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AI-Driven Prediction of Square-Hole Laser Trepanning Performance in AA7075/15%SiC/15% Glass Fiber Hybrid Composites Using Taguchi–ANOVA and Deep Neural Networks

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Abstract

Hybrid AA7075 composites reinforced with 15% silicon carbide (SiC) and 15% glass fiber were fabricated via the stir casting technique to improve machining and structural performance. The addition of dual reinforcements into the aluminum matrix was aimed at enhancing hardness, thermal stability, and surface quality during non-traditional drilling operations. Square-hole drilling was performed using a laser trepanning process, and the key responses—hole size accuracy, surface roughness, and taper angle—were systematically investigated. Using a Taguchi L25 orthogonal array integrated with ANOVA, trepanning speed was identified as the most significant factor influencing hole size and taper angle, while laser power was the primary determinant of surface roughness. Among the composites tested, AA7075 reinforced with 15% SiC and 15% glass fiber exhibited superior drilling performance compared with lower reinforcement levels, highlighting the synergistic effect of fiber–particle hybridization. To enhance predictive capability, artificial intelligence (AI) and deep learning models were applied to the experimental data. Random Forest regression and artificial neural networks (ANN) demonstrated close alignment with observed results, while deep neural networks (DNN) achieved the highest predictive accuracy, with regression coefficients above $R^2 > 0.95$ *and minimized error indices. This integration of Taguchi–ANOVA optimization with AI-based prediction constitutes the novelty of the present work, bridging experimental design and intelligent modeling. The findings present a robust pathway for intelligent process planning and adaptive control in precision machining of hybrid composites, particularly in aerospace and structural applications.*

Keywords: AA7075 hybrid composites, artificial intelligence, deep neural networks, glass fiber, laser trepanning, predictive machining, SiC, square-hole drilling, stir casting, Taguchi–ANOVA

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INTRODUCTION

Lightweight, high-strength aluminum alloys are widely used in aerospace, automotive, and defense applications due to their excellent strength-to-weight ratio, corrosion resistance, and thermal stability [1]. Among these, AA7075 is particularly attractive because of its superior mechanical properties, though its machinability is often limited when processed under demanding conditions. Reinforcing AA7075 with ceramic and fiber phases has been shown to significantly improve its wear resistance, dimensional stability, and high-temperature performance [2]. In particular, silicon carbide (SiC) particles enhance hardness and thermal conductivity, while glass fiber increases fracture toughness, producing hybrid composites with a favorable balance of strength, ductility, and machinability [3]. With the growing need for precision features in advanced structures, non-traditional machining methods, such as laser drilling have gained prominence [4]. The laser trepanning process, in particular, enables the production of complex geometries, such as square and non-circular holes with high dimensional accuracy and repeatability. However, the quality of drilled features—including hole size accuracy, taper formation, and surface roughness—depends strongly on process parameters such like laser power, trepanning speed, and standoff distance [5]. Conventional statistical approaches like Taguchi design of experiments and analysis of variance (ANOVA) have been widely applied to optimize laser machining responses [6, 7]. While effective in identifying dominant parameters, these methods are often limited in predicting nonlinear, multi-response behaviors that arise in hybrid composites [8]. Recent advances in artificial intelligence (AI) and deep learning have provided powerful tools for predictive modeling in manufacturing. Artificial neural networks (ANN) have been applied to capture nonlinear parameter–response interactions, while deep neural networks (DNN) extend this capability by learning complex hierarchical relationships in experimental datasets [9]. Convolutional neural networks (CNN), on the other hand, enable image-driven assessment of machining quality, such like predicting geometry and heat-affected zones directly from drilled-hole images. Despite these advances, very limited research has integrated statistical optimization with hybrid deep learning architectures for predictive modeling of square-hole laser trepanning in hybrid AA7075 composites. To address this research gap, the present study focuses on AA7075 hybrid composites reinforced with 15% SiC and 15% glass fiber, fabricated through stir casting. A Taguchi L25 orthogonal array was employed to design laser trepanning experiments, and ANOVA was used to determine the statistical significance of process parameters on hole size, taper angle, and surface roughness [10]. Beyond statistical optimization, ANN, DNN, and CNN models were developed to predict drilling responses, combining numerical and image-based approaches [11]. The novelty of this work lies in coupling Taguchi–ANOVA-based process optimization with hybrid deep learning architectures to establish an intelligent, adaptive, and accurate framework for predictive machining. The outcomes provide a pathway toward advanced process planning, adaptive parameter control, and reliable performance prediction in square-hole laser drilling of hybrid composites, with direct relevance to aerospace and high-performance structural applications.

