial test indicators. The sketching phase emphasized flexibility, simplicity, and ergonomic design to ensure user-friendly operation. Building on these sketches, Figure 2 showcases the transition to precise 3D modeling using SolidWorks and Fusion 360 software. This phase involved refining the jig's components' dimensions, tolerances, and interconnectivity to ensure functional integration and manufacturability.

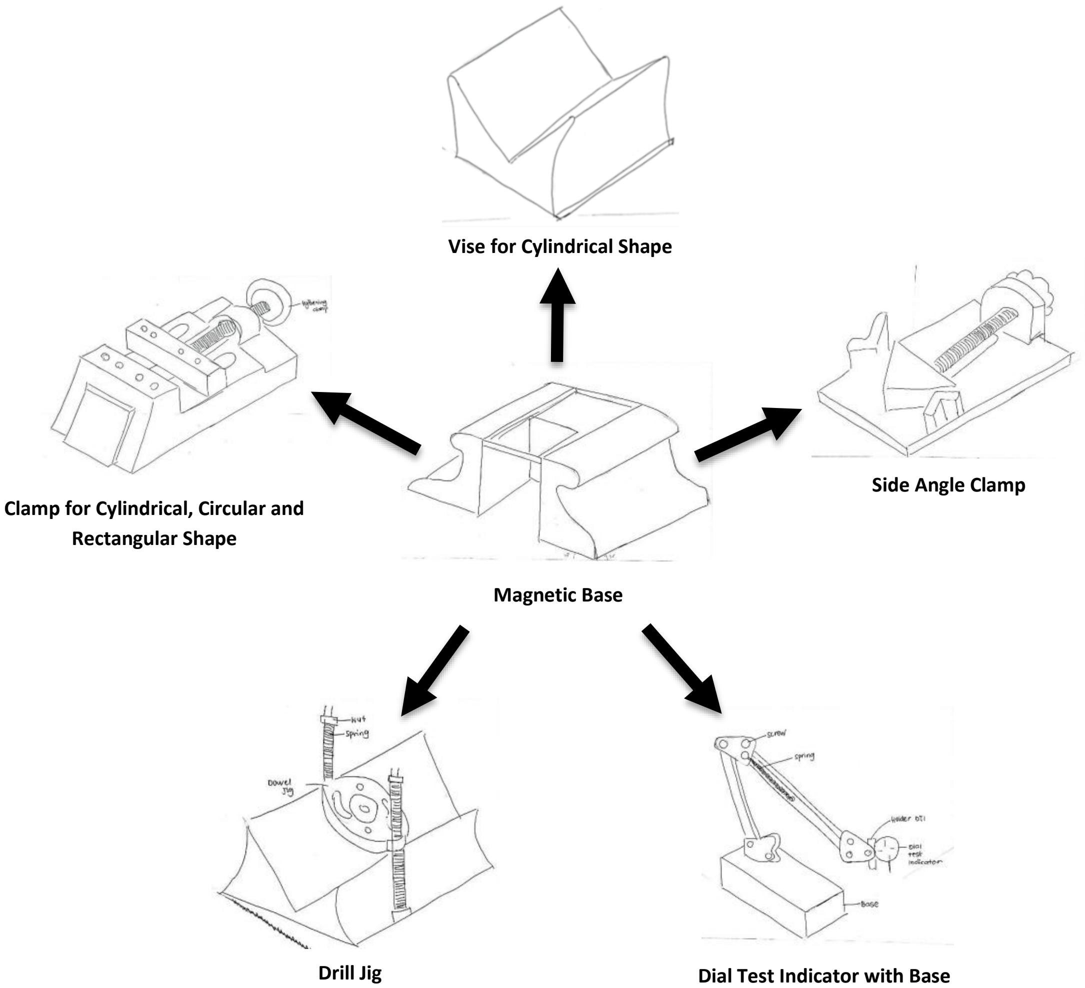


Fig. 1. Design concept of magnetic base and attachments

The 3D model provides a comprehensive visualization of the jig, validating its structural integrity and compatibility with various workpieces and environments. This detailed representation also serves as a blueprint for fabrication, ensuring accuracy and consistency in the production process. The magnetic portable jig exemplifies innovative engineering by combining a robust magnetic base with interchangeable attachments. This design approach maximizes functionality while minimizing the complexity of traditional clamping systems, thereby addressing the growing demand for adaptable and efficient tools in diverse applications.

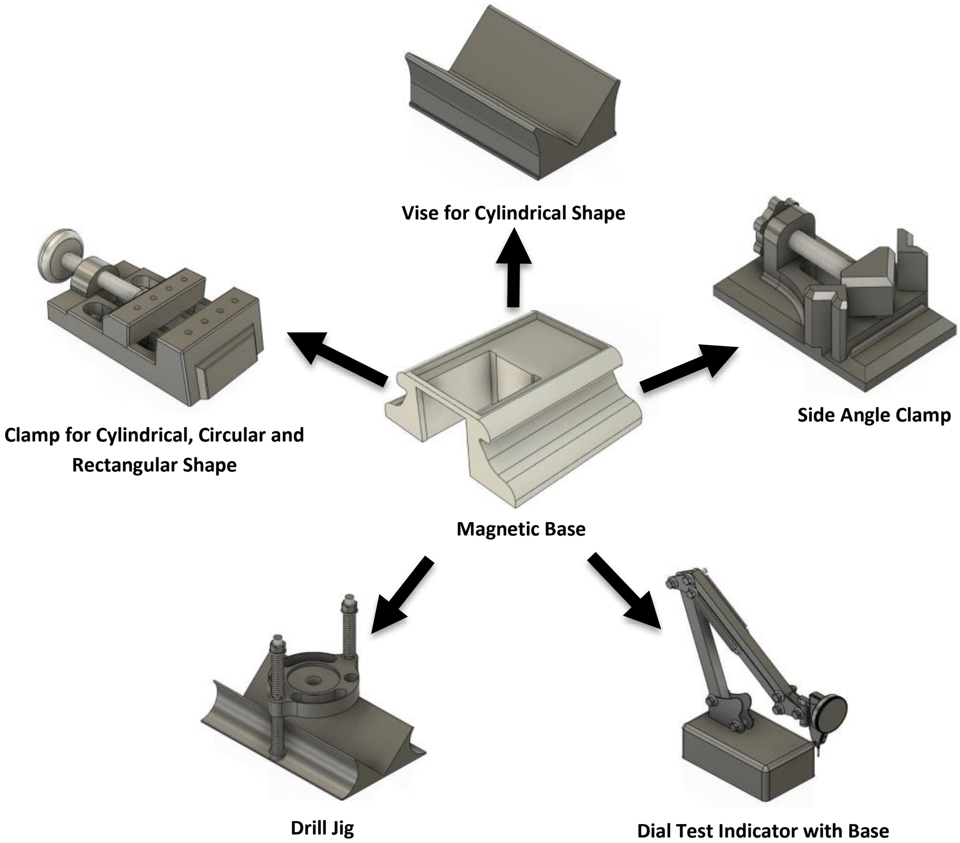
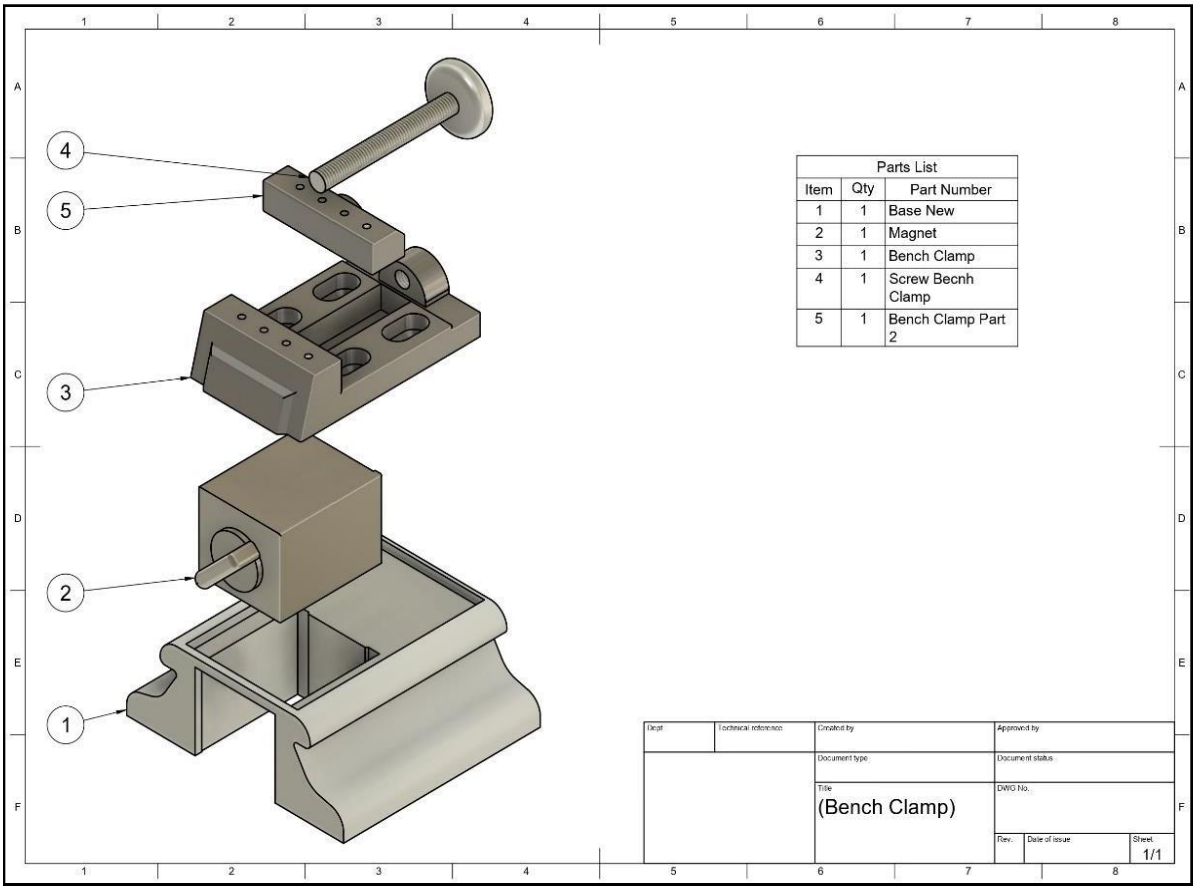


