

Advanced Manufacturing Solutions for Traditional Motifs: Proof of Concept Development for Islamic-Indonesian Ceramic Puzzle Tile Wall

Tonny Yuniarto

Department of Industrial Engineering, Universitas Atma Jaya Yogyakarta, Jl. Babarsari, Janti, Sleman, Yogyakarta Special Region, Indonesia
tonny.yuniarto@outlook.com (corresponding author)

Eliasar Margoadi Pamungkas

Department of Mold Making, PT. Yogya Presisi Tehnikatama Industri, Jl. Cangkringan, Duri, Tirtomartani, Kec. Kalasan, Kabupaten Sleman, Yogyakarta Special Region, Indonesia
eliazarmargoadi95@gmail.com

Oktavianus Dwi Wahyu Widyanarka

PT. Gyan Kreatif Indonesia, Cebongan, Argomulyo, Salatiga, Central Java, Indonesia
hellonaruna@gmail.com

Nesrin Yesilmen

Faculty of Art and Design, Mardin Artuklu University, Diyarbakır Road Artuklu, Mardin, Turkiye
nesrinyesilmen@gmail.com

Nugroho Mamayu Hayuning Bawono

Department of Engineering Management, Institut Ilmu Hukum dan Pembangunan Papua, Jl. Karya Abri, Manokwari, West Papua, Indonesia
nugrohomb@outlook.com

Paulus Wisnu Anggoro

Department of Industrial Engineering, Universitas Atma Jaya Yogyakarta, Jl. Babarsari, Janti, Sleman, Yogyakarta Special Region, Indonesia
p.wisnuanggoro@gmail.com

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ABSTRACT

This research develops a manufacturing solution for producing Islamic-Indonesian ceramic puzzle tile walls using Computer-Aided Design and Computer-Aided Manufacturing (CAD/CAM) technology with Computer Numerical Control (CNC) router machining. Traditional ceramic production methods present a significant challenge: conventional single-piece molds result in a 35-40% failure rate during demolding when producing complex ornamental patterns with high-relief geometric designs. This leads to substantial material waste and limits commercial viability. This study introduces a modular mold system that strategically segments Islamic-Indonesian motifs into smaller, geometrically optimized components to overcome demolding challenges while preserving aesthetic authenticity. The methodology used a four-stage approach: problem identification through forum group discussion with industry stakeholders, virtual design processing using ArtCAM Pro 2015 software for pattern analysis and 3D modeling, virtual manufacturing using Autodesk PowerMill CAM software for toolpath optimization, and comprehensive

result evaluation. The research team collected 150 ornamental motifs from Islamic and Indonesian batik patterns to create ten master pattern molds and produce ceramic wall puzzle products for architectural applications. The modular mold system showed a reduction in the stuck rate from 35-40% to less than 5%, consistent dimensional accuracy with 13% shrinkage rates and error values under 0.1 mm, and a 90% reduction in production cycle time compared to traditional methods.

Keywords-Islamic-Indonesian ceramic puzzle; ArtCam Pro 2015; Islamic-Indonesian batik pattern; CNC router

I. INTRODUCTION

Ceramics are clay-based materials, shaped and heated to high temperatures until they harden [1]. This art form has existed since ancient civilizations and extends from the Mediterranean to Scandinavia. Ceramic tiles are used to decorate walls, floors, and ceilings [2, 3]. Due to their low maintenance requirements, durability, and aesthetic versatility, ceramic materials have gained renewed interest in contemporary architecture, making them suitable for various applications, from residential buildings to public spaces [4, 5]. The Indonesian ceramic industry is developing culture-based products for the creative economy, though most production remains traditional (handmade) [6]. These products are in high demand among local and international consumers. Naruna Ceramic Studio, consistently applies Science Technology Engineering and Mathematics (STEM) to its marketing activities and stakeholder relations. The company's digital marketing success through websites, social media, and e-commerce has increased consumer interest, customer engagement, and brand equity, facilitating market expansion domestically and exports to Qatar, Australia, and India [7]. Traditional ceramic manufacturing methods present significant challenges, especially when producing complex ornamental designs. The conventional slip-casting process, in which liquid clay is poured into plaster molds, depends on the artisan's skill and experience, resulting in inconsistent dimensional accuracy and limited reproducibility [8, 9]. Material property variations during the production cycle compound these difficulties. Ceramic materials undergo significant physical transformations during the drying and heating processes, such as shrinkage, from 10% to 20%, depending on the clay's composition, water content, and temperature [10]. This shrinkage is non-uniform, creating warping and dimensional distortions that are difficult to predict and compensate for in traditional mold design. These designs create undercuts and negative draft angles, which can result in mechanical lock within mold cavities during the demolding process. The stuck rate reaches 35-40%, resulting in substantial material waste and increased labor costs for mold repair and remake. Production cycles are extended, requiring 10-12 months from the initial design concept to production-ready molds. Furthermore, each piece requires inspection for dimensional accuracy, surface finish quality, and structural integrity, creating significant difficulties for ceramic manufacturers who want to increase production of culturally significant ornamental designs while maintaining artistic authenticity. Digital technologies have been introduced in ceramic manufacturing, using various CAD/CAM techniques, while CNC processing has been used with superior marginal fit compared to conventional casting methods [11].

