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Design and Development of an Electromagnetic Portable Drill Guide for Improved Precision and Efficiency in DIY Applications

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ABSTRACT

This study investigates the design and performance of an electromagnetic portable drill guide aimed at enhancing precision, efficiency, and sustainability in educational and hobbyist applications. Using a combination of CAD modeling, Finite Element Analysis (FEA), and additive manufacturing, the developed drill guide demonstrated significant improvements in operational precision and portability. Circularity tests on different materials revealed minimal errors, with plywood exhibiting the lowest error rate of 0.40% and sheet metal the highest at 3.2%. FEA simulations confirmed the drill guide's structural integrity, with a maximum von Mises stress of 78.97 MPa (below the yield strength of the material), maximum displacement of 0.18 mm, and a safety factor of 3.48. The prototype, fabricated from mild steel and ABS plastic, was lightweight (5-7 kg) and versatile, supporting a wide range of materials including plywood, acrylic, and sheet metal. These findings highlight the drill guide's potential to improve precision tooling practices while promoting cost-effective and sustainable manufacturing, particularly in educational and DIY settings. Further enhancements are suggested to optimize ergonomic design and extend application versatility.

1. Introduction

The continuous advancement of manufacturing processes has heightened the demand for precision, efficiency, and sustainability across various sectors [1]. Drilling, as a fundamental operation in fabrication, frequently encounters challenges related to energy inefficiency, lack of precision, and limited adaptability when using conventional equipment [2]. Traditionally, jigs and fixtures have improved accuracy in drilling operations. However, conventional designs often fail to address modern demands for flexibility, cost-effectiveness, and environmental responsibility [3,4]. Recent innovations have focused on overcoming these limitations by integrating advanced technologies [5].

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This study addresses existing drilling technologies' gaps by designing and developing an electromagnetic portable drill guide specifically tailored for educational, DIY, and hobbyist use. By leveraging CAD for design, FEA for structural testing, and FDM for rapid prototyping, this project will deliver a solution that balances portability, precision, and sustainability [6,7]. The guide is designed to be versatile enough to meet the diverse needs of modern manufacturing while being compact and cost-effective for educational environments [8]. The research further emphasizes sustainable manufacturing practices, reducing waste and energy-efficient production processes [9]. The development and testing of this electromagnetic portable drill guide will demonstrate the design's efficacy and contribute to the broader goal of integrating sustainability into precision tooling [10].

Electromagnetic drilling concepts have emerged as a promising solution, offering enhanced stability, precision, and versatility compared to traditional tools [11,12]. Applying electromagnetism allows for a secure attachment to ferromagnetic surfaces, greatly improving control during drilling, reducing the margin for error, and improving overall accuracy [13]. Furthermore, electromagnetic drills contribute to energy conservation and sustainability efforts. Despite these advantages, comprehensive designs and guidelines for developing electromagnetic portable drill guides remain scarce, particularly in educational and hobbyist settings [14]. Ergonomic considerations are equally important in the design of jigs and fixtures. Poor ergonomics can lead to operator fatigue and reduce overall productivity. Recent developments in adaptive jigs, which can be easily adjusted to accommodate various workpiece sizes, have demonstrated the potential to enhance flexibility and worker comfort [15,16]. Such designs reduce setup time and are well-suited to high-mix, low-volume production environments where frequent adjustments are required [17,18].

Educational applications also benefit significantly from the development of these innovative jigs. Technical Vocational Education and Training (TVET) programs, which aim to prepare students for technical careers, are increasingly incorporating practical tools to enhance learning outcomes [19,20]. Studies have shown that integrating real-world tools into educational curricula improves students' technical skills and problem-solving abilities, making them more workforce-ready [21,22]. Developing portable, user-friendly tools like drill guides is critical for bridging the gap between theoretical knowledge and practical application in educational settings [23]. Therefore, the study of an electromagnetic portable drill guide represents a significant advancement in precision manufacturing tools. By incorporating advanced design methodologies, sustainable materials, and modern fabrication techniques, this project aims to meet the demands of contemporary manufacturing and educational settings [24]. The findings from this research will provide valuable insights into improving the precision, efficiency, and sustainability of drilling operations, with implications extending beyond the immediate scope of manufacturing to vocational training and sustainable development.

2. Methodology

2.1 Product Planning

Product planning identifies the portfolio of electromagnetic portable drill guides considering the planning process determined by various sources, including primary and secondary data. Primary data involves past journal articles, published patents and related references for addressing any gaps in designing and developing a drill guide through precision and additive manufacturing process concepts. Based on observation findings conducted at a university workshop together with distributed questionnaires among students consisting of 30 respondents, highlighting the limitations in current jig design, which are often bulky and lack versatility. Those findings as secondary data provide user requirements that can be used for establishing initial product specifications, as described in Table 1. Since the aim of this jig was for DIY, hobbyist and educational applications, this study focuses on designing and developing a cost-effective, portable and safe electromagnetic drill guide that evolving needs of modern manufacturing. The detailed research process flow was applied from the 7th edition of the Product Design and Development Book by [25], as shown in Figure 1.