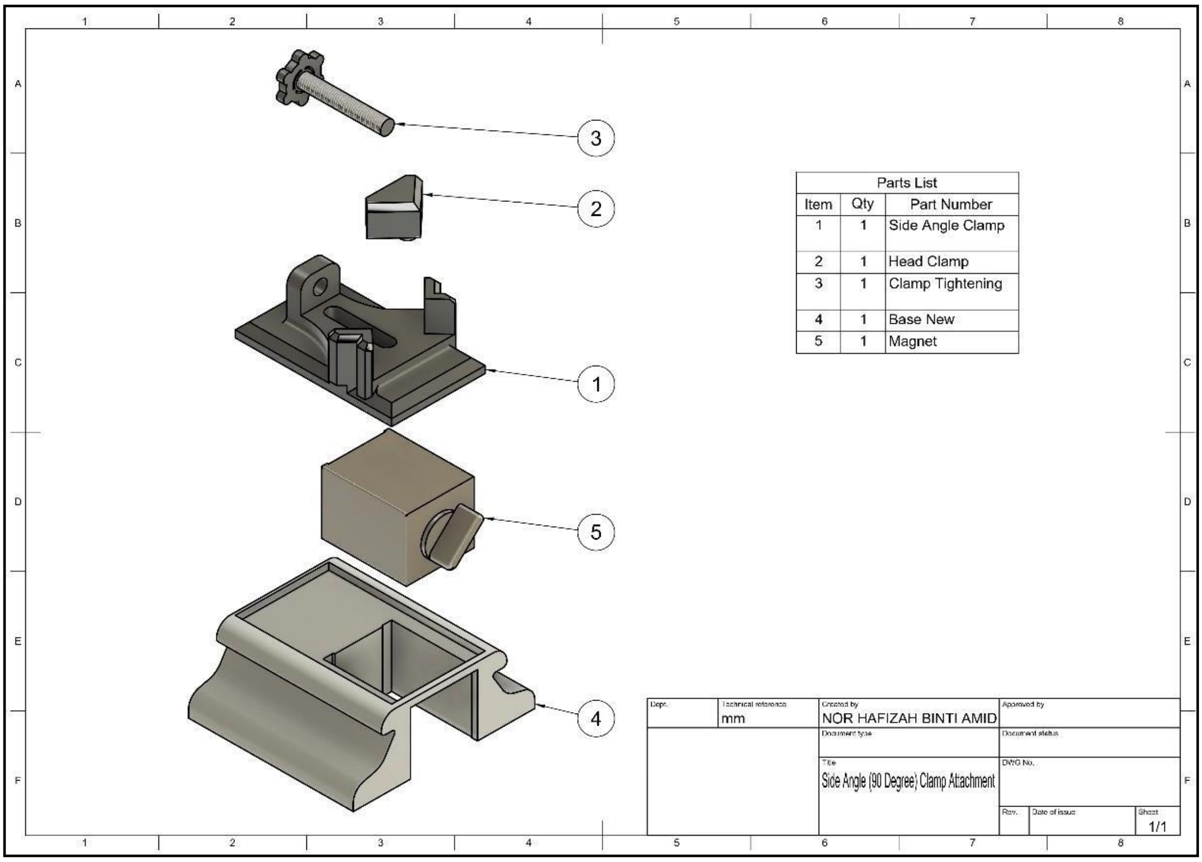
Fig. 2. Magnetic base and attachments (3D modeling)

2.2 Exploded View

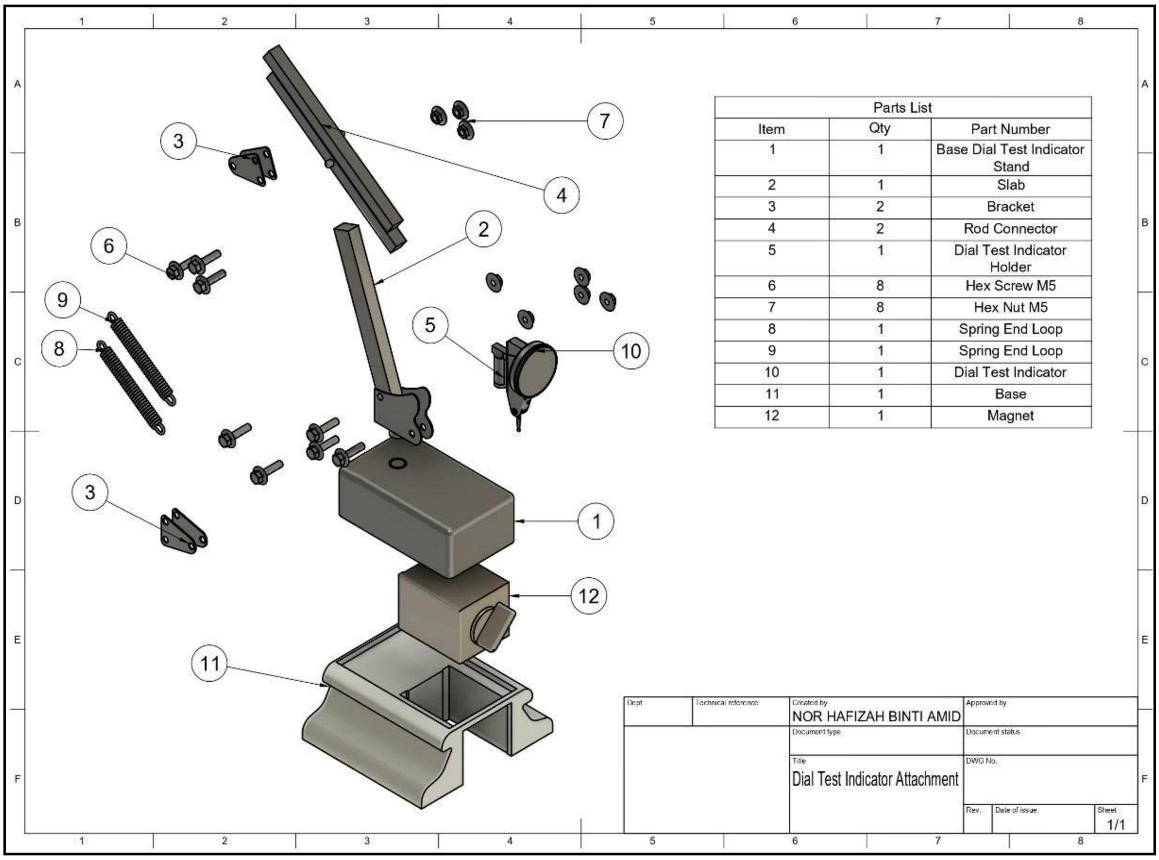
Figure 3 illustrates the comprehensive exploded view of the universal magnetic portable jig, emphasizing its modular construction and operational functionality. This visualization dissects the key structural components, including the magnetic base, as the central hub for connecting various modular attachments. The exploded view underscores the adaptive nature of the system, highlighting how individual components interconnect, thereby supporting diverse clamping applications across DIY, educational, and industrial settings. The primary attachment displayed is the Jaw Bench Clamp (a), which is engineered to secure workpieces on flat surfaces firmly. This clamp features an adjustable mechanism accommodating various workpiece sizes, ensuring stability during machining, welding, and measurement tasks. The magnetic base is a stable anchor, enhancing precision and operational efficiency. The Side Angle Clamp (b) is another integral attachment purpose-built for holding workpieces at fixed angles. This function is vital for precision-based tasks such as angular cutting or welding. The exploded view illustrates the seamless integration of this attachment with the magnetic base, ensuring robust and accurate positioning.