Authors in [12] examined the technical feasibility of applying subtractive manufacturing to ceramic materials for functional applications, though not artistic ones. The transition to artistic and architectural ceramics was made with advances in 3D scanning and reverse engineering technologies. Researchers developed methods for digitizing traditional ceramic artifacts using structured light scanning, enabling the preservation and reproduction of cultural heritage pieces [13]. However, this approach was mainly for documentation purposes and did not address manufacturing scalability challenges. Additive manufacturing has emerged as an alternative production method for ceramic components. Authors in [14, 15] used Digital Light Processing (DLP) technology for producing complex ceramic geometries, achieving high resolution and design freedom. While these additive approaches offer advantages in geometric complexity, they are limited in terms of production speed, material costs, and surface finish quality, making them impractical for the large-scale production of architectural tiles [16, 17]. The application of CNC machining to ceramic mold production specifically represents a more recent development that bridges digital design capabilities with established manufacturing processes [18, 19]. Authors in [20, 21] developed an integrated workflow that converts 2D image patterns into 3D solid models suitable for the CNC machining of ceramic master molds. Their methodology used ArtCAM software to transform JPEG images into relief surfaces with controlled depth profiles and subsequently generated toolpaths for CNC router machines.

The dimensional accuracy was within 1.00 mm–2.00 mm and successfully managed mold shrinkage below 15% through empirical compensation factors, while the design-to-production time was reduced by 90%, from 10–12 months to approximately 1–1.5 months. However, a critical analysis of their work reveals limitations that constrain its applicability to complex, traditional motifs: the image-to-3D conversion process was effective for patterns with relatively simple relief geometries and moderate depth variations but struggled with the intricate, interlocking elements and deep undercuts, characteristic of Islamic geometric art. Automated relief generation from 2D images could not distinguish between foreground and background elements in complex patterns adequately, resulting in ambiguous depth assignments and compromised aesthetic fidelity. The mold designs used the conventional single-piece approach. However, despite the improved manufacturing precision, the main demolding challenges of complex geometries remained unsolved. Finally, they achieved technological feasibility with basic ornamental patterns, but their validation did not extend to high-relief designs with the geometric complexity typical of traditional Islamic-Indonesian ceramics. Authors in [22] examined advanced CNC strategies for ceramic processing, emphasizing

the importance of toolpath optimization and multi-axis machining for achieving complex surface textures. It was recognized that the geometric complexity of artistic ceramics requires more than just precise machining capabilities, that is, mold design strategies to address the physical constraints of ceramic material behavior during production cycles. The innovation of this study lies not in the modular mold concept as a general principle but in developing a specific digital workflow that systematically applies modularity to overcome the challenges of producing high-relief Islamic-Indonesian ceramic art. Pattern analysis algorithms were used to automatically identify optimal segmentation boundaries based on geometric complexity analysis, including draft angle calculations that consider aesthetic requirements and demolding constraints, as well as parametric mold design rules to ensure that modular components maintain precision while adapting to ceramic shrinkage behavior. The workflow includes specialized toolpath generation strategies that optimize surface finish quality on high-relief features while minimizing machining time and allowing ceramic manufacturers to systematically convert intricate traditional designs into feasible modular mold systems. The methodology provides a replicable framework that can be applied to other complex traditional ceramic arts worldwide, not just Islamic-Indonesian patterns. The modular nature of ceramic tiles simplifies the installation process, reducing labor costs and time [23], while enabling flexibility in design and application to accommodate various architectural styles and requirements [24, 25]. Authors in [26] proved, by using historical applications in Seville and Samarkand, the significant role ceramics play in the visual appeal of buildings. This research advances STEM integration in traditional craft industries by providing ceramic manufacturers with a replicable framework to adopt digital fabrication technologies while preserving cultural heritage motifs.

Proof of concept (PoC) development is critical for validating innovative manufacturing technologies before full-scale industrial implementation [27], while quantifying performance improvements under controlled conditions, allowing for early detection of issues that could arise during production [28, 29]. This phase involves selecting representative Islamic-Indonesian motifs of varying geometric complexity, applying the full digital workflow from pattern analysis to CNC machining of master molds, and producing ceramic tiles with these molds under standard production conditions. Critical performance metrics were evaluated, reducing the stuck rate (from 35-40% to below 5%), ensuring dimensional accuracy compared to digital design specifications, assessing surface finish quality, evaluating high-relief features, and measuring total production cycle time from design to finished tiles. This study addresses the critical gap between digital manufacturing capabilities and the specific requirements of complex, traditional ceramic art production, by developing a digital workflow that decomposes complex Islamic-Indonesian patterns into optimized, modular mold components, using and validating CNC machining strategies that achieve aesthetic fidelity and manufacturing practicality for high-relief ornamental designs, quantifying performance improvements in reduction of the stuck rate, dimensional

accuracy, and production cycle time compared to conventional approaches, and demonstrating practical application by producing architectural ceramic tiles suitable for commercial installation.