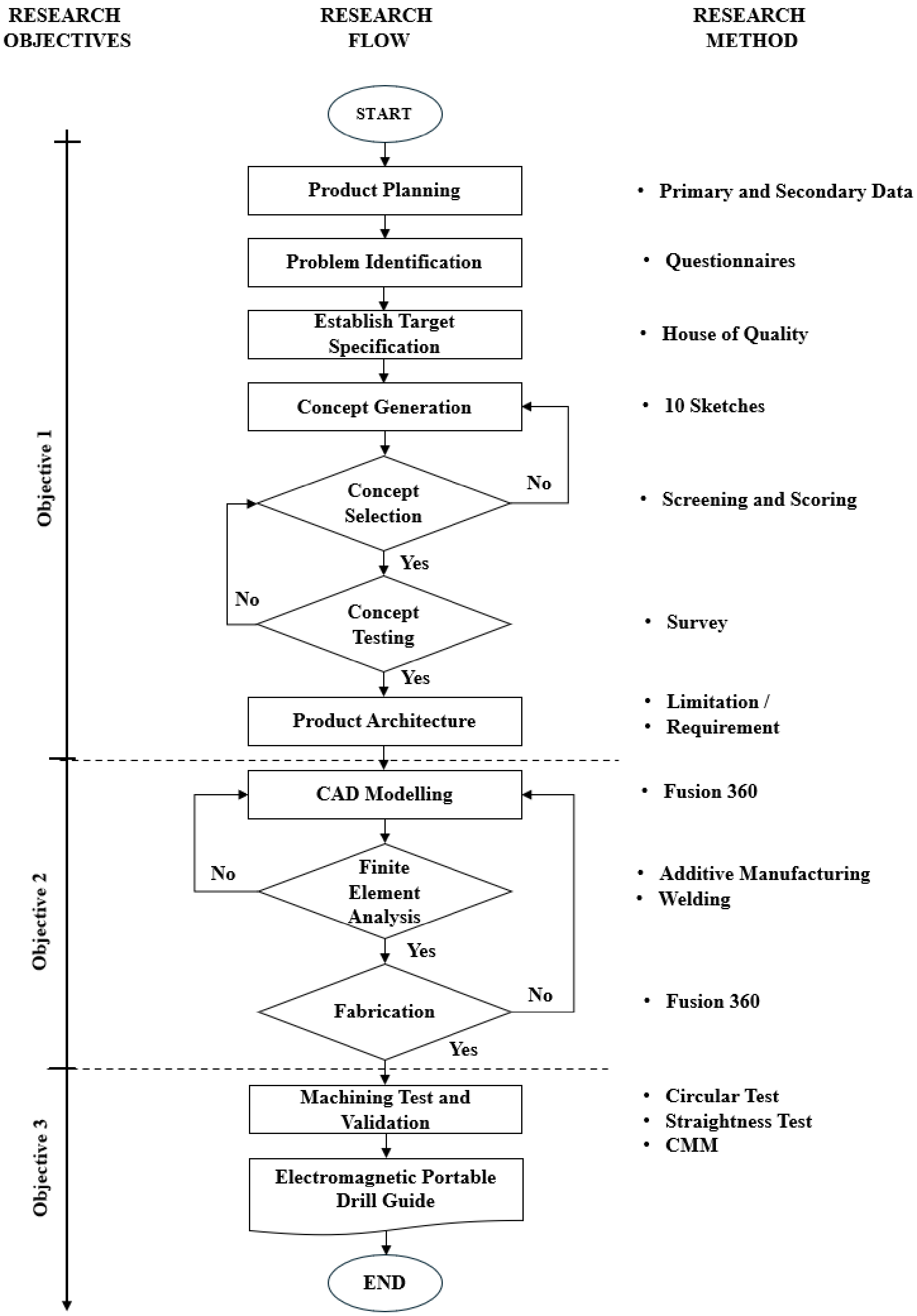


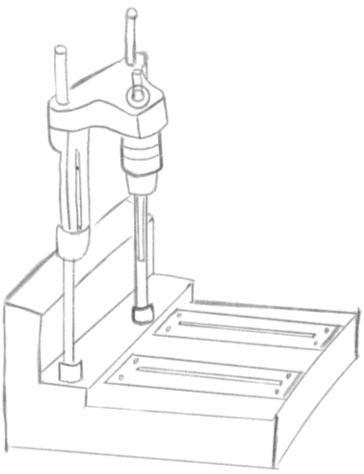
Fig. 1. Research process flow

Table 1
Initial product specifications

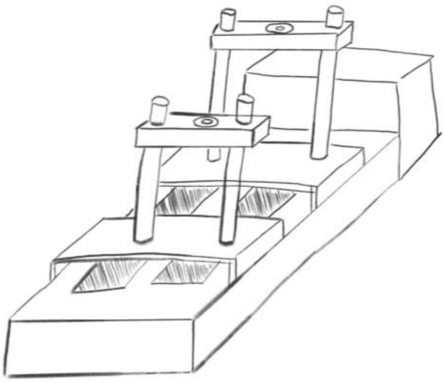
No.	Technical Requirements	Target Values	Unit
1	Size	340 (L) x 170 (W) x 350 (H)	mm
2	Chuck Size	13 mm Bosch Drill Chuck	mm
3	Electromagnetic Specification	Magnetic Lock Up to 272 kg, 12V	kg, v
4	Magnetic Surface Area	250 (L) x 100 (W)	mm
5	Maximum Drill Height	Up to 100 mm (Based on Drill Bit Length)	mm
6	Drill Machine Type	Cordless Drill	-
7	Material	Mild Steel & ABS	-
8	Total Weight	5 - 7	kg

2.2 Concept Generation

The ideation phase involved generating and refining design concepts through online research and expert consultations. After creating several design sketches, a structured screening and scoring process was applied to select the most viable design. The feedback from consultations led to iterative redesigns, resulting in a mock-up that met 50% of the project's manufacturing goals. The process of selecting four concepts (Concept A, Concept B, Concept C and Concept D) was analysed through screening and scoring methods, as illustrated in Figure 2. This progressed after 10 sketches were screened, and the four best sketches were selected to be scored before 3D model development. Concept A, with 3.55, and Concept D, with 3.4, were the highest total rank scores, as shown in Table 2, and both concepts were combined for further refinement and included additional features for enhanced usability before moving to the technical drawing phase. Analyzing existing drill guides served as a benchmark for the new product, ensuring the design incorporated essential features like torque variability, ergonomic handling, and material durability. These benchmarks helped set the final product specifications, focusing on high performance and user satisfaction. Mild steel and ABS plastic were chosen as the primary materials for the drill guide due to their strength, cost-effectiveness, and durability through consultation with manufacturing experts and stakeholders' decisions.