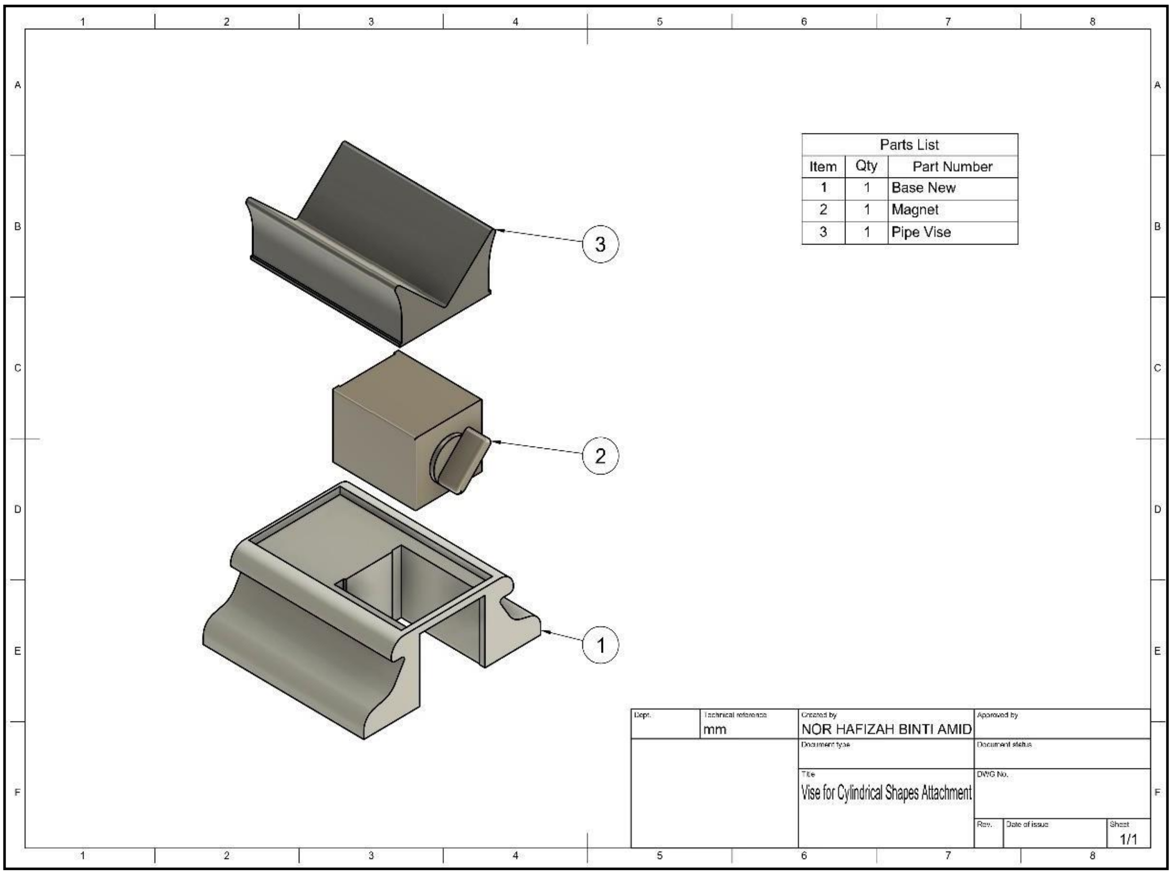
a) Jaw bench clamp attachment



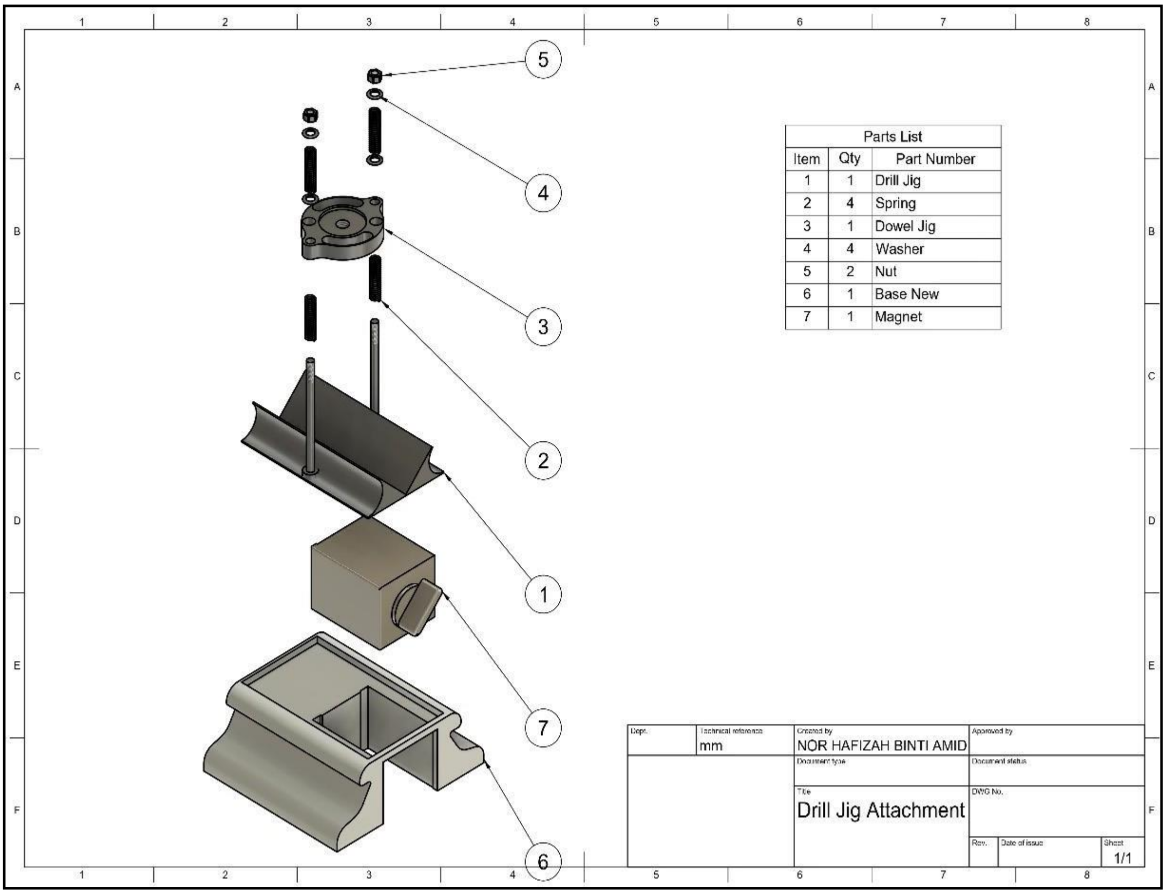
b) Side angle clamp attachment



c) Dial test indicator attachment



d) Vise for cylindrical shapes attachment



e) Drill jig attachment

Fig. 3. Exploded view of the project

The Dial Test Indicator Holder (c) also facilitates precise measurement operations by securely mounting a dial test indicator. Its inclusion in the exploded view highlights its precision-oriented design, ensuring stability for accurate measurements during inspection and alignment tasks. The Vise for Cylindrical Shapes (d) is tailored explicitly for cylindrical workpieces like pipes or rods. Its clamping mechanism adjusts to different diameters while maintaining a firm grip, as demonstrated in the exploded view. This attachment enhances the jig's versatility in handling non-standard shapes. Lastly, the Drill Jig (e) ensures precise and repeatable drilling by accurately guiding drill bits. The exploded view details its structural components, emphasizing its role in maintaining consistent drilling performance, especially in repetitive tasks. In summary, the exploded view in Figure 3 reveals a thoughtfully engineered system characterized by modularity, adaptability, and precision. Each attachment is meticulously designed for specific clamping and holding tasks, ensuring seamless interchangeability and operational efficiency in various technical applications.