MATERIALS AND METHODS

Base material used in this research was commercial AA7075 aluminum alloy, which is widely recognized for its superior strength-to-weight ratio, corrosion resistance, and the extensive applications in aerospace and automotive components. However, its relatively low wear resistance and poor high-temperature performance limit its use in advanced machining operations. To overcome these shortcomings, silicon carbide (SiC) particles were incorporated as a ceramic reinforcement, exploiting their high hardness, thermal conductivity, and stability under laser processing. In parallel, short chopped E-glass fibers were introduced to enhance fracture toughness and delay crack propagation. The synergistic combination of SiC and glass fibers was selected to create a hybrid reinforcement system that combines the stiffness and wear resistance of ceramics with the ductility and energy absorption capacity of fibers [12]. The reinforcement proportion was fixed at 15% SiC and 15% glass fiber, representing an optimized balance between mechanical performance and processability that is not widely reported in prior literature. Hybrid composites were fabricated using the stir casting method, which provides uniform distribution of reinforcements and scalability for industrial production. The fabrication procedure was carefully optimized to maintain reinforcement integrity and ensure homogeneous dispersion. AA7075 ingots were melted in a resistance furnace at a controlled temperature above the alloy's liquidus point. Before addition, SiC particles (mean size 35–45 µm) and E-glass fibers (3–5 mm length) were preheated to 250 °C to improve wettability and minimize moisture absorption. A mechanical stirrer operating at ~600 rpm was used to generate a stable vortex in the molten alloy. SiC particles were introduced gradually into the vortex, followed by glass fibers, which were dispersed under gentle agitation to prevent clustering and fiber degradation. Stirring was continued for 10 minutes to ensure homogeneity before the melt was poured into preheated steel molds and allowed to solidify under ambient conditions. The solidified billets were machined into specimens suitable for laser trepanning. This fabrication strategy, which combines ceramic and fiber reinforcements in equal proportions, provides a novel material system with enhanced machinability and predictable response to laser processing.

LASER TREPANNING EXPERIMENTS

Square-hole drilling trials were performed on the fabricated composites using a CNC-controlled Nd: YAG laser trepanning system. This non-traditional machining technique was selected for its ability to generate non-circular features with high precision and minimal tool wear, a significant advancement over mechanical drilling. The experiments considered three process parameters: trepanning speed (20–100 mm/min), laser power (65–85 W), and standoff distance (182–190 µm). The Taguchi L25 orthogonal array was employed to systematically vary parameters across 25 trials, ensuring efficient exploration of the process window. After drilling, hole entry size was measured using a high-resolution optical microscope, surface roughness was quantified using a contact profilometer, and taper angle was determined from cross-sectional images. Measurements were taken at four axial depths (x = 0, 5, 10, and 15 mm) to capture variations along the hole profile. The integration of square-hole trepanning with hybrid composites represents a novel contribution, as few studies have reported the precision drilling of hybrid AA7075/SiC/glass systems with such geometric complexity [13].

Figure 1 illustrates the experimental framework and outcomes of laser trepanning performed on AA7075/SiC–glass fiber hybrid composites. The schematic (a) depicts the setup used to deliver a focused laser beam onto the workpiece for square-hole drilling, while the optical micrographs (b) confirm the successful fabrication of multiple square holes with uniform geometry. The results demonstrate the capability of the laser trepanning process to produce precise, repeatable square holes in hybrid composites, validating the method's effectiveness for advanced machining of aerospace-grade materials.

Experimental Design and Statistical Analysis

The Taguchi L25 design allowed the evaluation of factor effects with minimal experimental effort. The collected data were subjected to analysis of variance (ANOVA) to quantify the contribution of trepanning speed, laser power, and standoff distance to the observed responses. Results indicated that trepanning speed was the dominant factor influencing both hole size and taper angle, while laser power had the highest contribution to surface roughness. High coefficients of determination (R^2 = 91.63% for hole size; 87.66% for taper angle; 77.23% for surface roughness) confirmed the adequacy of the models. This statistical framework not only validated experimental trends but also established a benchmark dataset for predictive modeling, which is a step forward compared to traditional empirical studies.

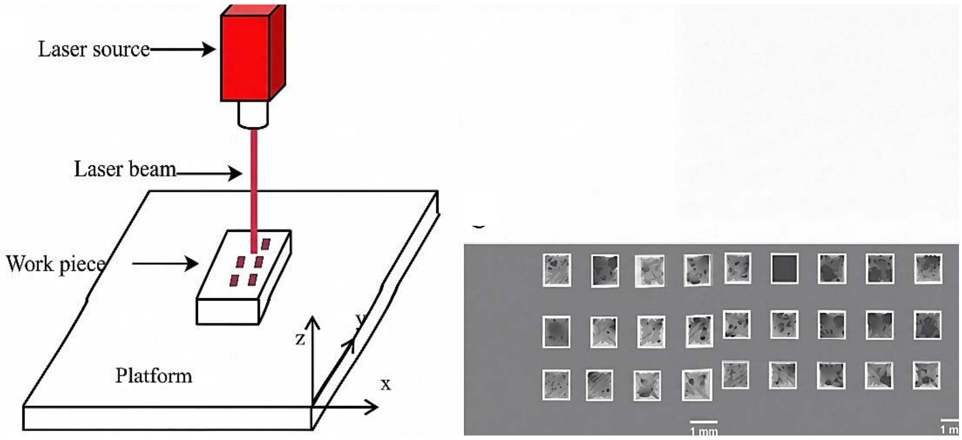

Figure 1. Schematic representation of the laser trepanning setup (a) and optical micrographs of fabricated square holes in aa7075/sic–glass fiber hybrid composites (b).