Concept A



Concept B

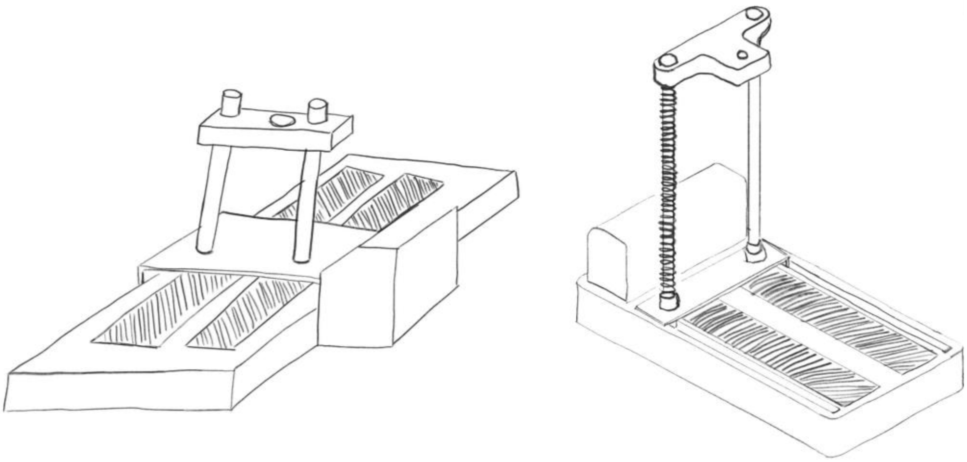


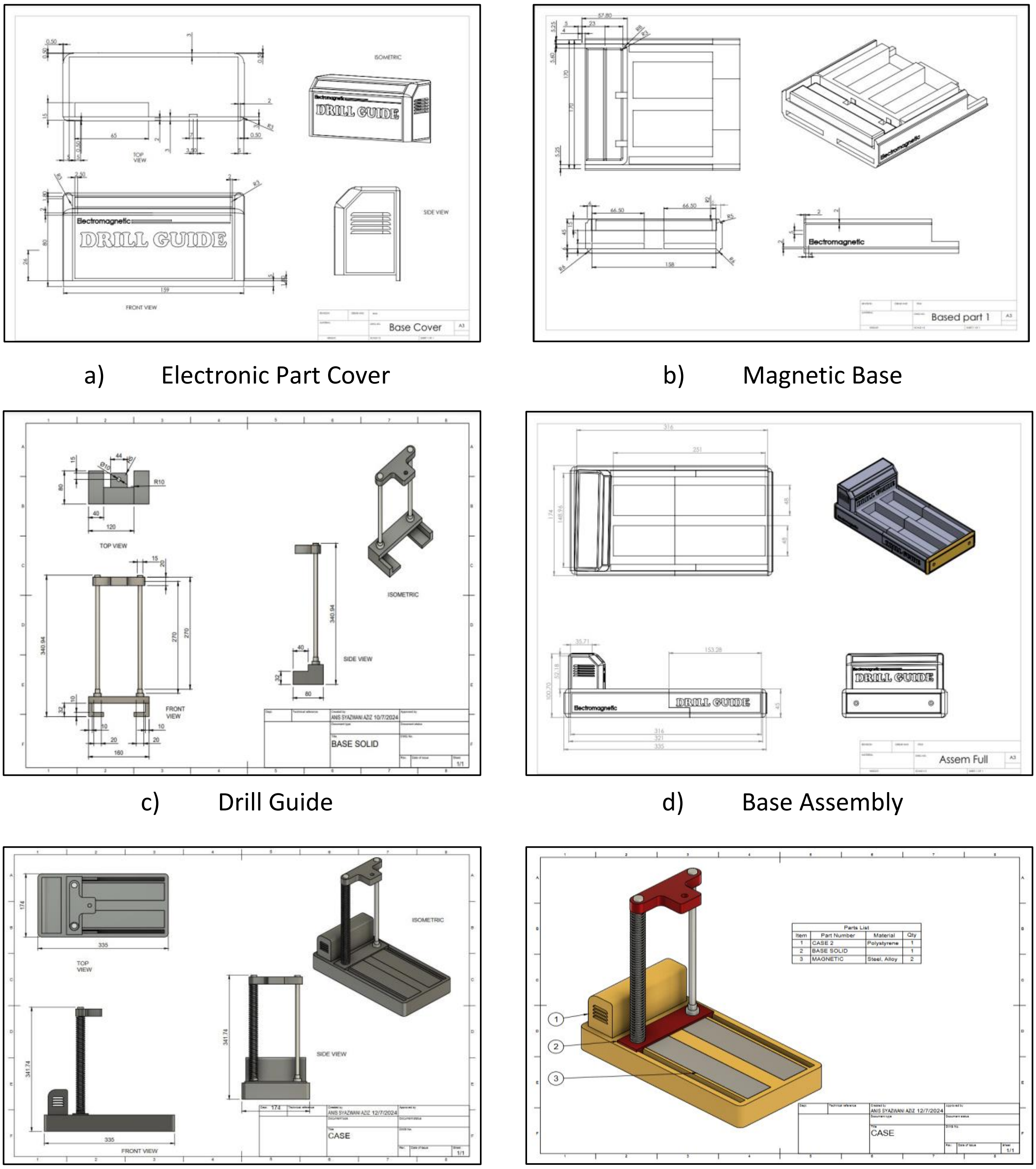
Fig. 2. Electromagnetic portable drill guide concept ideations

Table 2
The concept-scoring matrix

		Concepts							
		A (Reference)		B		C		D	
Selection Criteria	Weight	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score
Compact Size	15%	4	0.6	2	0.3	3	0.45	4	0.6
Chuck Size	10%	4	0.4	3	0.3	4	0.4	4	0.4
Magnetic Working Area	15%	3	0.45	4	0.6	5	0.75	3	0.45
Drill Height	15%	5	0.75	3	0.45	3	0.45	4	0.6
Drill Machine Types	15%	3	0.45	3	0.45	3	0.45	3	0.45
Portability	15%	4	0.6	2	0.3	3	0.45	4	0.6
Light to Heavy Duty	10%	3	0.3	2	0.2	3	0.3	3	0.3
	Total Rank	3.55		2.6		3.25		3.4	
	Score	1		4		3		2	
Continue?		Combine		No		No		Combine	

2.3 Concept Finalization

The finalized concept was created using Fusion360 software, prioritizing user-friendly features and aesthetic appeal. Detailed technical drawings were produced, including specific measurements and component breakdowns. These drawings were subjected to Finite Element Analysis (FEA) to ensure the design's structural integrity and material compatibility. Figure 3 presents the technical drawing of the electromagnetic portable drill guide, detailing its main components and overall assembly. The design consists of three key parts: the electronic part cover, the magnetic base, and the drill guide assembly, each of which plays a crucial role in the functionality and stability of the device. The drawing provides a comprehensive view of these components, showcasing how they integrate to enhance the drill guide's precision, portability, and overall performance. The magnetic base serves as the core of the drill guide, housing the electromagnetic system that allows the device to attach to ferromagnetic surfaces securely. This feature is essential for ensuring stability during drilling operations, particularly when working on uneven or inclined surfaces. The technical drawing offers detailed dimensions and mounting points, demonstrating the effective positioning of the electromagnetic system to allow for precise control during operation.



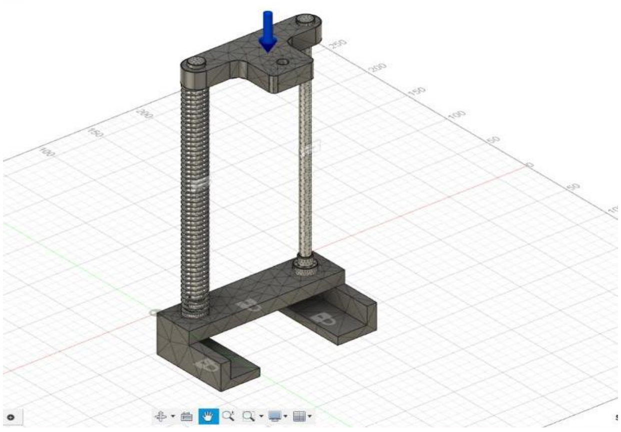
a) Electronic Part Cover
b) Magnetic Base
c) Drill Guide
d) Base Assembly
e) Full Assembly
f) Bill of Materials

Fig. 3. Technical drawing of the electromagnetic portable drill guide

2.4 Finite Element Analysis (FEA)

FEA was conducted to assess the structural integrity and material compatibility of the design. This analysis evaluated whether the drill guide could endure operational stresses, ensuring its long-term durability and reliability, or if it would fail under specific stress conditions. Key parameters such as Von Mises stress, displacement, and safety factors were analyzed, with plans for redesign if the desired results were not achieved. Additionally, the 3D modeling provided critical dimensions for each component of the drill guide, along with the setup parameters for the selected materials (mild steel and ABS plastic) to examine concentrated stress on specific parts, as outlined in Table 3. The analysis was performed using Fusion 360 software.