2.3 Machining and Fabricating Process

The machining and fabrication of the universal magnetic portable jig involved a structured sequence of precision-driven processes to transform conceptual designs into a fully functional product. The process began with material selection, emphasizing components that balance strength, durability, and manufacturability. Metals were selected for the magnetic base and attachments due to their structural integrity, while ABS filament was employed for 3D-printed components. As shown in Figure 4, the initial fabrication step encompassed cutting raw materials to precise dimensions using

CNC machines and precision tools. This step ensured compatibility with design specifications, allowing seamless component integration. Subsequent milling operations shaped complex features like grooves and slots, enabling secure connections among modular parts. Surface grinding refined component flatness, ensuring optimal contact and enhancing magnetic adhesion for stable jig performance. MIG welding provides robust joints, particularly for metal components requiring high structural integrity. Post-welding, surface filing, and finishing eliminated sharp edges and improved handling comfort. Additive manufacturing was key in creating intricate components such as the jaw bench and side angle clamp.

Fig. 4. Milling process to flatten magnet surface

Fig. 5. Bambu lab 3D printer to printing 3D modelling

As shown in Figure 5, using a Bambu Lab 3D printer, layers of ABS filament were precisely extruded, forming detailed features that would be challenging to achieve using traditional methods. All components underwent protective surface treatments, including spraying or powder coating, to enhance durability. This process ensured resistance to wear, corrosion, and environmental degradation while enhancing the jig's aesthetic appeal. The machining and fabrication of the universal magnetic portable jig involved a structured sequence of precision-driven processes to transform conceptual designs into a fully functional product. The process began with material selection, emphasizing components that balance strength, durability, and manufacturability. Metals were selected for the magnetic base and attachments due to their structural integrity, while ABS filament was employed for 3D-printed components.

2.3.1 Fabrication of magnetic base, vise for cylindrical shapes, and drill jig

The magnetic base was manufactured using a combination of additive and subtractive processes. ABS filament, chosen for its strength and durability, was 3D-printed with precision using a Bambu Lab 3D printer. Post-production milling of the magnetic surface ensured a flat finish, enhancing both magnetic adhesion and the overall stability of components. This hybrid approach allowed for precise tolerances and dependable magnetic performance. The Vise for Cylindrical Shapes and Drill Jig were constructed using metal to meet the functional demands of high mechanical strength. CNC cutting was employed to define the initial dimensions of the components, followed by MIG welding to establish strong and durable joints. Subsequent surface treatments, including filing and protective coating, further improved the components' durability and appearance, ensuring reliable, long-term performance across various applications.

2.3.2 Side angles clamp and jaw bench clamp

The side angles and jaw bench clamp were fabricated using additive manufacturing techniques, specifically 3D printing with the Bambu Lab 3D printer. The choice of 3D printing allowed for creating complex geometries that would be difficult to achieve through traditional machining methods. ABS filament was used as the material, providing the necessary strength and flexibility for these components. The layer-by-layer extrusion process ensured each component was built precisely according to the detailed 3D models designed using 3D modeling software. Once printed, any remaining support material was carefully removed, and the surfaces were cleaned to prepare the components for finishing.

2.3.3 Surface finishing and coating

The surface finishing and coating processes were meticulously carried out to improve all components' functionality, durability, and aesthetics. The process began with grinding and filing for the metal parts to eliminate sharp edges and imperfections that could affect safety or performance. Protective coatings shielded the components from corrosion, wear, and environmental factors. These coatings enhanced the durability of the metal parts and provided a smooth, uniform surface finish for improved appearance.

For 3D-printed components, the finishing process focused on refining their surfaces. Support structures were carefully removed, and visible layer lines were smoothed through sanding and polishing, resulting in a cleaner, more polished appearance. Additionally, post-processing treatments, such as surface primers or sealants, were used to enhance the printed parts' structural integrity and visual quality. This comprehensive approach to surface finishing and coating ensured that all components were both highly functional and visually appealing, contributing to the overall quality and reliability of the final product.

2.4 Final Product Assembly

The final assembly of the universal magnetic portable jig brought together pre-fabricated components into a fully functional and cohesive system, as depicted in Figure 6. The assembly process emphasized precise alignment to ensure modular attachments were securely connected to the magnetic base. Each attachment underwent thorough testing to verify its fit, stability, and functionality before permanent integration.

Fastening mechanisms were inspected for tightness and durability while moving parts were fine-tuned for smooth operation. Rigorous quality assurance checks were performed, including dimensional accuracy, joint strength, and magnetic adhesion assessments. These measures guaranteed the jig met all design requirements and could endure operational demands. The completed jig demonstrated exceptional modularity, versatility, and user-friendliness. The efficient assembly process highlighted the jig’s suitability for various applications, from educational settings to industrial workshops, solidifying its role as a multifunctional and reliable clamping solution.

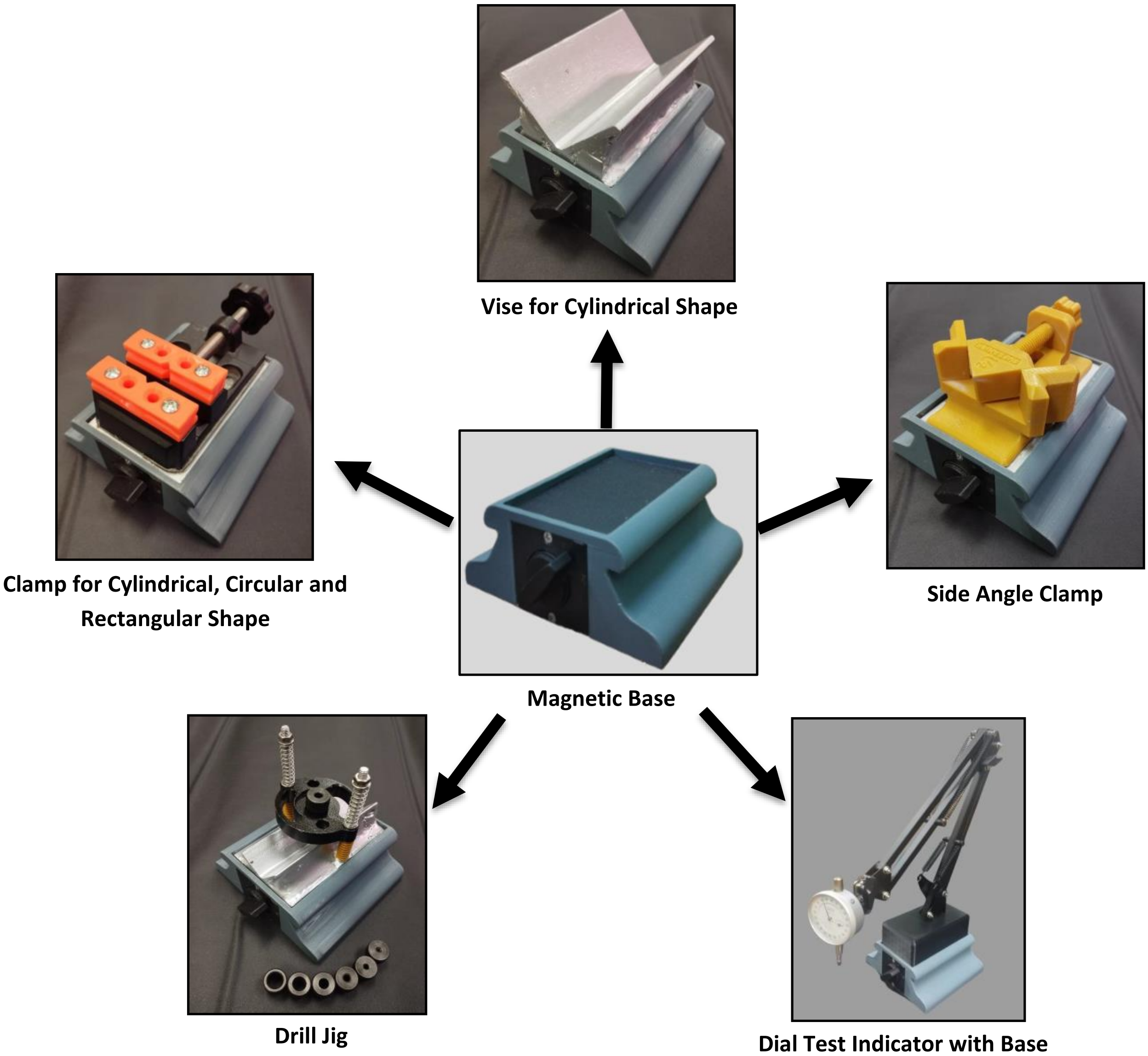


Fig. 6. Final product assembly

2.5 Testing and Validation Process

The testing and validation of the universal magnetic portable jig involved a comprehensive evaluation of its mechanical performance, assembly accuracy, and user functionality. DFMA principles guided this process, emphasizing ease of assembly, modular flexibility, and system durability. Usability tests were conducted to assess the jig's performance and attachment-specific limitations. Load-bearing assessments, component fit analyses, and operational tests verified the system’s robustness under varying conditions. The modular attachments were repeatedly interchanged to ensure reliability and resistance to wear.