II. MATERIALS AND METHODS

This research used the PoC design methodology to systematically validate the modular mold system for Islamic-Indonesian ceramic puzzle tiles. The five-stage method helps ensure that the design aligns with real business needs and is technically feasible, ensuring that the right stakeholders are involved at each step [27]. This framework was chosen because it addresses the study's core challenge of turning a new manufacturing idea into a practical, market-ready solution while avoiding the unnecessary expenditure of time and resources on unvalidated concepts. A four-stage methodology was applied to develop ceramic wall tiles using CAD/CAM technology, as presented in Figure 1. The first stage used forum group discussions to identify problems and assess manufacturing limitations in ceramic production. The second stage involved processing virtual designs with ArtCAM Pro 2015 software. The digital files converted the 2D model tile wall data and processed them through Netfabb Basic software for mesh verification. Design parameters, including geometric details and precision specifications, were established during this phase to ensure manufacturing compatibility. The third stage included virtual manufacturing processes, beginning with the creation of a 3D object and the setting of block parameters. Then, tooling design configuration was performed, followed by toolpath strategy optimization using Autodesk PowerMill CAM software. Toolpath simulation verified the accuracy of the machining process before generating the NC code for the CNC router. Design parameters included dimensional specifications, precision tolerances, tooling characteristics, and toolpath strategies based on the properties of the ceramic material. The final stage involved evaluating the results through analysis and discussion. Data collection focused on dimensional accuracy, production time, and manufacturing consistency. The CAD/CAM approach was compared with traditional handmade methods to determine its effectiveness in improving precision manufacturing, production efficiency, and quality control. Statistical analysis evaluated shrinkage rates and dimensional variations throughout the manufacturing process, from digital design to the final ceramic products.

A. Machining Parameters

The CNC machining process for producing ceramic master molds employed a multi-stage strategy optimized to achieve manufacturing efficiency and surface quality requirements. During the roughing stage, an offset area clearance strategy with offset-all tool movement (progressing from the perimeter to the center) was used to efficiently remove bulk material. This operation used a 6-mm-diameter end mill cutter at a spindle speed of 8,500 RPM with a feed rate of 600 mm/min. The Depth of Cut (DoC) was set at 1 mm, and the Stepover (SO) was set at 4.5 mm to maintain a 0.3 mm thickness allowance for subsequent finishing operations. This aggressive roughing strategy significantly reduced machining time while leaving sufficient material for the precision finishing stages. The semi-finishing stage transitioned to an optimized constant

Z strategy to refine the surface geometry and prepare it for the final finishing stage. This operation used a 3 mm ball-nose cutter at 8,500 RPM with a reduced feed rate of 400 mm/min to improve surface quality. The SO was decreased to 1 mm, and the thickness allowance was set to 0.1 mm. The DoC was

adjusted to match the remaining thickness from the roughing operation. This intermediate stage balanced material removal efficiency with surface preparation requirements for complex geometric features.

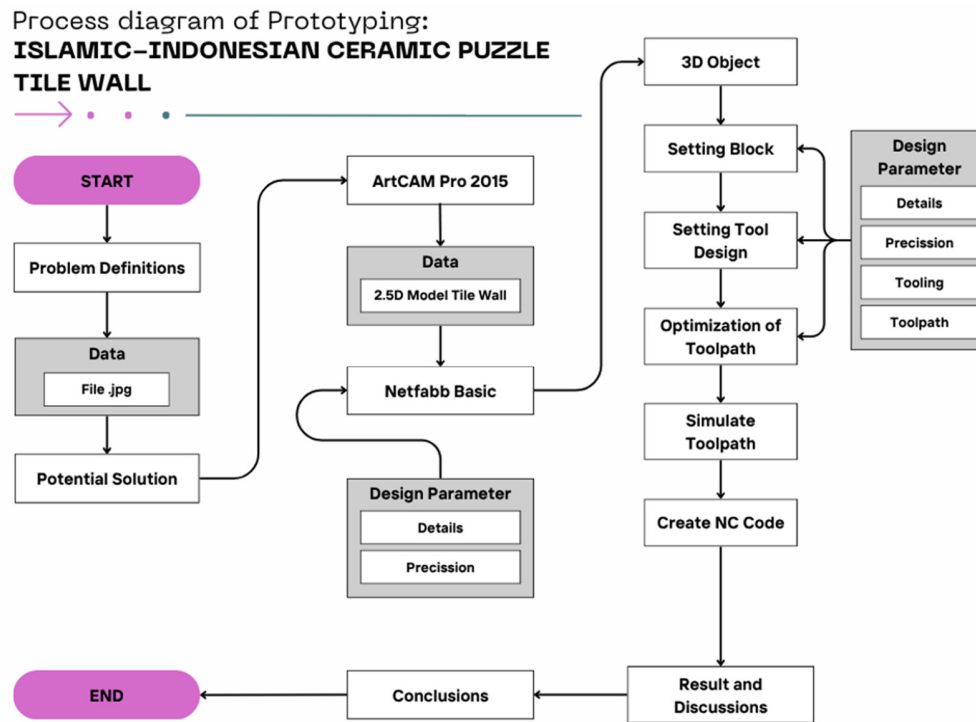


Fig. 1. Research methodology.

The finishing stage used a steep and shallow strategy, which was designed specifically to achieve optimal surface quality on inclined and curved surfaces, which are characteristic of high-relief ornamental patterns. This critical operation used a 1-mm-diameter ball-nose cutter that operated at 8,500 RPM with a conservative feed rate of 300 mm/min. The thickness allowance was reduced to zero, and DoC was automatically adjusted to remove all remaining material. The SO was set at a maximum of 10% of the cutter's diameter (0.1 mm). The DoC step was further refined to 0.05 mm (half the SO value) to ensure a smooth surface finish on inclined and curved geometries. Corner regions, which are particularly challenging in complex ornamental patterns, required specialized attention through a corner finishing strategy. This operation used the same 1-mm-diameter ball-nose cutter at 8,500 RPM with a feed rate of 300 mm/min. It referenced the previous semi-finishing tool's diameter (3 mm) to establish a 3-mm offset from the corner edges. This ensured complete material removal in intricate geometric intersections without compromising surface integrity.