Table 3
Directional and applied ford on selected geometry surface of drill guide parts

Part	Image	Description	Applied Force
Drill Guide		Downward force (Blue Arrow) indicating certain load was applied onto the selected surface	10.2 kg (100 N)

2.5 Prototype Fabrication

The fabrication process of the electromagnetic drill guide prototype consists of three primary components: the electronic part cover, the magnetic base, and the drill guide. Most components, such as the electronic parts and the magnetic base, were 3D printed using the Bambu Lab X1 Carbon printer within a controlled environment as shown in Figure 4. The chamber temperature was carefully maintained to prevent ABS filament warping, which can occur when the upper layers cause the lower layers to stretch upward. Parameters including printing speed, flow dynamics, flow rate, extruder settings, nozzle, bed temperature, and chamber temperature were meticulously calibrated to produce strong and optimal plastic parts. The drill guide, on the other hand, was fabricated using Metal Inert Gas (M.I.G) welding and tapering processes to accommodate different assembly methods. Detailed fabrication steps are outlined in Table 4. The entire assembly, including the wiring process, was completed in 3 hours, while the 3D printing process required a total of 27 hours.

Table 4
Manufacturing process of electromagnetic drill guide

No.	Parts	Manufacturing Process	Description
1	Drill Guide	MIG Welding, Drilling, Shearing, Tapering	Mild Steel 5mm thick
2	Electronic Part Cover and Magnetic Base	3D Printing (Bambu Lab X1 Carbon)	5 Wall line. 0.2 mm Layer Height. 50% infill. 260 ^{o}C Nozzle Temperature. 90 ^{o}C bed Temperature. 50 ^{o}C Chamber Temperature. 20% Cooling Fan Speed.

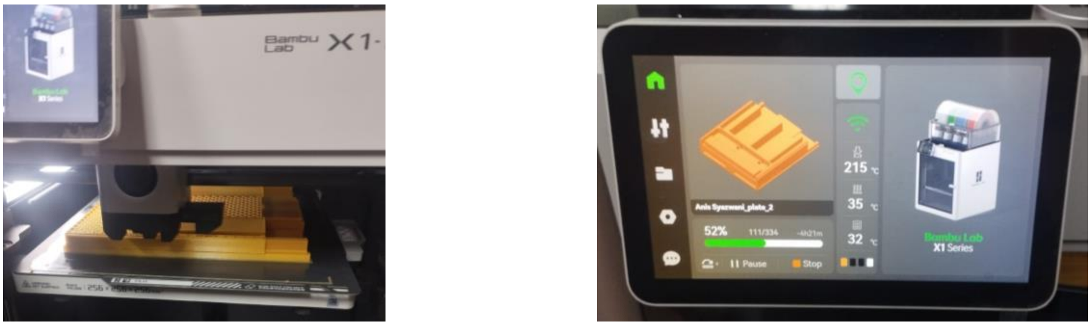


Fig. 4. 3D printing process by Bambu Lab X1 carbon printer

2.6 Shape and Dimension Deviations

The relationship between shape and dimension deviation and surface integrity is a critical aspect in evaluating the performance of machining processes, particularly in operations such as drilling. Shape and dimension deviations, which refer to the inaccuracies in achieving the intended geometrical features and dimensional tolerances of a workpiece, directly influence the quality of the surface produced during machining. These deviations are often caused by a combination of factors, including the workpiece material properties, cutting parameters, and machine tool performance.

Surface integrity encompasses the surface's topography and the subsurface properties affected by machining, including roughness, hardness, and residual stress. A high level of surface integrity is essential for ensuring the durability and functionality of a machined part. When deviations in shape and dimension occur, they often lead to irregularities in the surface texture, such as increased roughness or inconsistent surface patterns. These irregularities are detrimental as they can compromise the part's structural performance, wear resistance, and aesthetic appeal.

In the case of the electromagnetic portable drill guide, the circularity tests reveal that the roughness along the round part is significantly influenced by spindle speed. At low spindle speeds, the surface along the round part exhibits greater roughness compared to higher spindle speeds. This phenomenon can be attributed to the reduced stability and increased vibration at lower spindle speeds, which exacerbate shape and dimension deviations. These deviations create uneven contact between the cutting tool and the workpiece, resulting in an inconsistent material removal rate and a rougher surface finish.

Moreover, the sources of these errors namely, the workpiece and the machine tool—further underscore the interconnectedness of shape and dimension deviation with surface integrity. Workpiece-related factors, such as material heterogeneity and initial surface imperfections, can amplify deviations during machining. On the other hand, machine tool factors, including misalignment, tool wear, and inadequate clamping, can lead to instability and errors in maintaining the desired geometrical and dimensional accuracy. These factors collectively affect the energy transfer during cutting, thereby impacting the surface finish.

To improve surface integrity while minimizing shape and dimension deviations, optimizing cutting parameters, enhancing machine tool stability, and using advanced error compensation techniques are crucial. For instance, operating the drill guide at higher spindle speeds within the optimal range can reduce vibrations and improve surface smoothness. Additionally, incorporating real-time monitoring systems to detect and correct deviations can further enhance the precision and quality of the machining process.

2.7 Tolerance Zone

The tolerance zone for the electromagnetic portable drill guide was determined based on the specific requirements of its intended applications, such as precision machining in educational and DIY settings. Initial parameters for the tolerance zone were derived through benchmarking against existing drill guides and standards in precision machining. These benchmarks incorporated dimensions and shape constraints critical to ensuring functionality and compatibility with various workpiece materials, including plywood, acrylic, and sheet metal.

Empirical testing was conducted during the development phase, using circularity tests to assess deviations in drilled components. The results from these tests informed iterative refinements to the tolerance zone, ensuring that deviations remained within acceptable limits for surface integrity and dimensional accuracy. Additionally, feedback from stakeholders and manufacturing experts contributed to establishing tolerance thresholds, particularly in relation to spindle speed, vibration reduction, and material compatibility. By combining theoretical guidelines, empirical data, and expert input, the study established a tolerance zone that balances manufacturing feasibility with high precision and performance, aligning with the project’s overarching goals.

3. Results and discussion

3.1 FEA of the Drill Guide

The FEA was conducted to assess the mechanical performance of a drill guide design. A 3D model was developed and divided into smaller sections through meshing to simulate real-world conditions. This included applying material properties such as elastic modulus, Poisson’s ratio, and yield strength to ensure accurate results [26]. The analysis focused on static structural evaluations, including stress and displacement under different loads, and modal analysis to examine natural frequencies and deformation [27]. As shown in Table 5, the main goal was to evaluate the drill guide’s performance in stress distribution, displacement, and safety factors, confirming its ability to meet operational requirements.

The structural analysis simulated a 100N load applied along the Y-axis. The von Mises stress analysis revealed a maximum stress of 78.97 MPa, which is well below the yield strength of the chosen steel material. This suggests that the drill guide can safely handle the applied load without permanent deformation. The strain analysis supported this conclusion, with a maximum strain of 0.001, indicating minimal deformation. The highest strain occurred at the top screw, but it remained within acceptable limits. A safety factor of 3.48 was calculated, indicating a robust margin of safety, ensuring the drill guide can withstand operational conditions without failure. However, some areas with slightly higher strain may benefit from minor reinforcements to improve durability over time.

Mild steel was selected for its strength, availability, and cost-effectiveness, making it ideal for prototyping. The displacement analysis showed a maximum movement of 0.176 mm, within acceptable limits. The low von Mises stress and strain values highlight the design's strength and durability. Although there was higher strain around the top screw, it remained safe, and reinforcing this area could enhance the overall performance. The FEA demonstrated that the drill guide design is robust and reliable, with a safety factor providing a comfortable margin for operational use. Steel proved to be an efficient material, balancing cost and performance. While the current design meets operational demands, further reinforcement in high-strain areas could improve longevity and performance.