A DFMA analysis evaluated the jig’s assembly process using manual and automated calculations of the Design for Assembly (DFA) Index by the software using Eq. (1). The analysis examined assembly complexity, time requirements, and process efficiency by inputting step-by-step relevant data from Table 1 into DFMA software. The results confirmed the jig's compliance with its intended technical and operational specifications, validating its industrial and educational applicability.

$$DFA\ Index = \frac{(\text{Theoretical minimum number of parts}) \times (3\ seconds)}{Estimated\ total\ assembly\ time} \quad (1)$$

Table 1
Step to key in data in DFMA Software

Step	Procedure
1	Launch your DFMA software application
2	Go to the "File" menu and select "Import" or "Open." Navigate to your design file and choose the appropriate file format (e.g., STEP, IGES)
3	Enter details about each assembly process step, including the order and methods used.
4	Click on or select individual components from the design.
5	Review and input data related to handling each component (e.g., size, weight).
6	Go to the "Cost Estimation" or "Cost Analysis" section of the software.
7	Navigate to the "Time Analysis" or "Assembly Time" section.
8	Enter or adjust time estimates for each assembly step.
9	Click "Analyze" or "Calculate Time" to evaluate the total assembly time.
10	Examine the results from design analysis, cost estimation, and time analysis.
11	Navigate to the "Reports" or "Metrics" section of the software.

2.6 Mechanistic Insights and Design Rationale

The universal magnetic portable jig was designed to be versatile, robust, and user-friendly, accommodating diverse workpiece geometries such as cylindrical, rectangular, and angled shapes. Its modular design, centered on a magnetic base with interchangeable attachments, enhances adaptability for DIY, educational, and small-scale industrial applications.

Following DFMA principles, the jig ensures easy assembly, replacement, and maintenance while being lightweight to minimize user fatigue. Neodymium magnets were selected for their exceptional magnetic strength, providing superior clamping force and stability even under significant mechanical stress. This allows the jig to securely hold complex or irregular shapes and remain attached to metal surfaces during operations like drilling and welding. Material selection further supports the jig's effectiveness. ABS was used for 3D-printed components due to its strength, impact resistance, and compatibility with FDM.

At the same time, milled steel was chosen for the magnetic base and attachments for its ferromagnetic properties and durability. Surface machining of the magnetic base increased adhesion and ensured seamless integration with attachments, maximizing clamping efficiency. Combining these materials and design choices, the jig balances strength, versatility, and manufacturability to meet diverse clamping needs.

2.7 Comparative Analysis with Traditional Clamping Systems

A comprehensive comparison of the magnetic portable jig with traditional clamping systems reveals several unique advantages and potential limitations. Traditional clamping systems, such as manual and mechanical clamps, rely on physical adjustments and fastening mechanisms, which can be time-consuming and less adaptable to complex geometries. In contrast, the magnetic jig offers rapid setup and repositioning capabilities due to its neodymium magnetic-based clamping mechanism, which provides a secure hold without requiring additional adjustments. The magnetic jig excels in handling irregular and diverse workpiece geometries, such as cylindrical and angled shapes, which are often challenging for traditional clamps.

The strong magnetic force ensures stability even under significant mechanical loads, making it suitable for operations like drilling and welding. While compelling for standard geometries, traditional clamps may struggle with versatility and require multiple configurations or accessories for similar functionality. While the initial cost of the magnetic jig may be higher due to the inclusion of neodymium magnets and modular attachments, its durability, reduced setup time, and multifunctionality translate to long-term cost savings.

Although generally less expensive upfront, traditional clamps may necessitate the purchase of multiple tools for varied applications, increasing overall costs. The magnetic jig's lightweight and modular design makes it user-friendly and portable, especially in dynamic environments like educational workshops or DIY projects. Its rapid clamping and repositioning capabilities reduce operator effort and setup time compared to the manual adjustments required by traditional clamps. Despite its advantages, the magnetic jig may have limitations in applications involving non-ferromagnetic materials, as the magnetic base relies on ferrous surfaces for adequate adhesion.

Additionally, the magnetic force may be less effective for large or heavy workpieces than mechanical clamps designed explicitly for such loads. Combining a magnetic system's versatility and ease of use with the adaptability of modular attachments, the magnetic portable jig addresses many of the shortcomings of traditional clamping systems, offering a modern solution tailored to diverse applications.

2.8 Application Context and Practical Use Cases

The universal magnetic portable jig has demonstrated its versatility and effectiveness across various real-world applications, including educational workshops, DIY projects, and small-scale industrial manufacturing. The jig is particularly valuable for teaching clamping techniques and precision tasks such as drilling or welding in academic settings. Its modular design allows students to adapt the jig for different workpieces quickly, enhancing learning outcomes by providing hands-on experience with versatile tools. Case studies from educational workshops highlight its use in holding complex geometries securely, improving workflow efficiency and safety.

In DIY projects, the jig's portability and ease of use make it an ideal solution for hobbyists working on tasks that require precision and stability. For example, the jig has been used in woodworking and metalworking projects to secure cylindrical and angled workpieces, reducing the risk of misalignment and improving the quality of the final product. Feedback from DIY users emphasizes the jig's ability to save time during setup and provide consistent clamping force, which is crucial for achieving accurate results.

The jig offers a cost-effective alternative to traditional clamping systems for low-volume production tasks in small-scale industrial manufacturing. Its ability to adapt quickly to different geometries and strong magnetic force makes it suitable for precision drilling, welding, and measurement tasks. A notable example includes its application in assembling components with irregular shapes, where traditional clamps would struggle to provide adequate stability. The jig's modular attachments enhance its utility by allowing manufacturers to switch tasks without additional tools. Overall, the universal magnetic portable jig has proven to be a versatile and reliable tool across various settings. Its adaptability, ease of use, and strong clamping capabilities address the diverse needs of users, making it a practical solution for a wide range of applications.

3. Results
3.1 Limitation Test

The Limitation Test for the Universal Magnetic Portable Jig was conducted to evaluate the performance constraints of each attachment. As shown in Table 2, every attachment has a specific limitation regarding the size and shape of the workpiece it can effectively clamp. Exceeding these limitations results in diminished functionality. For example, the attachment designed for cylindrical shapes has a maximum diameter limit of 80mm. If a workpiece exceeds this size, the Vise attachment will fail to secure it properly, potentially leading to instability or the workpiece falling. These limitations are essential to ensure safe and effective operation, and users must adhere to them to avoid malfunctions and ensure optimal clamping performance.

Table 2
Limitations on each attachment

Variety of Shapes/Used	Size of Material Supported/Movement
Circular Shapes	15mm
90-degree Angle Workpiece	Width Range: 30mm
Cylindrical Shapes	Diameter Range: 30~80mm
Rectangular Shapes	Width Range: 5~50mm
	Length Range: 5~60mm
Drill Jig + Cylindrical Shape	Diameter Range: 25~50mm
	Bush Size Range: 1~7mm
Dial Test Indicator Holder	Movement: 180-degree
	Height: -5~250mm

3.2 DFMA Analysis Result

The DFMA analysis evaluated the ease and efficiency of assembling the Universal Magnetic Portable Jig by calculating the DFA Index. This metric quantifies the complexity of the assembly process based on the number of parts, assembly time, and overall design efficiency. A higher DFA Index indicates that the product is easier and faster to assemble. Among the attachments, the Vise for Cylindrical Shapes achieved the highest DFA Index of 112.97, reflecting its simplicity, with only two parts involved and no need for elimination. In contrast, the Dial Test Indicator Holder had the lowest DFA Index of 3.01, comprising 23 components, with 19 parts eligible for elimination, making it more complex and time-consuming to assemble. The analysis shows that the Vise for cylindrical shapes is the most efficient in terms of assembly time and simplicity. At the same time, more complex attachments, such as the dial test indicator, are less efficient due to their higher part count and longer assembly process. The total count, which refers to the number of parts, including fasteners and connectors, generally correlates with assembly complexity. A higher total count often leads to more assembly steps, increasing the required time.

Therefore, products with fewer parts and streamlined processes, like the Vise for cylindrical shapes, demonstrate better assembly efficiency. This DFMA analysis provides valuable insights into improving product designs by simplifying parts and minimizing assembly time, ensuring that the Universal Magnetic Portable Jig is efficient and practical for its users. The DFA analysis conducted on various attachments of the universal magnetic portable jig revealed varying degrees of assembly efficiency. Among the components, the Vise for Cylindrical Shapes (Figure 7) demonstrated the highest DFA Index of 112.97, indicating superior efficiency with minimal assembly time of 5.86 seconds and only two essential parts. This attachment exemplifies an optimal design with no need for further assembly enhancements.