III. RESULTS AND DISCUSSION

The study collected 150 ornamental motifs from Islamic and Indonesian batik patterns from multiple sources. The main data collection sites were *Türk Tezyini San'atlarında Motifler* [30], a book describing many Islamic motifs; the *Al Huda*

Mosque in Jakarta [31]. These motifs were documented as digital photographs, as shown in Figure 2. The collected motifs were classified chronologically and geographically based on their origin and usage period. Classifications included Turkish (Iznik), Persian (Safavid), and local Nusantara influences (classical Yogyakarta and Solo batik). Each motif underwent a formal analysis that examined constructive geometry, ratios, scale, line thickness, pattern density, and dominant colors. This classification system enabled an understanding of the visual characteristics and pattern structures required for digital reconstruction. Integrating Islamic Geometric Patterns (IGP) with Indonesian Batik Motifs (IBM) resulted in 2D and 3D ceramic wall puzzle designs with precise, accurate embossed patterns suitable for mass production. The invention process included creating geometric files from 2D objects (photos or images) that were processed through artistic CAD software into 2D vectors. These vectors were then generated into 3D design models for ceramic wall puzzle master products. Verification using Netfabb Basic software confirmed the quality of the mesh formation during the artistic CAD generation process. This verification step preceded the creation of master pattern molds on 3D printers. The manufacturing process produced master pattern molds for ceramic wall motifs, which were subsequently used to create core and cavity molds in the ceramic industry using plaster techniques with gypsum materials.

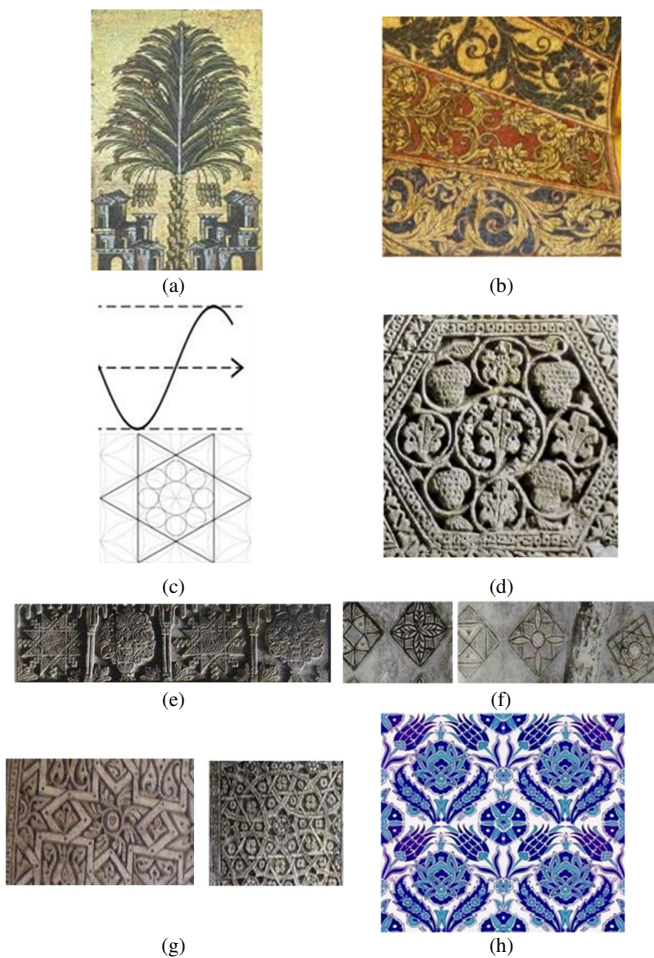


Fig. 2. (a) Dates tree at Umayya Mosque, (b) mihrab in Cordoba, (c) abbasiya ornament; (d) 9th century relief from Samarra, (e) great mosque of Kairouan, (f) basic geometric shape of Islamic interior, (g) ibn-tulun mosque in Egypt, (h) turkish Iznik style.

A. Iznik Ceramic Pattern

Iznik ceramics, as illustrated in Table I, originating from the town of İznik in northwestern Turkey [32], represent a significant artistic tradition within the Ottoman Empire [33], flourishing between the late 15th and early 17th centuries. They played a crucial role in the empire's cultural and artistic expression, serving as symbols of imperial power and sophistication [34], reaching their zenith under Sultan Süleyman the Magnificent [35]. These ceramics were functional and decorative, enhancing the aesthetic appeal of imperial and religious architecture [36]. Integrating selected Iznik motifs with Indonesian batik patterns is based on their shared emphasis on geometric rhythm and botanical forms. Together, they enrich the cultural dialogue between Eastern and Southeast Asian traditions. The chosen motifs represent some of the most technically demanding and visually significant elements of the Iznik pattern. Peony flowers became central to Iznik decoration during the 16th century, symbolizing abundance and prosperity in Ottoman culture [37, 38]. Their large, multi-petaled forms often display layered compositions that create a strong sense of depth. From a

production perspective, the overlapping petals create undercut areas that necessitate advanced mold design with multiple parting lines and carefully planned draft angles to ensure clean release during demolding. Elongated bilobed leaves illustrate the transition from geometric abstraction to a more naturalistic representation [39, 40]. Their flowing, organic lines contrast with the rigid frameworks of earlier Ottoman ornamentation. Manufacturing these motifs poses challenges because of the narrow connections between lobes, which concentrate stress, making them susceptible to cracking or thermal shock during heating.