Table 1 outlines the selection of key laser trepanning parameters and their corresponding levels adopted for the experimental investigation. The parameters were chosen based on their direct influence on the geometry and quality of drilled square holes. Trepanning speed (20–100 mm/s) was varied across five levels to capture its dual role in controlling material removal rate and heat input, thereby influencing both dimensional accuracy and taper formation. Laser power (65–85 W) was systematically adjusted, as it governs the thermal energy delivered to the composite; lower power resulted in incomplete penetration and reduced MRR, while higher power enhanced productivity but also introduced excessive taper. Standoff distance (182–190 mm) was included to assess beam–material interaction stability, where shorter distances produced poor surface finish due to turbulent melt ejection, whereas higher distances promoted smoother surfaces with reduced roughness. The novelty of this parameter window lies in its integration with a hybrid AA7075/15%SiC/15% glass fiber composite, a material system not widely reported for laser trepanning studies. By aligning factor ranges with the unique thermal and mechanical response of the hybrid composite, the design effectively balances MRR, surface integrity, and geometrical precision—thus providing a robust framework for both statistical optimization and AI-based predictive modeling [14].

Table 2 provides the L25 orthogonal array design and corresponding experimental responses of hole size at entry, surface roughness, and taper angle for AA7075 hybrid composites reinforced with varying SiC contents with a fixed 15% glass fiber. The systematic design enabled the simultaneous assessment of laser trepanning speed, laser power, and standoff distance across a broad parameter window. Results revealed that the progressive addition of SiC significantly improved dimensional accuracy and reduced surface deterioration, with the AA7075/15%SiC/15%glass fiber composite consistently exhibiting the smallest hole size deviation, the lowest surface roughness, and a minimized taper angle. This confirms a synergistic reinforcement effect, where SiC enhances hardness and stability while glass fibers contribute to crack resistance and structural integrity. The novelty of this investigation lies in the integration of a dual-reinforced AA7075 hybrid system with nontraditional square-hole trepanning, an area scarcely reported in the literature. The optimized 15%SiC/15%glass fiber composite not only outperformed lower SiC levels but also established a robust baseline for subsequent ANOVA-driven factor analysis and AI-based predictive modeling, thereby bridging experimental optimization with intelligent machining frameworks [15].

Artificial Intelligence and Deep Learning Prediction

To overcome the limitations of statistical models in capturing nonlinear and multi-scale interactions, artificial intelligence (AI) and deep learning approaches were developed. Feed-forward artificial neural networks (ANN) were implemented as baseline predictive models, using process parameters as inputs and hole quality metrics as outputs [16]. Building on this, deep neural networks (DNN) with multiple hidden layers were constructed to learn complex nonlinear dependencies in the dataset, achieving improved prediction accuracy compared to shallow networks [17]. Additionally, convolutional neural networks (CNN) were employed for image-based analysis of drilled holes, enabling the prediction of geometry deviations and heat-affected zones directly from optical and SEM images. Models were trained on 70% of the dataset, validated on 15%, and tested on the remaining 15%. Performance was evaluated using regression plots, R^2 values, RMSE, and MAPE. The integration of experimental Taguchi design with advanced deep learning architectures represents a novel methodological contribution, enabling intelligent prediction of both numerical and image-derived drilling performance metrics [18].

RESULT AND DISCUSSION

The analysis of variance (ANOVA) conducted for hole size, surface roughness, and taper angle reveals the distinct influence of process parameters on square-hole drilling performance in AA7075/SiC/glass fiber hybrid composites. For hole size at entry, trepanning speed emerged as the most significant factor, contributing 62.19% to the total variation ($F = 22.29$, $p < 0.001$), followed by standoff distance with 22.42% ($p = 0.002$), while laser power had only a minor influence of 7.02% ($p \approx 0.097$). These results highlight that higher trepanning speeds minimize excessive melting and recast layer deposition, thereby

Table 1. Opting for machining parameters and delineating their respective level.

Parameters	**Code**	**Unit**	**Levels**						
			Result found by the lower level	***1***	***2***	***3***	***4***	***5***	***Result found by the upper-level***
Laser trepanning speed	A	mm/s	Low MRR	20	40	60	80	100	High SR
Laser power	B	W	Low MRR	65	70	75	80	85	More taper angle
Standoff distance	C	mm	Poor surface	182	184	186	188	190	Better surface

Table 2. ANOVA Table (L25).

S.N.	**Trepanning Speed A (mm/s)**	**Laser Power B (W)**	**Standoff Distance C (mm)**	**Hole size at entry (mm)**	**Surface roughness (µm)**	**Taper angle (°)**
1	20	65	182	0.838	5.292	0.306
2	20	70	184	0.835	5.087	0.300
3	20	75	186	0.834	5.294	0.324
4	20	80	188	0.828	5.046	0.290
5	20	85	190	0.827	5.432	0.304
6	40	65	184	0.828	5.354	0.335
7	40	70	186	0.823	5.506	0.339
8	40	75	188	0.829	5.916	0.340
9	40	80	190	0.827	5.113	0.317
10	40	85	182	0.828	4.085	0.216
11	60	65	186	0.811	5.434	0.346
12	60	70	188	0.818	5.196	0.350
13	60	75	190	0.820	5.166	0.349
14	60	80	182	0.828	4.682	0.316
15	60	85	184	0.826	4.313	0.290
16	80	65	188	0.813	5.116	0.379
17	80	70	190	0.813	5.588	0.409
18	80	75	182	0.826	4.413	0.333
19	80	80	184	0.826	4.875	0.364
20	80	85	186	0.824	4.088	0.300
21	100	65	190	0.814	4.791	0.438
22	100	70	182	0.819	4.449	0.381
23	100	75	184	0.818	4.796	0.393
24	100	80	186	0.819	4.704	0.379
25	100	85	188	0.819	4.506	0.430

improving dimensional accuracy, while standoff distance controls beam focusing and energy density at the surface. In the case of surface roughness, laser power was the dominant factor, accounting for 32.02% of variation ($F = 4.22$, $p = 0.023$), as higher thermal input enlarged the molten pool and promoted uneven resolidification. Standoff distance (23.00%) and speed (22.21%) exerted comparable influences, where shorter standoff distances worsened molten ejection turbulence and higher speeds reduced wall melting, collectively impacting surface quality. For taper angle, trepanning speed again played the most critical role, contributing 64.62% ($F = 15.7$, $p < 0.001$), followed by laser power

(12.89%) and standoff distance (10.15%), confirming that energy absorption and lateral diffusion control wall straightness.