3.2 Electromagnetic Portable Drill Guide Prototype

In the fabrication phase, appropriate materials were selected, and a combination of conventional machining methods and 3D printing was used to produce the necessary components. The electromagnetic systems were then integrated into the assembled guide. Finally, the testing phase involved performance evaluations to verify the guide's accuracy through circularity tests and assessments of its sustainability. This comprehensive manufacturing process aims to produce a multifunctional, flexible, and user-friendly drill guide that meets contemporary market demands. The development of this innovative electromagnetic portable drill guide supports the adoption of advanced drilling technologies across a wide range of applications, including manufacturing and technical education. The complete prototype of electromagnetic portable drill guide are shown in Figure 5.

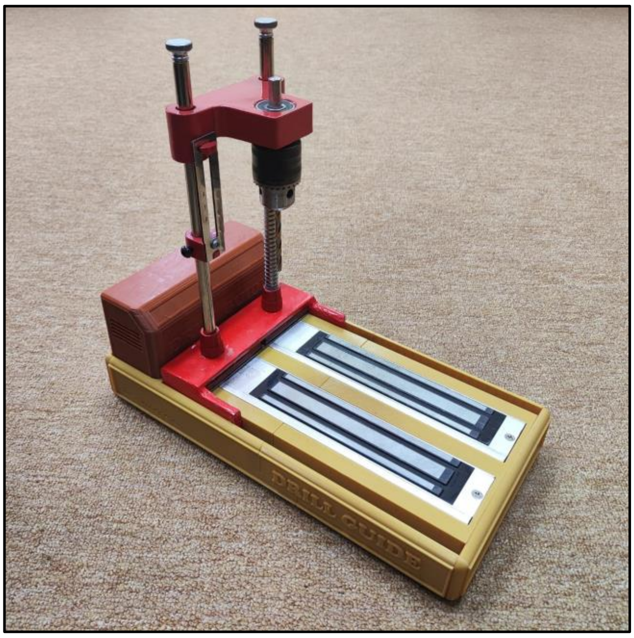
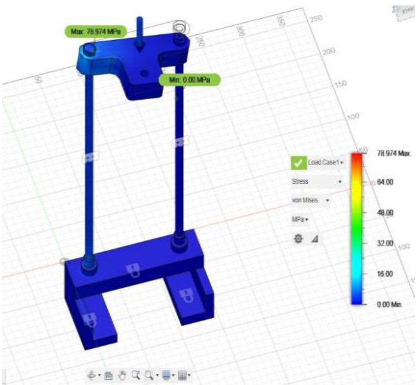
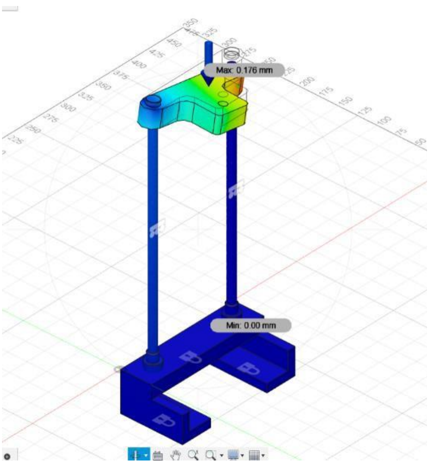
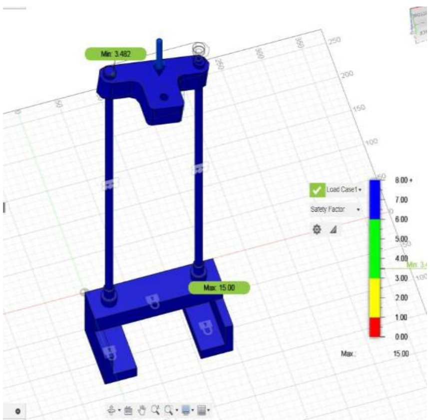


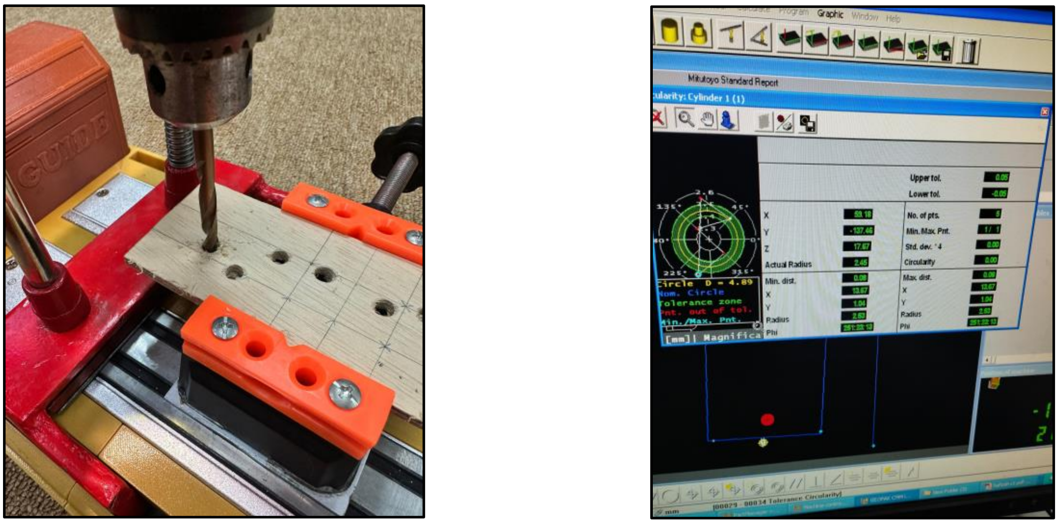
Fig. 5. Electromagnetic portable drill guide prototype

3.3 Machining Test and Validation

This test was conducted to determine the capabilities of the electromagnetic portable drill guide compared to larger, more space-consuming machines. The drill guide is evaluated using a 5 mm drill bit to drill into plywood (5mm), sheet metal (5mm), acrylic, and High-Density Polyethylene (HDPE) as shown in Figure 6. The initial tests determine whether the drill guide can move up and down and whether the electromagnetic base fully functions. A critical step is to control the movements to monitor the drilling process of the plywood (5mm), sheet metal (5mm), acrylic, and HDPE blocks. The fundamental knowledge is sufficient to model the electromagnetic drills guide to identify defects, potential collisions, or inefficiencies. This study's coding testing requires circular motion drilling profile. The parameter of circular testing was referred [28,29].