TABLE I. IZNIK PATTERN ORNAMENT IMAGE

Source	Ceramic Puzzle	Islamic Pattern Evolution	Explanation
		 Peony Flower (Safawi, 1501 - 1736)	Tiered floral forms exhibiting similar ornamental configurations.
		 Elongated Bilobed Leaf (Ottoman, 1290 - 1923)	Elongated foliate ornamental forms divided into symmetrical left and right segments.
		 Peony Flower (Safawi, 1501 - 1736)	Similar ornamental configurations of the central floral elements.
		 Lotus Flower (Safawi, 1501 - 1736)	Comparable fundamental floral forms across hierarchical levels and generated imagery.
		 Saz/Long Dentate/Serrate Leaf (Ottoman, 1290 - 1923)	Foliate sections containing similar miniature floral elements.
		 Buds (Safawi, 1501 - 1736)	Leaf terminals featuring similar budding formations.

Lotus flowers, with their clear links to Persian and Central Asian influences, embody the cosmopolitan character of Ottoman art [41]. Their radial symmetry and recessed central forms require precise CNC machining to ensure uniform depth and surface quality while maintaining structural integrity. Saz leaves, also known as long, dentate, or serrated leaves, highlight the botanical sophistication of İznik design [42]. Their intricate outlines require precise micro-machining to be reproduced accurately, especially when translated into relief on

ceramic surfaces. Finally, bud motifs complete the organic vocabulary, symbolizing growth and renewal [43]. Their enclosed geometries present challenges in slip casting because they require careful venting systems to avoid air entrapment and ensure complete ceramic formation. The final products, combine Turkish Iznik style with traditional batik aesthetics while incorporating modern manufacturing precision. Batik motifs, representing Indonesian cultural heritage, were successfully translated into ceramic wall designs that combine art and technology. The diverse batik motifs reflect the philosophies of various Indonesian customs and cultures and include themes of human figures, animals, abstract forms, and geometric patterns. This approach preserves the historical significance and narrative elements of Indonesian batik, enabling its integration into modern architecture, particularly in mosque buildings.

B. Digital Conversion Process

Figure 3 presents the digital conversion using ArtCAM 2015R2 software, which can generate 2.5-dimensional relief models from 2D images. This 2.5D modeling creates raised surface reliefs that provide visual depth resembling manual carving. This methodology converts .jpg images into 3D solid models in .stl format for ceramic applications [6, 21, 43]. The conversion process first transforms .jpg images into 2D vectors and then processes them into solid digital models in .stl format. Manual and semi-automatic tracing ensured the accurate capture of visual elements, including smooth curves, symmetrical details, and micro-ornaments that are difficult to replicate manually. Users could adjust the vector resolution and control the digital carving depth to produce outputs that closely resemble the original patterns [44].

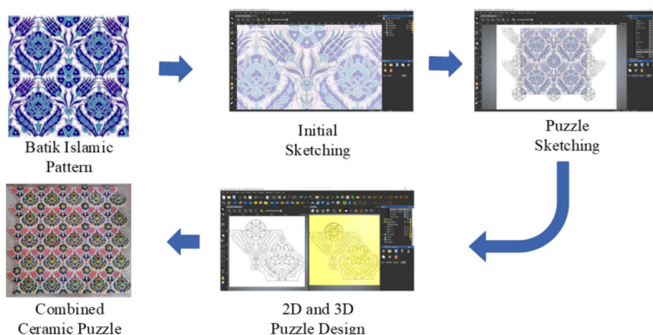


Fig. 3. Digital conversion process.

C. Modular Design Implementation

Each tile pattern used modular design principles based on the evolution and diversity of Islamic ornamentation [2]. The Iznik-inspired motifs were divided into structural components: center, corner, edge, and connecting elements, such as cloud ornaments or floral borders. This modular approach established a direct link to traditional Islamic decorative systems. The design included peony flowers in puzzle 1, small flowers in puzzle 2, large and small flowers in puzzle 3, and long leaves in puzzles 2 and 3. To ensure precision during production, the modular design, as displayed in Figure 4, was supported by a locking system built into the master mold. Registration pins, guide slots, and mechanical stops secured the position of the

mold sections within the core-cavity assembly, minimizing dimensional deviations during casting. The system prevented displacement during gypsum pouring and ensured the accurate alignment of decorative elements across repeated cycles. The original base design included draft angles where the upper sections were wider than the lower ones, creating undercuts that hindered machining. Eliminating these angles enabled successful CNC processing while preserving design integrity. This modification highlights the importance of design-for-manufacturing principles in ceramic production.