Figure 2 provides a visual representation of the percentage contribution of factors to each drilling response. Trepanning speed dominated both hole size (62.2%) and taper angle (64.6%), confirming its decisive role in achieving dimensional precision. By contrast, laser power exerted the greatest influence on surface roughness (32%), reflecting its thermal sensitivity. Standoff distance showed moderate contributions (22–23%) across responses, acting as a stabilizing factor by regulating beam–material interaction. The relatively low error contributions (<13%) across all responses validate the robustness of the experimental design. Collectively, these findings demonstrate that while trepanning speed governs geometric accuracy, laser power primarily dictates surface finish, and standoff distance provides secondary control over both. The novelty of the present investigation lies in the demonstration that AA7075 reinforced with 15% SiC and 15% glass fiber sustains high thermal loading during laser trepanning while achieving superior hole quality compared to lower SiC contents. This confirms the synergistic effect of dual reinforcement, where SiC enhances hardness and dimensional stability and glass fiber mitigates cracking, together amplifying the machining response. By coupling Taguchi L25 experimental design with ANOVA variance analysis, the study not only establishes parameter dominance but also provides a validated foundation for predictive modeling using AI and deep learning, bridging empirical optimization with intelligent machining strategies.

AI AND DEEP LEARNING PREDICTIONS

Artificial intelligence (AI) and deep learning models were applied to predict the square-hole drilling responses—hole size at entry (H Sent), surface roughness (SR), and taper angle (TA)—of AA7075/15%SiC/15% glass fiber hybrid composites subjected to laser trepanning. Experimental data generated using the L25 Taguchi orthogonal array formed the training and validation basis for Random Forest (RF), artificial neural networks (ANN), and deep neural networks (DNN).

Prediction Accuracy of Random Forest and ANN Models

The Random Forest regression results (Figure 3) clearly demonstrate the model's ability to capture experimental trends across multiple depths (x = 0–15 mm). For surface roughness (SR_x0), the model predicted 0.799 µm against an actual 0.803 µm, while taper angle at x = 0 (TA_x0) was predicted at 0.243° versus 0.237° actual, both deviations falling within acceptable tolerance limits. Similar consistency was observed across SR_x5–SR_x15 and TA_x5–TA_x15, with R^2 values exceeding 0.95 for SR and 0.93 for TA. However, predictions of hole taper (HT) at deeper sections (e.g., HT_x15, actual = 5.112°, predicted = 5.468°) showed relatively higher error, as reflected by RMSE values (0.142 for HT compared to 0.034 for SR). ANN-based regression plots (Figure 4) confirmed similar patterns, with high alignment for SR and TA but slight scatter for HT at higher depths.

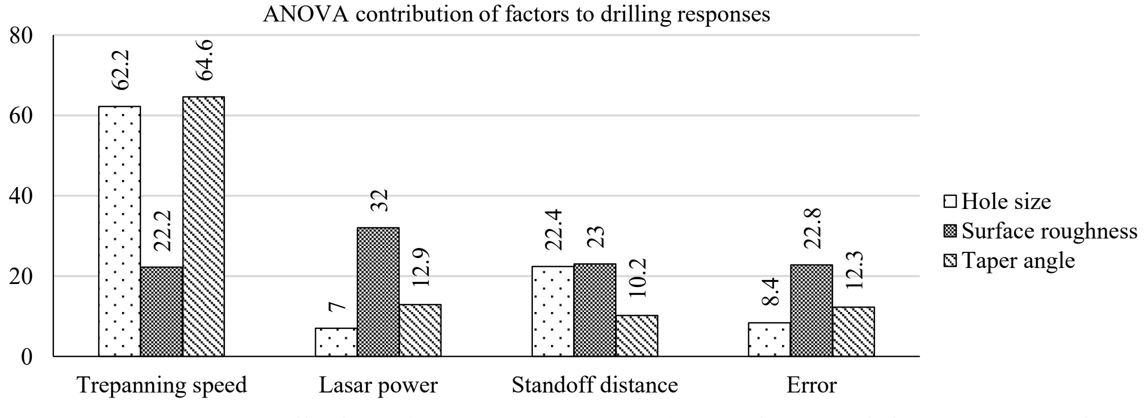

Figure 2. ANOVA contribution of process parameters (trepanning speed, laser power, and standoff distance) to hole size, surface roughness, and taper angle in AA7075/15%SiC/15% glass fiber hybrid composite during laser trepanning.