Conversely, the Dial Test Indicator Stand (Figure 10) exhibited the lowest DFA Index of 3.01, reflecting a significantly more complex and time-consuming assembly process. With 23 parts and an assembly time of 342 seconds, it became evident that there is substantial room for improvement by eliminating non-essential components, which account for over 90% of the total assembly time. The Side Angle Clamp (Figure 8) and the Jaw Bench Clamp (Figure 9) demonstrated relatively efficient assembly processes, with DFA Indices of 20.70 and 19.73, respectively. These attachments showed potential for improvement by replacing fasteners with snap-fit mechanisms, reducing their respective assembly times of 31.98 seconds and 33.55 seconds.

Entries including repeats	**Original**
Parts meet minimum part criteria	2
Parts are candidates for elimination	0
Analyzed subassemblies	0
Separate assembly operations	0
Total entries	2
Assembly labor time, s	
Parts meet minimum part criteria	5.86
Parts are candidates for elimination	0
Insertion of analyzed subassemblies	0
Separate assembly operations	0
Total assembly labor time	5.86
Design efficiency	
DFA Index	112.97

Fig. 7. DFA index of vise for cylindrical shapes

Entries including repeats	**Side Angle Clamp**
Parts meet minimum part criteria	2
Parts are candidates for elimination	1
Analyzed subassemblies	1
Separate assembly operations	0
Total entries	4
Assembly labor time, s	
Parts meet minimum part criteria	5.86
Parts are candidates for elimination	21.83
Insertion of analyzed subassemblies	4.29
Separate assembly operations	0
Total assembly labor time	31.98
Design efficiency	
DFA Index	20.70

Fig. 8. DFA index for side angle clamp

Entries including repeats	**Untitled**
Parts meet minimum part criteria	2
Parts are candidates for elimination	2
Analyzed subassemblies	1
Separate assembly operations	0
Total entries	5
Assembly labor time, s	
Parts meet minimum part criteria	5.86
Parts are candidates for elimination	24.76
Insertion of analyzed subassemblies	2.93
Separate assembly operations	0
Total assembly labor time	33.55
Design efficiency	
DFA Index	19.73

Fig. 9. DFA index of jaw bench clamp

Entries including repeats	**Dial Test Indicator**
Parts meet minimum part criteria	3
Parts are candidates for elimination	19
Analyzed subassemblies	1
Separate assembly operations	0
Total entries	23
Assembly labor time, s	
Parts meet minimum part criteria	15.75
Parts are candidates for elimination	321
Insertion of analyzed subassemblies	5.74
Separate assembly operations	0
Total assembly labor time	342
Design efficiency	
DFA Index	3.01

Fig. 10. DFA index of dial test indicator stand

Entries including repeats	**Drill Jig**
Parts meet minimum part criteria	5
Parts are candidates for elimination	9
Analyzed subassemblies	1
Separate assembly operations	0
Total entries	15
Assembly labor time, s	
Parts meet minimum part criteria	38.42
Parts are candidates for elimination	67.01
Insertion of analyzed subassemblies	2.93
Separate assembly operations	0
Total assembly labor time	108
Design efficiency	
DFA Index	16.33

Fig. 11. DFA index of drill jig

Lastly, the Drill Jig (Figure 11) performed moderately well with a DFA Index of 16.33 and an assembly time of 108 seconds. This attachment has the potential for further optimization by reducing its part count, which would enhance overall assembly efficiency by up to 60%. In conclusion, the Vise for Cylindrical Shapes is the most efficient component, while the Dial Test Indicator Stand requires significant improvements. The other attachments, including the Side Angle Clamp, Jaw Bench Clamp, and Drill Jig, demonstrate moderate efficiency with clear opportunities for enhancement through part reduction and design improvements. These insights are crucial for refining the design and ensuring the jig meets its intended purpose of providing a versatile and user-friendly clamping solution.

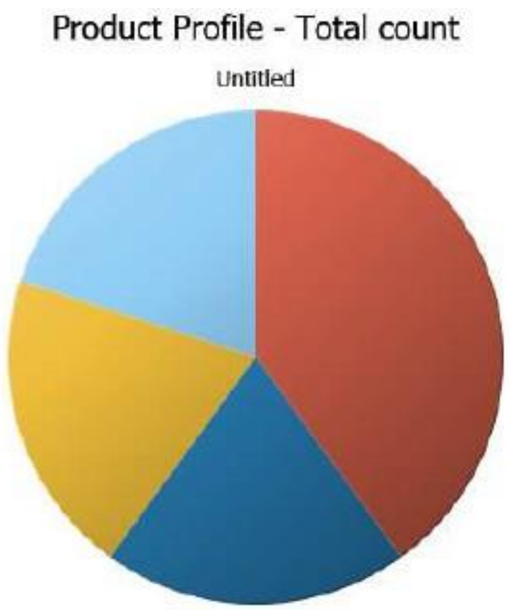
3.2.1 DFA analysis on jaw bench clamp attachment

The Jaw Bench Clamp Attachment has a DFA Index of 19.73, which is considered efficient, indicating that the assembly time is acceptable. The total time required for assembly, as shown in Figure 9, is 33.55 seconds. According to Figure 13, the attachment consists of two Necessary Items, which are not subject to elimination as they are critical for the product's functionality. However, two components, specifically the fasteners and connectors, are listed as candidates for elimination. These parts could be replaced with a more efficient design, such as a snap-fit mechanism instead of traditional fasteners.

As demonstrated in Figure 14, the Necessary Items account for 17.47% of the total assembly time or 5.86 seconds. At the same time, the fasteners occupy the majority of the assembly time at 21.83 seconds, representing 65.07% of the total assembly time. Replacing the fasteners with a snap-fit design could significantly reduce assembly time, further enhancing the overall efficiency of the product.

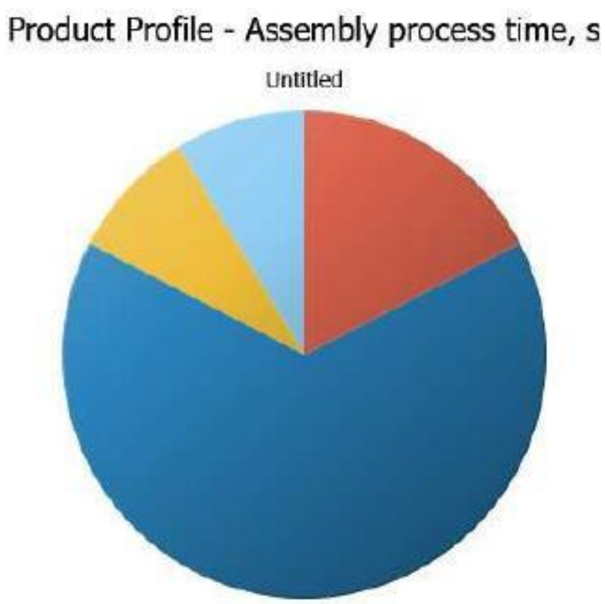
Name	Part number	Repeat count	Total count	Minimum items	Minimum part criteria	Process time per entry, s	Process time per product, s
Jaw Bench Clamp			5	2			33.55
Magnetic Base	1	1	1	1	Base part	2.93	2.93
Jaw Bench Clamp	2	1	1			2.93	2.93
Base Clamp	3	1	1	1	Different material	2.93	2.93
Clamp	4	1	1	0	Connector	2.93	2.93
Screw Tightening Clamp	5	1	1	0	Fastener	21.83	21.83

Fig. 12. Product worksheet of jaw bench clamp attachment



	1 Untitled	
Necessary items	2	40.00%
Fasteners	1.00	20.00%
Connectors	1.00	20.00%
Other candidates for elimination	0.00	0.00%
Analyzed subassemblies	1.00	20.00%
Separate operations	0.00	0.00%
Total	5.00	100%
Difference	0.00	

Fig. 13. Total count of jaw bench clamp attachment



	1 Untitled	
Necessary items	5.86	17.47%
Fasteners	21.83	65.07%
Connectors	2.93	8.73%
Other candidates for elimination	0.00	0.00%
Analyzed subassemblies	2.93	8.73%
Separate operations	0.00	0.00%
Total	33.55	100%
Difference	0.00	