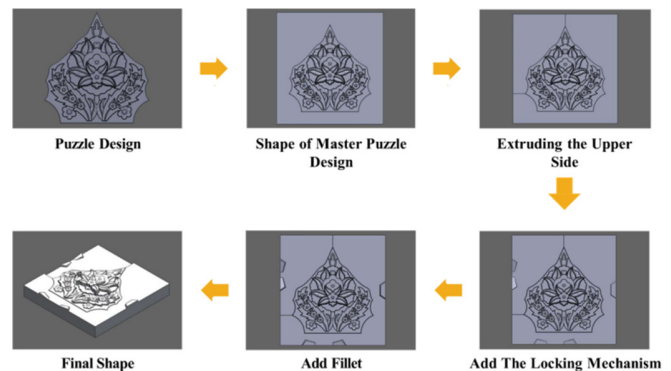


Fig. 4. Modular design ceramic puzzle.

The master pattern mold system, portrayed in Figure 5, consisted of ten parts distributed across three puzzle configurations. Puzzle 1 used two molds, while puzzles 2 and 3 each required four. This segmentation strategy offered several benefits, including reduced manufacturing complexity, improved quality control through inspection of individual parts, and greater production flexibility. The modular design enabled seamless pattern repetition across wall surfaces and allowed for flexibility in color and texture combinations for individual tiles. This approach simplified maintenance and repair because damaged sections could be replaced without dismantling the entire installation. Integrating IBM with IGP demonstrated strong compatibility by combining floral elements, such as leaves, flowers, branches, and roots, into unified ornamental compositions with embossed textures. The modular system improved production efficiency by reducing material waste through the selective manufacturing of only the necessary components. Standardized connection mechanisms and simplified assembly procedures enhanced installation speed. The design's flexibility supported customization for various architectural applications. At the same time, the use of standardized processes helped maintain cost-effectiveness in large-scale manufacturing.

D. Prototyping and Fabrication

Figure 6 illustrates the rapid prototyping process, which used CNC machining technology to create master molds from tooling board, polyurethane, and Ebalta chemical wood, enabling the precise reproduction of intricate Islamic-Indonesian ornamental patterns with fine detail retention. The master molds were scaled 15% larger than the final product dimensions to compensate for clay shrinkage during the firing process. The aim of CNC machining is to achieve high-precision surface finishes suitable for direct mold contact

applications [45]. Polyurethane chemical wood was chosen because of its strength and durability; the master mold must have low abrasion to withstand multiple casting cycles while maintaining dimensional accuracy and fine detail retention throughout production runs. Ceramic puzzle fabrication followed a systematic, six-stage process, as shown in Figure 7.

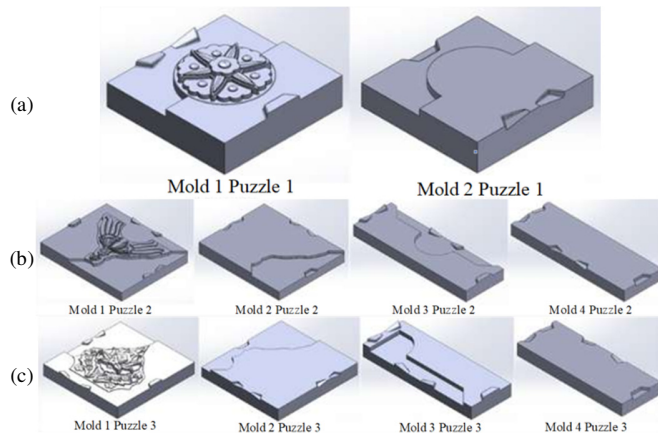


Fig. 5. Modular master mold of: (a) puzzle 1, (b) puzzle 2, (c) puzzle 3.

First, the puzzles were cast by pouring liquid clay into prepared gypsum molds containing Islamic-Indonesian motif patterns. The modular mold system enabled the simultaneous production of multiple puzzle pieces with consistent dimensional accuracy. Second, the puzzles were carefully demolded to prevent damage to the intricate embossed patterns. The modular design with removable side sections facilitated this process and reduced the risk of pattern distortion or breakage during extraction. Third, the dried ceramic puzzles underwent an initial air-drying process to remove excess moisture before heating. Fourth, the ceramic puzzle underwent heating in a kiln at approximately 950°C. This created the first fired state, which has the characteristic porosity necessary for glaze absorption. This stage produced initial dimensional shrinkage while maintaining pattern definition. Fifth, the ceramic puzzles were colored by applying glazes to achieve the desired aesthetic effects. Three distinct puzzle configurations (puzzle 1, 2, and 3) received different color treatments that highlighted their individual motif characteristics. Sixth, the final ceramic puzzle products underwent glaze firing at approximately 1,250°C, completing the manufacturing process. This final firing stage achieved full vitrification, final dimensional specifications, and complete color development. This systematic approach ensured consistent quality and maintained the integrity of the Islamic-Indonesian ornamental patterns throughout the manufacturing cycle.

Figure 8 and Table II depict the dimensional data of three ceramic samples, which display consistent shrinkage patterns during manufacturing. All measurement points record 13% total shrinkage from the CAD design to the final product, across different feature sizes and sample configurations. The manufacturing process displays distinct shrinkage phases. Early stages, from the CAD design to the CNC process to the gypsum mold, show minimal changes (typically under a 0.03 mm variation).