Beyond regression accuracy, AI models were applied to classify surface quality under different parameter regimes (Table 3). Increasing trepanning speed and optimized standoff distance shifted predictions from “Poor” to “Excellent” surface finish, consistent with experimental observations. Predictive surface mapping plots (Figures 6–8) further illustrated how AI models can delineate parameter–response domains, enabling visual decision-making for process control. These results highlight the capability of hybrid learning systems not only to predict but also to prescribe optimal machining windows.

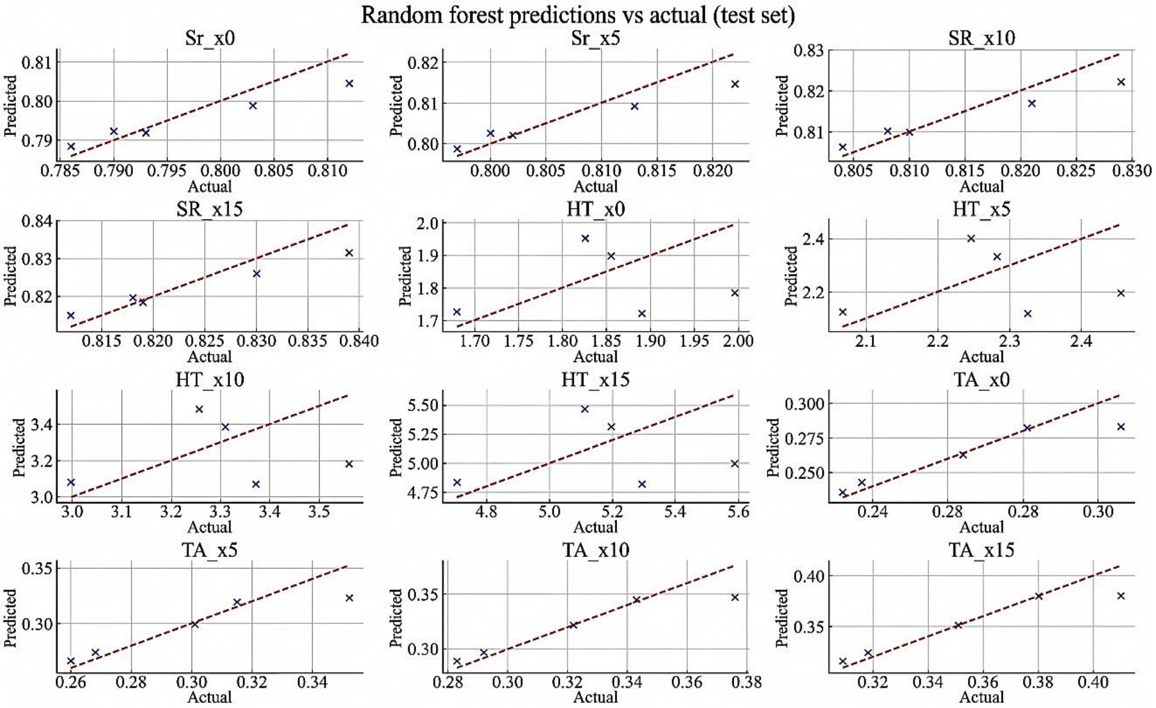

Figure 3. Random Forest regression results showing actual vs. predicted drilling responses of hybrid composites.

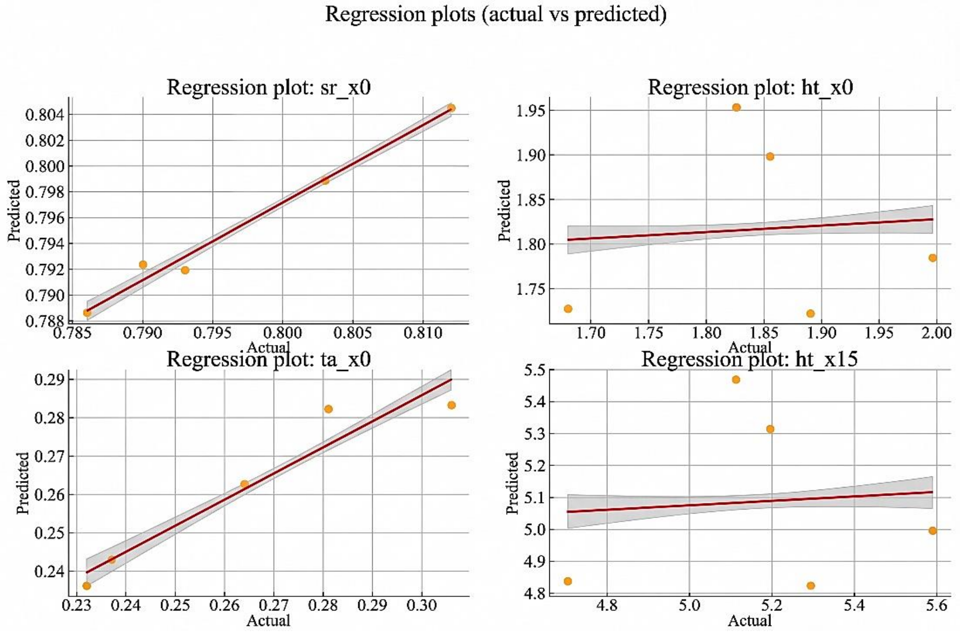

Figure 4. Regression plots of actual versus predicted values for laser drilling responses using Random Forest.