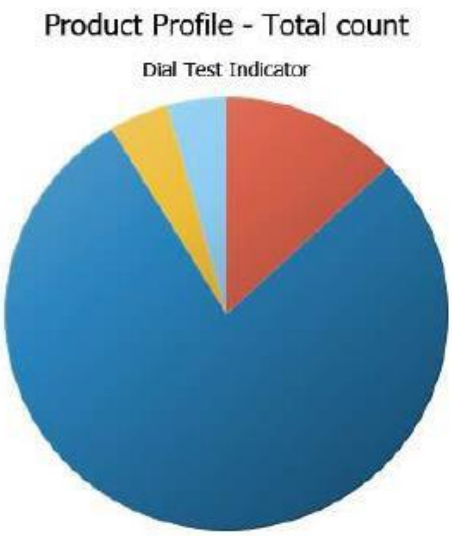
Fig. 14. Assembly process time (s) of jaw bench clamp attachment

3.2.2 DFA analysis on dial test indicator attachment

As illustrated in Figure 10, the Dial Test Indicator Attachment has a DFA Index of 3.01, which is considered relatively low for efficient assembly. This low value can be attributed to the high number of components involved in the attachment, totaling 23 parts. The overall assembly time for this attachment is 342 seconds, as shown in Figure 17. Upon reviewing the necessary components, three parts are essential for the attachment to function correctly: the magnetic base, height gauge, and dial test indicator, as indicated in Figure 15. These parts are labeled with a value of 1, signifying that they are crucial and cannot be eliminated. However, 19 parts have been identified as candidates for elimination. These non-essential components contribute significantly to the assembly time, consuming 320.83 seconds, which accounts for more than 90% of the total assembly time. Reducing or eliminating these parts would greatly improve assembly efficiency. Optimizing the design to reduce part count and complexity could improve production time, making the assembly process more efficient and cost-effective.

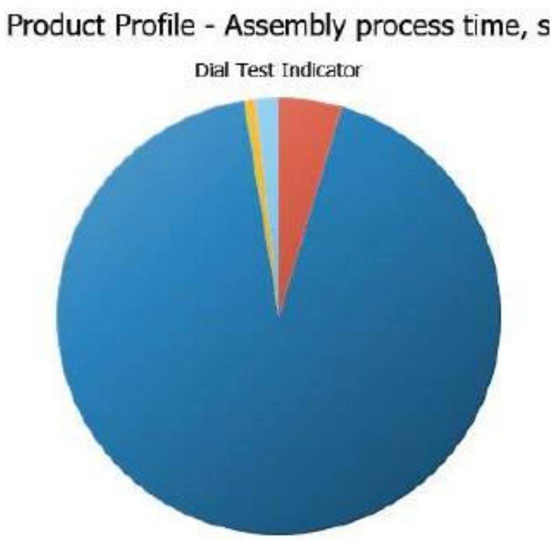
Name	Part number	Repeat count	Total count	Minimum items	Minimum part criteria	Process time per entry, s	Process time per product, s
Dial Test Indicator			23	3			342.32
Magnetic Base		1	1	1	Base part	2.93	2.93
Dial Test Indicator + Height Gauge		1	1			5.74	5.74
Base Gauge	2	1	1	0	Connector	2.93	2.93
Height Gauge	3	1	1	1	Assembly	5.60	5.60
Spring	4	4	4	0	Fastener	28.88	28.88
Screw	5	6	6	0	Fastener	120.62	120.62
Nut	6	6	6	0	Fastener	126.26	126.26
Dial Test Indicator	7	1	1	1	Different material	7.22	7.22
Clip		2	2	0	Fastener	42.14	42.14

Fig. 15. Product worksheet of dial test indicator attachment



	1 Dial Test Indicator	
Necessary items	3	13.04%
Fasteners	18.00	78.26%
Connectors	1.00	4.35%
Other candidates for elimination	0.00	0.00%
Analyzed subassemblies	1.00	4.35%
Separate operations	0.00	0.00%
Total	23.00	100%
Difference	0.00	

Fig. 16. Total count of dial test indicator attachment



	1 Dial Test Indicator	
Necessary items	15.75	4.60%
Fasteners	317.90	92.87%
Connectors	2.93	0.86%
Other candidates for elimination	0.00	0.00%
Analyzed subassemblies	5.74	1.68%
Separate operations	0.00	0.00%
Total	342.32	100%
Difference	0.00	

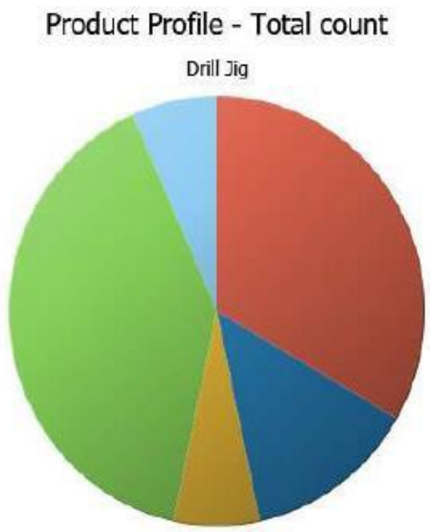
Fig. 17. Assembly process time (s) of dial test indicator attachment

3.2.3 DFA analysis on drill jig attachment

As shown in Figure 11, the Drill Jig Attachment has a DFA Index of 16.33, indicating a relatively efficient assembly process. The total assembly time for this attachment is 108 seconds, as seen in Figure 20. Out of the 15 components, only five are Necessary Items for its operation. As indicated in Figure 18, these critical components include the magnetic base, dowel jig, upper spring, and bush. The upper spring is vital in pushing the dowel jig onto the workpiece, ensuring the attachment remains in close contact throughout the operation.

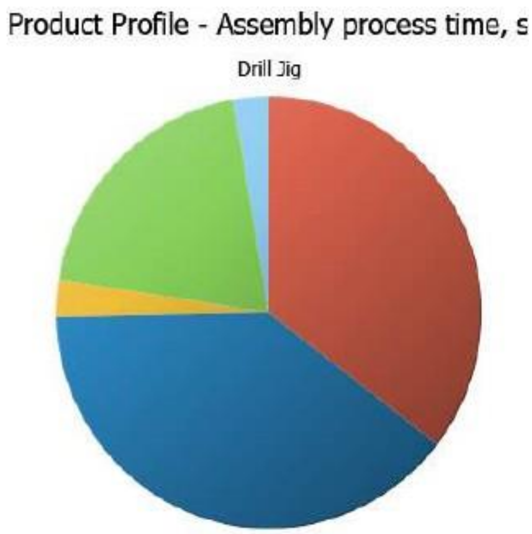
Name	Part number	Repeat count	Total count	Minimum items	Minimum part criteria	Process time per entry, s	Process time per product, s
Drill Jig			15	5			108.36
Magnetic Base		1	1	1	Base part	2.93	2.93
Drill Jig	1	1	1			2.93	2.93
V-Block	2	1	1	0	Connector	2.93	2.93
Lower Spring	3	2	2	0	(none)	6.44	6.44
Dowel Jig	4	1	1	1	Movement	6.93	6.93
Flat Washer	5	4	4	0	(none)	15.12	15.12
Upper Spring	6	2	2	2	Movement	6.44	6.44
Nut	7	2	2	0	Fastener	42.52	42.52
Bush	8	1	1	1	Different material	22.12	22.12

Fig. 18. Product worksheet of drill jig attachment



	1 Drill Jig	
Necessary items	5	33.33%
Fasteners	2.00	13.33%
Connectors	1.00	6.67%
Other candidates for elimination	6.00	40.00%
Analyzed subassemblies	1.00	6.67%
Separate operations	0.00	0.00%
Total	15.00	100%
Difference	0.00	

Fig. 19. Total count of drill jig attachment



	1 Drill Jig	
Necessary items	38.42	35.46%
Fasteners	42.52	39.24%
Connectors	2.93	2.70%
Other candidates for elimination	21.56	19.90%
Analyzed subassemblies	2.93	2.70%
Separate operations	0.00	0.00%
Total	108.36	100%
Difference	0.00	

Fig. 20. Assembly process time of drill jig attachment

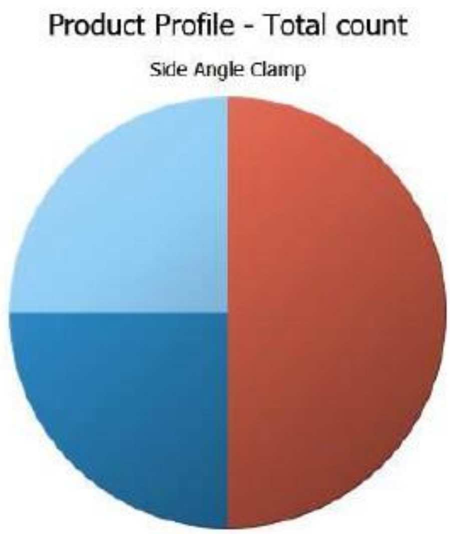
The remaining ten parts are identified as candidates for elimination, as they do not contribute significantly to the core functionality of the attachment. Removing these non-essential components can reduce the assembly time by 60%, improving the overall efficiency and simplifying the assembly process. This reduction in parts would streamline the production of the drill jig, making it faster and more cost-effective to assemble.