Table 5
FEA of drill guide part

No.	Analysis	Description
1		**Von Mises Stress:** Applied Force: 100 N Min: 0.00 MPa Max: 78.97 MPa
2		**Displacement:** Applied Force: 100 N Min: 0.00 mm Max: 0.18 mm
3		**Safety Factor:** Applied Force: 100 N Min: 3.48 ul Max: 15.00 ul



a) Drilling process on plywood b) Circular measurement by CMM

Fig. 6. Machining test and CMM validation

3.3.1 Circular test

Four tests are conducted for the circular test. The test parameters are listed in Table 6. Values for each circle of all tests were set at Ø 5 mm and the test results are shown in Figure 7 and 8. In contrast, Figure 5 represents the circles and deflections predicted from reference circles of acrylic, sheet metal (5mm), plywood (5mm), and HDPE. The best result from the round test reading is at 0.06, and the parameter plywood has an error of 0.40%. The results show that the highest circle test reading is 0.08, and the Sheet metal has an error percentage of 3.2%. The first thing that can be noticed from the results is that the surface along the round part with a low spindle speed is much rougher than the surface along the round part with a high spindle speed. These errors come from two main sources, which may be the workpiece and the machine itself.

Table 6
Circularity test of the acrylic, sheet metal (5mm), plywood (5mm), and HDPE

Part	Std. Dev.* 4	Actual R (mm)	Circle Ø(mm)	Circularity	Error (%) [Ø]
Acrylic					
1	0.28	2.75	4.98	0.08	
2	0.17	2.49	5.01	0.07	$\frac{\|4.90-5\|}{5} x100$
3	0.29	2.49	4.97	0.07	
4	0.24	2.50	4.65	0.06	
Avg	0.25	2.56	4.90	0.07	2.0
Sheet Metal					
1	0.25	2.5	4.94	0.06	
2	0.26	2.51	4.99	0.09	$\frac{\|4.84-5\|}{5} x100$
3	0.31	2.73	4.35	0.08	
4	0.33	2.73	5.06	0.09	
Avg	0.31	2.62	4.84	0.08	3.2
Plywood					
1	0.30	2.48	4.97	0.06	
2	0.31	2.45	4.98	0.05	$\frac{\|4.98-5\|}{5} x100$
3	0.21	2.43	4.96	0.07	

4	0.32	2.49	4.99	0.06	
Avg	0.28	2.46	4.98	0.06	0.40
HDPE					
1	0.31	2.48	4.99	0.08	
2	0.11	2.48	4.94	0.05	$\frac{\lvert 4.98-5\rvert}{5} x100$
3	0.30	2.73	5.00	0.08	
4	0.27	2.48	4.92	0.07	
Avg	0.25	2.54	4.96	0.07	0.8

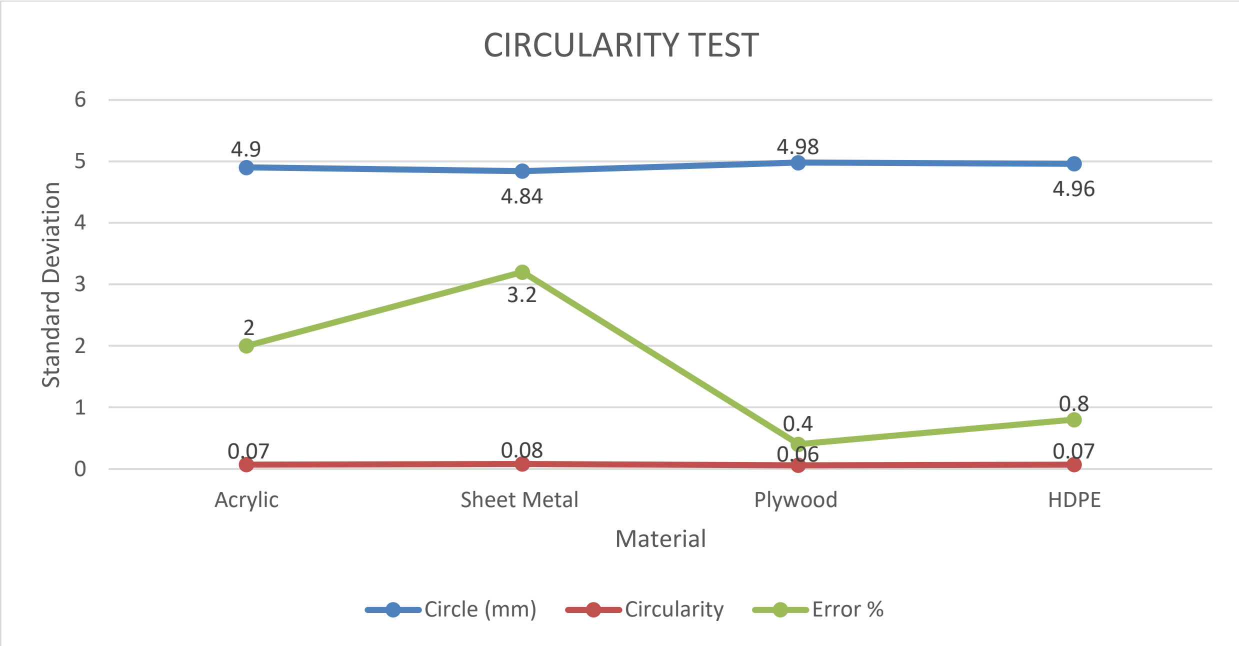
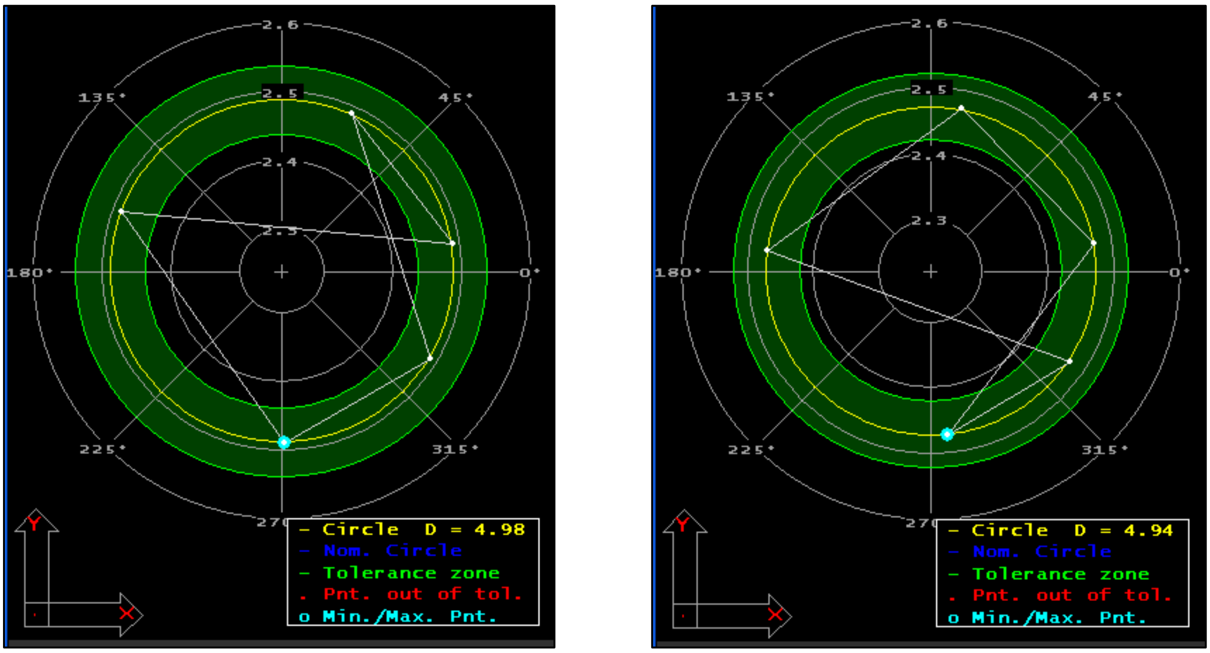
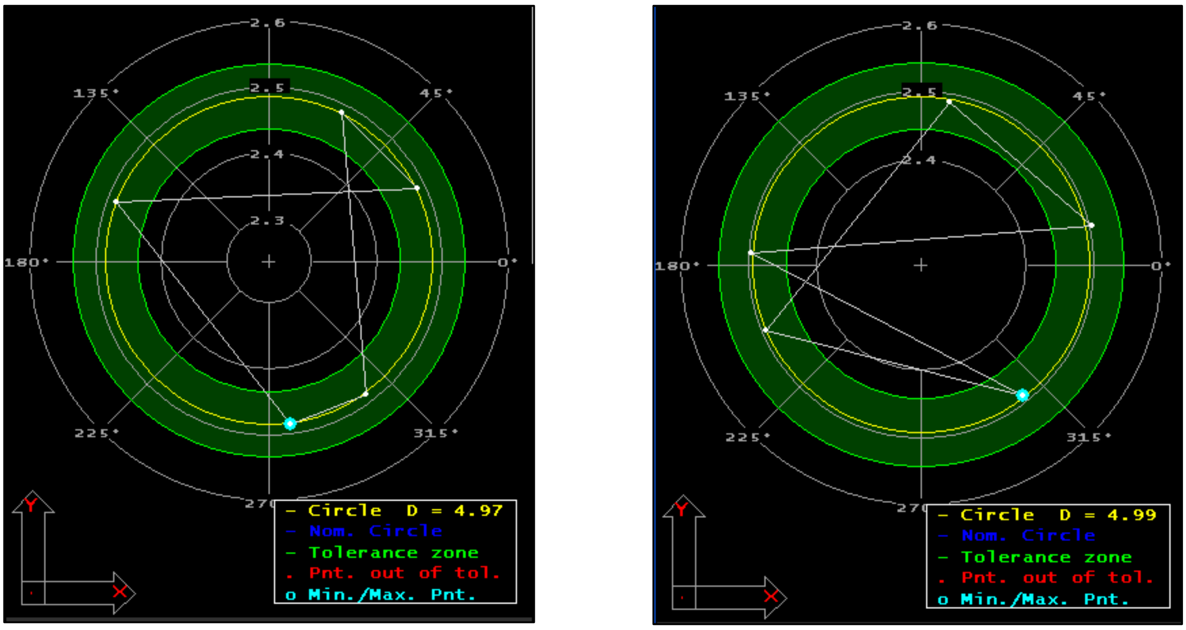