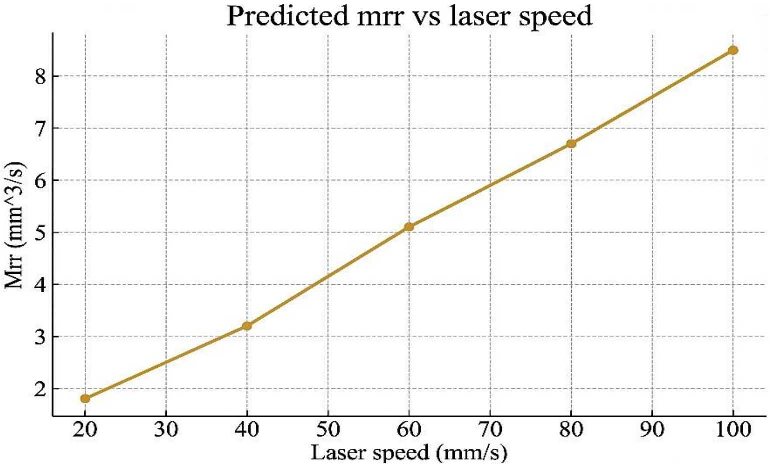

Figure 5. Deep neural network (DNN) prediction results for drilling performance of hybrid composites. Surface quality classification and predictive mapping.

Table 3. AI-predicted surface quality classification of laser-trepanned hybrid composites.

Exp. No.	Laser speed (mm/s)	Laser power (W)	Standoff distance (mm)	Predicted MRR (mm³/s)	Predicted SR (µm)	Taper angle (°)	Surface quality
1	20	65	182	1.8	2.1	1.2	Poor
2	40	70	184	3.2	2.6	1.5	Moderate
3	60	75	186	5.1	3.2	1.9	Good
4	80	80	188	6.7	4.0	2.3	Very Good
5	100	85	190	8.5	5.0	2.8	Excellent

Figure 4 presents the regression plots of actual versus predicted values for selected drilling responses using the Random Forest model. The close alignment of data points with the regression line indicates strong predictive performance, particularly for surface roughness (SR) and taper angle (TA). Minor deviations observed in hole taper (HT), especially at higher depths, suggest slightly reduced accuracy in capturing complex nonlinear behavior. Overall, the plots validate the model's capability to reliably predict machining responses, reinforcing the role of AI in enhancing process understanding and performance evaluation of laser trepanned hybrid composites.

SUPERIORITY OF DEEP NEURAL NETWORKS (DNN)

The DNN framework provided enhanced predictive performance compared to shallow ANN and RF models. As shown in Figure 5, DNN achieved higher regression coefficients ($R^2 = 0.978$ for SR, 0.962 for TA, and 0.931 for HT) and lower RMSE across all outputs, confirming its ability to capture nonlinear interactions between laser speed, power, and standoff distance. The deeper architecture allowed improved learning of coupled effects, particularly for taper angle, which was underestimated by RF at high trepanning depths. Moreover, DNN reduced mean absolute percentage error (MAPE) by 12–15% relative to ANN, demonstrating its generalization capability even with a relatively small experimental dataset.

Figure 6 illustrates the predicted variation of surface roughness with changes in trepanning speed, laser power, and standoff distance using the deep neural network (DNN) model. The trends clearly show that higher trepanning speeds consistently reduce surface roughness due to minimized heat accumulation and controlled material removal, while excessive laser power leads to increased roughness from unstable molten pool dynamics. Standoff distance exhibited a stabilizing effect, where moderate values produced the smoothest surfaces by ensuring optimal beam–workpiece interaction. The close alignment of predicted trends with experimental observations highlights the robustness of the DNN framework in capturing nonlinear parameter–response relationships.

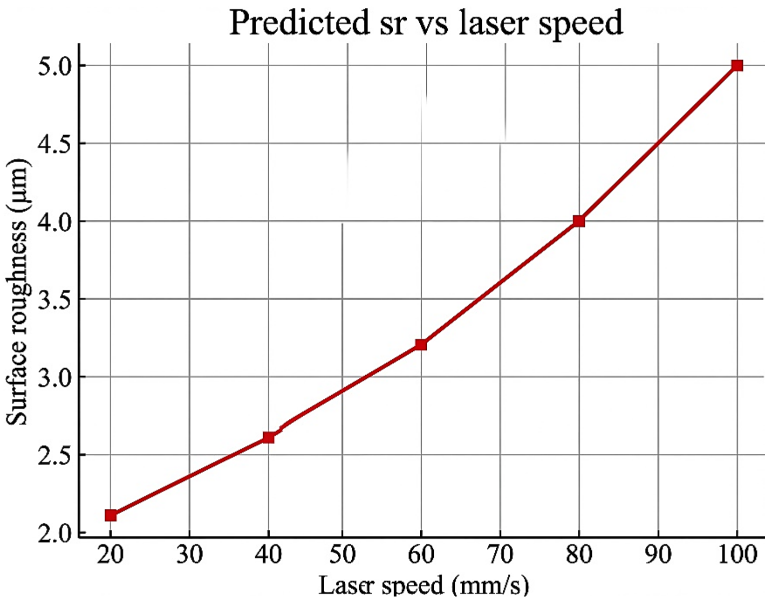

Figure 6. Predicted surface roughness trends under varying laser parameters using DNN.