3.2.4 DFA analysis on side angle clamp attachment

As shown in Figure 8, the Side Angle Clamp Attachment has a DFA Index of 20.70, reflecting the product's efficient assembly process. This high index indicates that minimal parts are required for assembly, contributing to its overall efficiency.

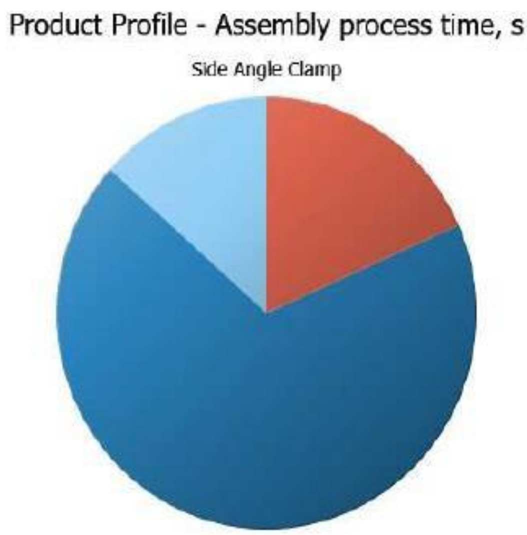
Name	Part number	Repeat count	Total count	Minimum items	Minimum part criteria	Process time per entry, s	Process time per product, s
Side Angle Clamp			4	2			31.98
Magnetic Base	1	1	1	1	Base part	2.93	2.93
Side Angle Clamp Base	2	1	1			4.29	4.29
Angle	3	1	1	1	Movement	2.93	2.93
Screw Tightening Clamp	4	1	1	0	Fastener	21.83	21.83

Fig. 21. Product worksheet of side angle clamp attachment



	1 Side Angle Clamp	
Necessary items	2	50.00%
Fasteners	1.00	25.00%
Connectors	0.00	0.00%
Other candidates for elimination	0.00	0.00%
Analyzed subassemblies	1.00	25.00%
Separate operations	0.00	0.00%
Total	4.00	100%
Difference	0.00	

Fig. 22. Total count of side angle clamp attachment



	1 Side Angle Clamp	
Necessary items	5.86	18.32%
Fasteners	21.83	68.26%
Connectors	0.00	0.00%
Other candidates for elimination	0.00	0.00%
Analyzed subassemblies	4.29	13.41%
Separate operations	0.00	0.00%
Total	31.98	100%
Difference	0.00	

Fig. 23. Assembly process time of side angle clamp attachment

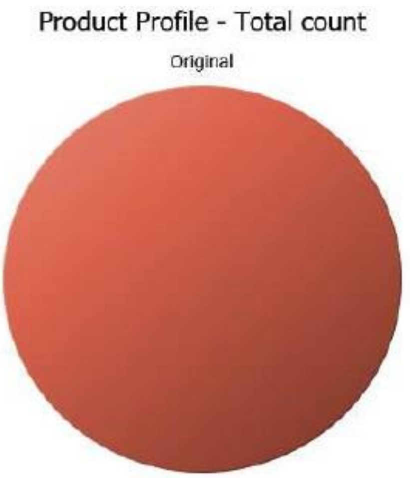
The total assembly time for this attachment is 31.98 seconds, as depicted in Figure 23. The attachment consists of two essential parts, which account for 50% of the total component count. These parts are crucial for the product's functionality and cannot be eliminated. However, the screw-tightening clamp (fasteners) has been identified as a candidate for elimination. The fasteners take up a significant portion of the assembly time, consuming 21.83 seconds, or 68.26%. Replacing the fasteners with a more efficient design, such as a snap-fit mechanism, could significantly reduce the assembly time, improving productivity and cost-effectiveness. This redesign would streamline the assembly process, enhancing the overall efficiency of the Side Angle Clamp Attachment.

3.2.5 DFA analysis on vise for cylindrical shapes attachment

As shown in Figure 7, the Vise for Cylindrical Shapes Attachment has a DFA Index of 112.97, indicating a highly efficient assembly process. The data confirms that this attachment achieves maximum assembly efficiency. The total assembly time for this attachment is only 5.86 seconds, as depicted in Figure 26.

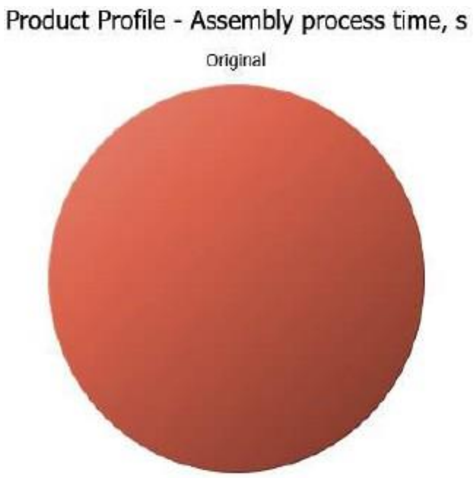
Name	Part number	Repeat count	Total count	Minimum items	Minimum part criteria	Process time per entry, s	Process time per product, s
Vise Jig			2	2			5.86
Magnetic Base	1	1	1	1	Base part	2.93	2.93
Vise (V-Block)	2	1	1	1	Different material	2.93	2.93

Fig. 24. Product worksheet of vise for cylindrical shapes attachment



	1 Original	
Necessary items	2	100.00%
Fasteners	0.00	0.00%
Connectors	0.00	0.00%
Other candidates for elimination	0.00	0.00%
Analyzed subassemblies	0.00	0.00%
Separate operations	0.00	0.00%
Total	2.00	100%
Difference	0.00	

Fig. 25. Total count of vise for cylindrical shapes attachment



	1 Original	
Necessary items	5.86	100.00%
Fasteners	0.00	0.00%
Connectors	0.00	0.00%
Other candidates for elimination	0.00	0.00%
Analyzed subassemblies	0.00	0.00%
Separate operations	0.00	0.00%
Total	5.86	100%
Difference	0.00	

Fig. 26. Assembly process time of vise for cylindrical shapes attachment

This attachment consists of only two essential parts necessary for its function. These critical parts cannot be eliminated, so they are listed as essential components. Given the simplicity of the design and the minimal number of parts, there is no requirement or need to reduce the assembly time further. The current design ensures optimal assembly efficiency, demonstrating that the Vise for Cylindrical Shapes Attachment is well-optimized for quick and effective assembly, with no further improvements needed.

4. Conclusions

The development of the Universal Magnetic Portable Jig has demonstrated its transformative potential in addressing the limitations of traditional clamping systems. This innovative jig integrates modularity, adaptability, and advanced manufacturing techniques to deliver a versatile clamping solution for diverse educational, DIY, and small-scale industrial applications. Combining a robust magnetic base and interchangeable attachments enables users to effectively secure workpieces of various geometries, including cylindrical, rectangular, and angled shapes. Advanced manufacturing methods such as 3D printing, CNC machining, and MIG welding ensured high precision, durability, and a streamlined fabrication process, validating the jig's capacity for demanding operational environments. The study’s comprehensive testing and DFMA analysis underscore the jig's assembly efficiency and operational reliability. Components such as the Vise for Cylindrical Shapes achieved an exemplary DFA Index of 112.97, demonstrating superior design simplicity and assembly speed. Conversely, more complex attachments like the Dial Test Indicator Holder identified opportunities for design optimization through part reduction. Despite these disparities, the jig consistently showcased its reliability across clamping and positioning tasks. Identified limitations, including size constraints for larger workpieces and dependency on ferromagnetic surfaces, provide a basis for targeted improvements in future iterations.

This study contributes significantly to optimizing clamping tools by bridging gaps in traditional systems and prioritizing innovation, usability, and efficiency. The Universal Magnetic Portable Jig addresses immediate market needs and sets a precedent for future research. Key areas for development include scaling the jig's capabilities for larger and non-magnetic workpieces, enhancing magnetic strength, and incorporating automated adjustment features. Moreover, adopting advanced assembly methods such as snap-fit mechanisms and eliminating non-essential components can further improve manufacturing efficiency and cost-effectiveness. In conclusion, the Universal Magnetic Portable Jig represents a milestone in clamping technology. Its development highlights the successful integration of engineering ingenuity with practical usability, offering a modern, efficient, and adaptable solution to contemporary clamping challenges. By addressing these challenges, the jig contributes to enhanced productivity and innovation, providing a foundation for further advancements in manufacturing tools.

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