Fig. 7. Graphs of circularity and predicted deflections from the reference circle of the acrylic, sheet metal, plywood, and HDPE



a) Circular test acrylic

b) Circular test sheet metal



c) Circular test plywood d) Circular test HDPE

Fig. 8. Graphical representation of the circularity test for sample part

4. Conclusions

This study presents a comprehensive analysis of the design and development of an electromagnetic portable drill guide, aimed at addressing the limitations of traditional drilling tools in terms of precision, portability, and sustainability. The innovative approach adopted in this research integrates advanced methodologies, including 3D CAD modelling, FEA, and additive manufacturing techniques, resulting in a tool tailored for diverse applications in educational, DIY, and industrial contexts. Key findings of the study demonstrate enhanced precision, as evidenced by circularity tests, which revealed minimal errors during drilling operations. The FEA further validated the mechanical robustness of the design, showcasing low-stress levels, minimal displacement, and a high safety factor. The choice of mild steel and ABS plastic, coupled with hybrid manufacturing techniques, facilitated the creation of a durable and cost-effective prototype.

Despite these promising outcomes, the study highlights the need for comparative benchmarking against standard equipment to substantiate the claimed improvements in precision and efficiency. Additionally, future research is recommended to explore the development of angular portable drill guides to accommodate more complex drilling operations. These efforts should emphasize evaluations of torque distribution, structural integrity, and ergonomic usability to ensure precision and safety across a wide range of conditions. The findings of this study contribute significantly to the fields of precision manufacturing and technical education by offering a sustainable and portable solution to drilling challenges. Future iterations and comparative analyses will further enhance the design's adaptability to evolving technological and educational demands, solidifying its potential as a versatile tool in modern manufacturing and educational settings.

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References

[1] Rong, Yiming Kevin. Computer-Aided Fixture Design: Manufacturing Engineering and Materials Processing Series/55. CRC Press, 1999. https://doi.org/10.1201/9781482273779

[2] Said, Nor Azinee, Muhammad Afiq Roslan, Norsilawati Ngah, Ahmad Joraimee Mohamad, Ummi Nazahah Roslan, Raja Manisa Raja Mamat, Nor Bahiyah Baba, Mohd Habir Ibrahim, Kamarul Adnan Abd Aziz, and Mohd Faizul Azuan Yusof. "Design and Fabrication of Jig and Fixture for Drilling Machine in the Manufacturing Industry to Improve Time Productivity." Journal of Advanced Research in Applied Sciences and Engineering Technology 29, no. 2 (2023): 304-313. https://doi.org/10.37934/araset.29.2.304313

[3] Abeykoon, Chamil, Pimpisut Sri-Amphorn, and Anura Fernando. "Optimization of fused deposition modeling parameters for improved PLA and ABS 3D printed structures." International Journal of Lightweight Materials and Manufacture 3, no. 3 (2020): 284-297. https://doi.org/10.1016/j.ijlmm.2020.03.003

[4] Ahmad, Mohd Nazri, Mohamad Ridzwan Ishak, Mastura Mohammad Taha, Faizal Mustapha, Zulkiflle Leman, Debby Dyne Anak Lukista, Irianto, and Ihwan Ghazali. "Application of Taguchi method to optimize the parameter of fused deposition modeling (FDM) using oil palm fiber reinforced thermoplastic composites." Polymers 14, no. 11 (2022): 2140. https://doi.org/10.3390/polym14112140

[5] Al-Qahtani, Amal S., Huda I. Tulbah, Mashael Binhasan, Maria S. Abbasi, Naseer Ahmed, Sara Shabib, Imran Farooq et al. "Surface properties of polymer resins fabricated with subtractive and additive manufacturing techniques." Polymers 13, no. 23 (2021): 4077. https://doi.org/10.3390/polym13234077

[6] Okpala, Charles Chikwendu, and Ezeanyim Okechukwu. "The design and need for jigs and fixtures in manufacturing." *Science Research* 3, no. 4 (2015): 213-219. https://doi.org/10.11648/j.sr.20150304.19

[7] Paunescu, Tudor, and Rodica Paunescu. "Accuracy analysis of the modular fixturing systems with grid pattern threaded holes." In *MATEC Web of Conferences*, vol. 94. EDP Sciences, 2017. https://doi.org/10.1051/matecconf/20179405007