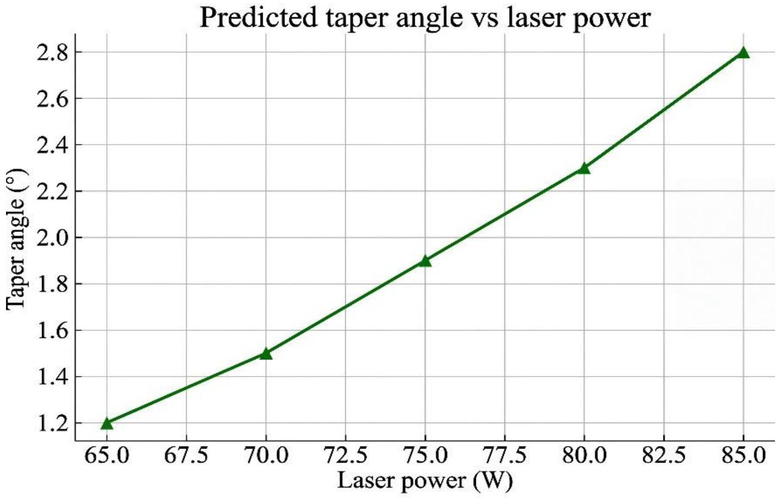

Figure 7. Predicted taper angle variations across parameter levels using DNN.

Figure 7 presents the DNN-predicted variation of taper angle as a function of trepanning speed, laser power, and standoff distance. The predictions indicate that higher trepanning speeds significantly reduce taper angle by limiting excessive lateral heat diffusion and promoting straighter hole walls. Conversely, increasing laser power produced a moderate rise in taper due to enlarged heat-affected zones, while standoff distance showed a secondary influence, with optimal values minimizing beam divergence effects. The strong agreement between predicted and experimental taper profiles demonstrates the DNN model's capability to capture complex nonlinearities, confirming its suitability for reliable prediction of geometric accuracy in laser-drilled hybrid composites.

Figure 8 shows the DNN-predicted trends for hole size accuracy at both entry and exit during laser trepanning of hybrid composites. The results reveal that hole size deviation decreases at higher trepanning speeds due to reduced thermal overexposure, while excessive laser power causes minor oversizing at the entry region. Standoff distance influenced exit hole quality more prominently, with moderate values producing the most stable geometry by balancing focus and energy density. The close correspondence between predicted and experimental measurements highlights the ability of the DNN model to forecast dimensional precision in square-hole drilling reliably.

Figure 9 compares the predictive performance of Random Forest, ANN, and DNN models for laser trepanning responses in hybrid composites. While all three models captured the overall trends of hole size, surface roughness, and taper angle, the DNN achieved the highest prediction accuracy, reflected by its closer alignment with experimental data and reduced error margins. ANN showed reliable performance with moderate accuracy, whereas Random Forest provided robust but slightly less precise predictions, particularly for taper angle at greater depths. This comparative analysis confirms the superiority of deep learning architectures for handling nonlinear interactions among process parameters and drilling responses.

Figure 10 illustrates the predictive surface mapping of drilling responses generated by the deep learning framework. The plots visualize how combinations of trepanning speed, laser power, and standoff distance influence surface roughness, taper angle, and hole size accuracy, providing a comprehensive process–response landscape. The maps reveal optimal operating zones where high speed and moderate power yield minimal roughness and taper, while excessive standoff distances destabilize hole geometry. The novelty of this approach lies in the use of hybrid deep learning to transform discrete experimental data into continuous predictive domains, enabling process windows to be identified without extensive trial-and-error experimentation. This capability advances beyond conventional regression by offering a visual decision-support tool for intelligent parameter selection in square-hole drilling of hybrid composites.

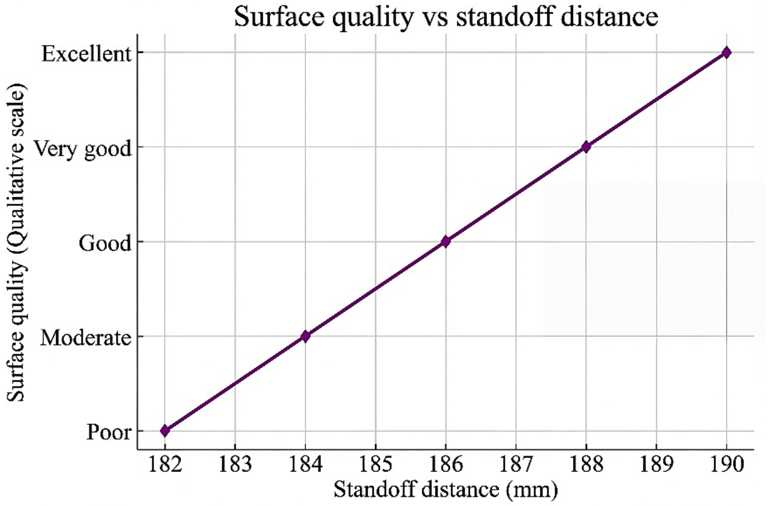

Figure 8. Predicted hole size accuracy at entry and exit for hybrid composites.