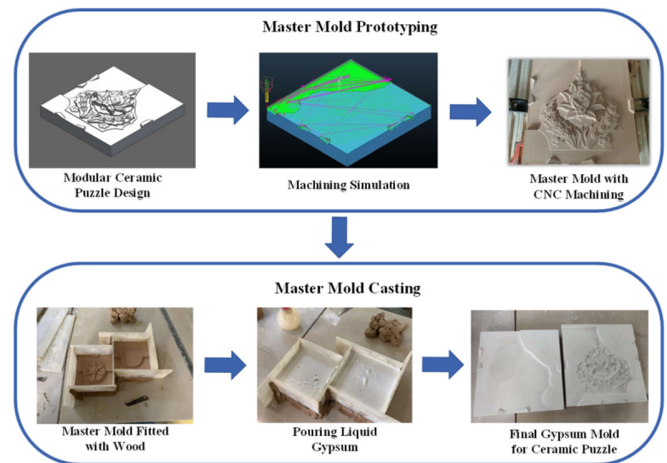


Fig. 6. Master mold prototyping and casting.

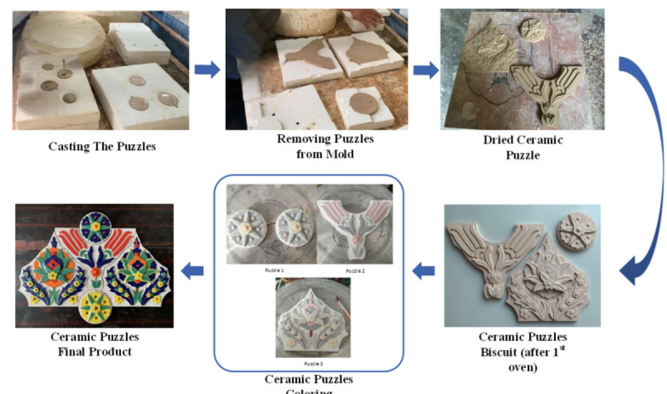


Fig. 7. Ceramic puzzle fabrication.

The clay forming stage maintains dimensions, with slight decreases of 0.01–0.02 mm. Major shrinkage occurs during the firing processes. Clay-to-biscuit firing produces approximately 6–7% shrinkage, and final glazing adds another 6–7%, reaching the total 13% reduction. This pattern applies uniformly to all measured features, regardless of size. Small features, like 7.61 mm (puzzle 1, point F), and large dimensions, like 215.63 mm (puzzle 2, point A), both demonstrate identical shrinkage percentages. This enables accurate design compensation, allowing manufacturers to scale CAD models by 15% to account for the 13% reduction and ensure that the final products match the target dimensions. The analysis of dimensional accuracy shows that all measured points fall within ± 2 mm of the theoretical values, which are based on 13% shrinkage compensation. The largest difference, 0.02 mm, was observed in puzzle 2, point A (predicted: 187.48 mm; actual: 187.50 mm), which corresponds to a relative error of only 0.011%. The comparison of feature sizes reveals no significant relationship between initial dimension and shrinkage accuracy, as small features (8.25 mm–14.53 mm) behave identically to larger features (86.23 mm–215.61 mm). This supports the assumption that ceramic shrinkage is governed by volumetric scaling rather than surface-related effects.

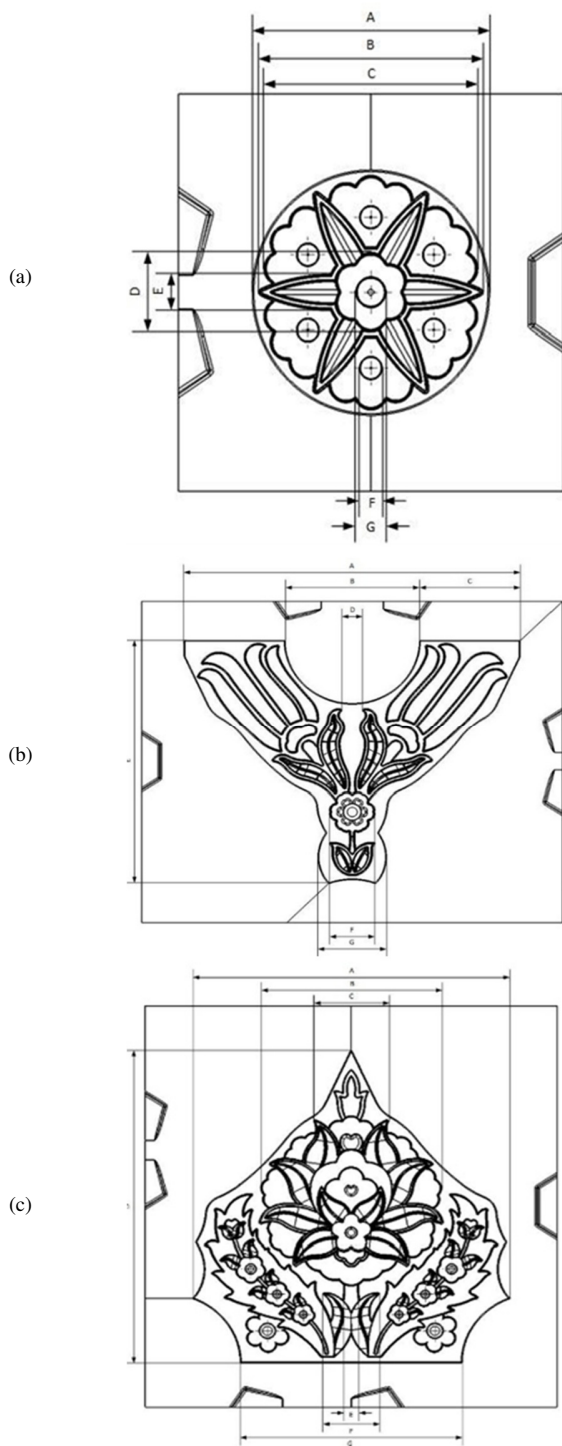


Fig. 8. Dimension analysis of ceramic puzzle: (a) puzzle 1, (b) puzzle 2, (c) puzzle 3.