[8] Niati, Dewi Rama, Zulkifli Musannip Efendi Siregar, and Yudi Prayoga. "The effect of training on work performance and career development: the role of motivation as intervening variable." *Budapest International Research and Critics Institute (BIRCI-Journal): Humanities and Social Sciences* 4, no. 2 (2021): 2385-2393. https://doi.org/10.33258/birci.v4i2.1940

[9] Rohr-Mentele, Silja, and Sarah Forster-Heinzer. "Practical validation framework for competence measurement in VET: a validation study of an instrument for measuring basic commercial knowledge and skills in Switzerland." *Empirical Research in Vocational Education and Training* 13, no. 1 (2021): 1-25. https://doi.org/10.1186/s40461-021-00122-2

[10] Aqlan, Faisal, and Lawrence Al-Fandi. "Prioritizing process improvement initiatives in manufacturing environments." *International Journal of Production Economics* 196 (2018): 261-268. https://doi.org/10.1016/j.ijpe.2017.12.004

[11] Ibrahim, Z., S. B. Mohamed, M. Minhat, A. S. Mohamed, M. R. Musanih, Z. Abd Rahman, and Zairi Ismael Rizman. "Reason maintenance in product modelling via open source CAD system." International Journal on Advanced Science, Engineering and Information Technology 6, no. 6 (2016): 990-996. https://doi.org/10.18517/ijaseit.6.6.953

[12] Cheng, Jun, Jian-hua Zhao, Jin-yong Zhang, Yu Guo, Ke He, Jing-Jing Shang-Guan, and Fu-lin Wen. "Microstructure and mechanical properties of galvanized-45 steel/AZ91D bimetallic material by liquid-solid compound casting." *Materials* 12, no. 10 (2019): 1651. https://doi.org/10.3390/ma12101651

[13] Coogan, Timothy J., and David Owen Kazmer. "Bond and part strength in fused deposition modeling." *Rapid Prototyping Journal* 23, no. 2 (2017): 414-422. https://doi.org/10.1108/rpj-03-2016-0050

[14] Dalle Mura, Michela, and Gino Dini. "Optimizing ergonomics in assembly lines: A multi objective genetic algorithm." CIRP Journal of Manufacturing Science and Technology 27 (2019): 31-45. https://doi.org/10.1016/j.cirpj.2019.08.004

[15] Urakseev, M. A., N. A. Avdonina, K. V. Vazhdaev, Kh A. Sattarov, and K. K. Zhuraeva. "Electric current and magnetic field strength measuring system based on magneto-optical effect." In *2020 International Conference on Electrotechnical Complexes and Systems (ICOECS)*, pp. 1-4. IEEE, 2020. https://doi.org/10.1109/icoecs50468.2020.9278439

[16] Mat, Shabudin Bin, Richard Green, Roderick Galbraith, and Frank Coton. "The effect of edge profile on delta wing flow." *Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering* 230, no. 7 (2016): 1252-1262. https://doi.org/10.1177/0954410015606939

[17] Costa, Claudio, F. J. G. Silva, Ronny M. Gouveia, and R. P. Martinho. "Development of hydraulic clamping tools for the machining of complex shape mechanical components." *Procedia Manufacturing* 17 (2018): 563-570. https://doi.org/10.1016/j.promfg.2018.10.097

[18] Radhwan, H., M. S. M. Effendi, Muhamad Farizuan Rosli, Z. Shayfull, and K. N. Nadia. “Design and Analysis of Jigs and Fixtures for Manufacturing Process.” In *IOP Conference Series: Materials Science and Engineering*, vol. 551, no. 1, p. 012028. IOP Publishing, 2019. https://doi.org/10.1088/1757-899X/551/1/012028

[19] Patil, Ankita, K. S. Rambhad, and D. R. Bele. “Concept of Jigs and Fixture Design–A Review.” *Int. J. Anal. Exp. Finite Elem. Anal* 4, no. 4 (2017): 73-77. https://doi.org/10.26706/ijaefea.4.4.20171004

[20] Gothwal, Suman, and Tilak Raj. “Different aspects in design and development of flexible fixtures: review and future directions.” *International Journal of Services and Operations Management* 26, no. 3 (2017): 386-410. https://doi.org/10.1504/IJSOM.2017.081944

[21] Kumar, S., R. D. S. G. Campilho, and F. J. G. Silva. “Rethinking modular jigs’ design regarding the optimization of machining times.” *Procedia Manufacturing* 38 (2019): 876-883. https://doi.org/10.1016/j.promfg.2020.01.169

[22] Xu, Liang, Ke Chen, and Wen-wen Du. “The application and the calculation of deflection angle of the adjustable modular fixture which has space double angle.” *Integrated Ferroelectrics* 210, no. 1 (2020): 175-188. https://doi.org/10.1080/10584587.2020.1728858

[23] Hussein, H. M. A., A. Mahrous, A. F. Barakat, and Osama Monier Dawood. “Computer Aided Tradition Jigs and Fixtures Design.” In *Proceedings of the 17th Int. AMME Conference*, vol. 19, p. 21. 2016. https://doi.org/10.21608/amme.2016.35218

[24] Rohr-Mentele, Silja, and Sarah Forster-Heinzer. “Practical validation framework for competence measurement in VET: a validation study of an instrument for measuring basic commercial knowledge and skills in Switzerland.” *Empirical Research in Vocational Education and Training* 13, no. 1 (2021): 1-25. https://doi.org/10.1186/s40461-021-00122-2

[25] Ulrich, K. T., Eppinger, S. D., & Yang, M. C. “Product desin and development (seventh). McGraw-Hill (2020).

[26] Abd Rahman, Zammeri, Saiful Bahri Mohamed, Mohamad Minhat, Mohd Shahir Kasim, Zulkifli Abd Rahman, Razwan Rohimi, Nur Hanis Hidayah Taufik, and Wawan Trisnadi Putra. "Optimisation of Structural Design in Benchtop CNC Milling Machines for Enhanced Performance and Efficiency." Journal of Advanced Research in Applied Mechanics 129, no. 1 (2024): 57-74.

[27] Rahman, Z. Abd, S. B. Mohamed, M. Minhat, A. R. Zulkifli, and M. A. M. Norman. "Design and Structural Analysis of 3-Axis CNC Benchtop Milling Machine." International Journal of COMADEM 25, no. 4 (2022).

[28] Abd Rahman, Zammeri, Saiful Bahri Mohamed, Mohamad Minhat, and Zulkifli Abd Rahman. “Design and development of 3-axis Benchtop CNC milling machine for educational purpose.” *International Journal of Integrated Engineering* 15, no. 1 (2023): 145-160. https://doi.org/10.30880/ijie.2023.15.01.013

[29] Abd Rahman, Z., S. B. Mohamed, A. R. Zulkifli, M. S. Kasim, and W. N. F. Mohamad. “Design and fabrication of a PC-Based 3 axis CNC milling machine.” *International Journal of Engineering Trends and Technology* 69, no. 9 (2021): 1-13. https://doi.org/10.14445/22315381/IJETT-V69I9P201