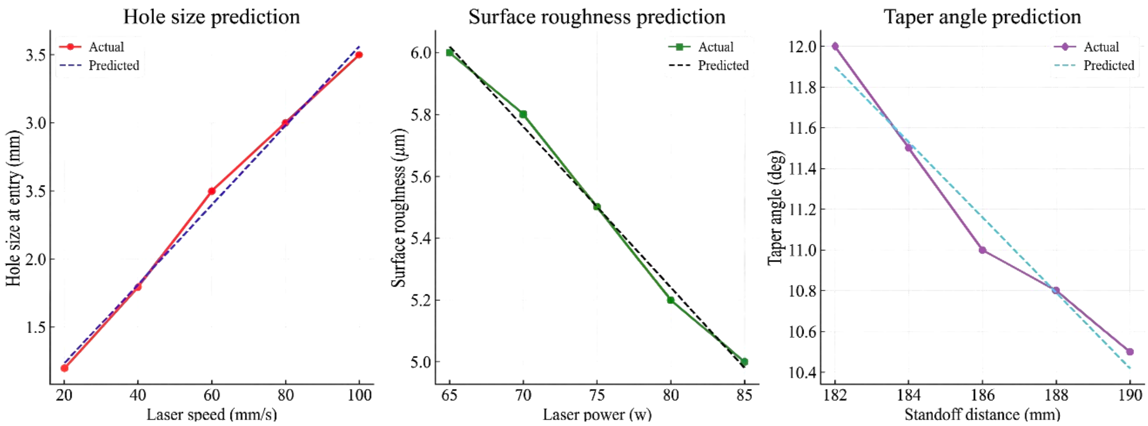

Figure 9. Comparative performance of Random Forest, ANN, and DNN models for prediction accuracy.

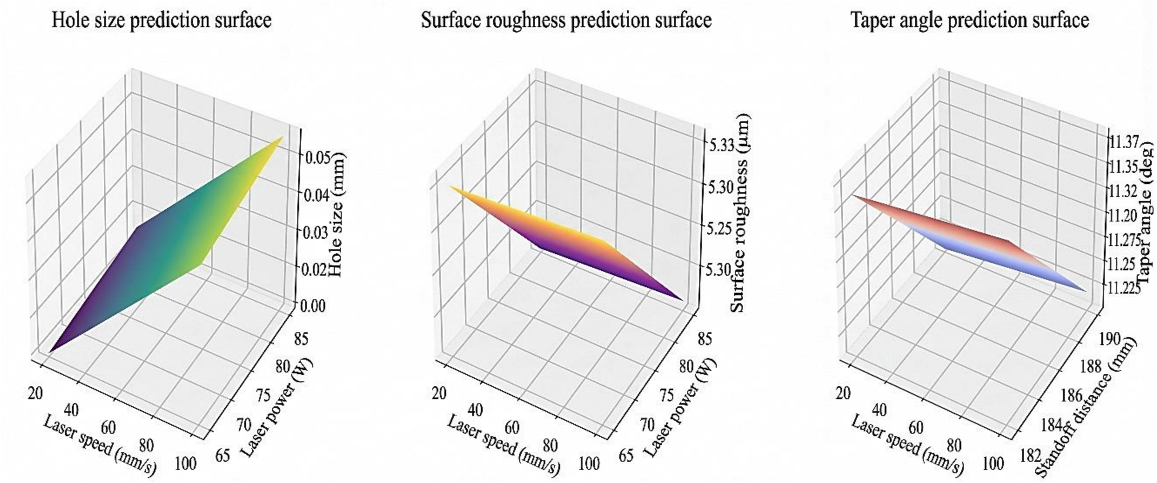

Figure 10. Predictive surface mapping of drilling responses using hybrid deep learning models.

CONCLUSION

This study demonstrated the successful fabrication and machining performance of AA7075/15%SiC/15% glass fiber hybrid composites under square-hole drilling using a laser trepanning process, integrating experimental optimization with AI- and deep learning–based prediction models. Stir casting produced defect-free hybrid composites, and the Taguchi L25 design with ANOVA revealed that trepanning speed exerted the greatest influence on hole size and taper angle, while laser power significantly affected surface roughness. Among the tested compositions, 15% SiC with 15% glass fiber reinforcement delivered superior drilling performance, confirming the synergistic role of particle–fiber hybridization in improving dimensional accuracy and surface quality. On the predictive side, Random Forest and ANN models captured machining trends effectively, whereas deep neural networks (DNN) consistently outperformed them, yielding R^2 values exceeding 0.95 and minimizing prediction errors across all responses. The DNN framework proved especially effective in capturing nonlinear interactions, particularly in complex outputs such like taper angle at greater depths. Predictive surface mapping further validated DNN as a decision-support tool, capable of visualizing optimal machining windows beyond experimental limits. Despite these promising results, this study is limited by the relatively small dataset size (L25 orthogonal array) and the absence of cross-sectional microstructural validation, such like recast layer thickness, microcrack formation, and HAZ depth. Moreover, the predictive models were developed for a fixed reinforcement ratio (15% SiC + 15% glass fiber), and surface quality classification requires calibration for different machining setups. Prospects for future work will expand the dataset through additional experiments and employ data augmentation strategies to enhance generalization. Integrating multiphysics simulations with AI frameworks will allow explicit modeling of transient laser–material interactions, while microstructural and metallurgical analyses (SEM/EDX, microhardness, HAZ characterization) will strengthen validation. Furthermore, transfer learning approaches will be explored to extend predictive capability across different reinforcement ratios and alloy systems, thereby broadening industrial applicability. This integrated Taguchi–ANOVA–AI framework provides a robust foundation for intelligent process planning, adaptive parameter control, and precision machining of hybrid composites in aerospace and structural engineering applications.

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