The CNC-based master mold provides greater dimensional consistency than traditional manual methods, with a standard deviation of 0.015 mm across all validation points (well below the ± 2 mm tolerance). This enables the prediction of final ceramic dimensions with high confidence, ensuring efficient and repeatable production. Process stability is demonstrated by

consistent shrinkage across three puzzle geometries of varying complexity without significant deviations or irregularities. This confirms maintained process control throughout the clay preparation, forming, and firing stages, and demonstrates the potential for scalability in commercial applications requiring accurate dimensions and geometric detail in Islamic-Indonesian ornamental tile patterns.

E. Final Product

Figure 9 shows the completed Islamic-Indonesian ceramic puzzle tile wall, which highlights the successful integration of traditional ornamental motifs with modern CNC machining technology. The assembled display features intricate geometric designs incorporating traditional Islamic elements, including stylized floral motifs, circular medallions, and interlocking arabesque patterns. These elements are presented in deep blue, emerald green, golden yellow, and burgundy red against a white background. Each ceramic tile exhibits precise dimensional accuracy and reliable interlocking capability, confirming the effectiveness of the modular design concept. The puzzle-like configuration produces a continuous flow of patterns across tile boundaries, minimizing visible joints and maintaining visual coherence. The relief surfaces have consistent depth and fine detail, demonstrating the advantages of CNC-machined master molds over traditional handcraft techniques. The final ceramic puzzle consists of multiple interlocking tiles that form a unified decorative surface. The uniformity of color and glaze finish across all tiles reflects stable glazing and firing conditions during production. The assembled wall tile shows no visible defects, dimensional variations, or gaps between pieces, demonstrating that the target specifications were achieved.

IV. CONCLUSIONS

This study examined the use of artistic Computer-Aided Design and Computer-Aided Manufacturing (CAD/CAM) technology with Computer Numerical Control (CNC) router machining processes for designing and producing ceramic wall puzzle master pattern molds. The study successfully generated ten 3D model master pattern molds, ten master pattern molds made of Ebalta material, and ceramic wall puzzle products measuring 100 cm x 100 cm, all of which were manufactured at Naruna Ceramic Studio. Dimensional analysis comparing the shrinkage rates from the 3D modeling design phase in SolidWorks with the final ceramic wall puzzle products revealed a shrinkage ratio of 13%, with error values of less than 0.1 mm. This level of precision demonstrates an accurate correlation between the design specifications and the manufactured products, as evidenced by the quality of the final printed ceramic wall products. Integrating STEM-based artistic CAD/CAM technology successfully overcame the limitations of traditional ceramic manufacturing, particularly in producing complex embossed ornamental patterns with geometric precision. This methodology enables the mass production of customized ceramic products that maintain cultural authenticity through Indonesian batik and Islamic geometric motifs. This technological advancement supports Indonesia's creative economy sector by combining traditional craftsmanship with modern manufacturing capabilities and creating opportunities for domestic market expansion and international exports.

TABLE II. DIMENSION ANALYSIS

Part of pattern	Point of Measure	Raw clay model (mm)	With 13% shrinkage (mm)	Lower limit (-2 mm)	Final ceramic tile (control limit)	Upper limit (+2 mm)	Decision
Puzzle 1	A (large feature)	86.23	75.02	73.02	75.01	77.02	Safe to fabricate
	F (small feature)	7.58	6.59	4.59	6.62	8.59	Safe to fabricate
Puzzle 2	A (large feature)	215.61	187.48	185.48	187.50	189.48	Safe to fabricate
	D (small feature)	14.53	12.64	10.64	12.65	14.64	Safe to fabricate
Puzzle 3	D (large feature)	195.05	169.63	167.63	169.64	171.63	Safe to fabricate
	E (small feature)	8.25	7.18	5.18	7.19	9.18	Safe to fabricate



Fig. 9. Final product of ceramic puzzle.

Future research should systematically document and digitize these diverse patterns, analyze their geometric complexities, and establish optimization parameters for each pattern within the modular mold design framework. Additionally, integrating multiple indigenous motifs into unified ceramic tile systems could result in innovative fusion designs that celebrate Indonesia's multicultural heritage while preserving the authenticity of each pattern. To achieve this, the digital workflow must be expanded to include more sophisticated pattern recognition algorithms, enhanced geometric analysis tools, and flexible parametric design rules that can adapt to varying cultural aesthetic requirements. Furthermore, it should explore adaptations for other cultural traditions, including Chinese, Middle Eastern, and European decorative systems. Investigating alternative ceramic compositions and optimizing heating schedules could further improve the manufacturing process while maintaining dimensional precision and cultural aesthetic integrity.

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