OPTIMIZATION OF MACHINING PROCESSES USING METAHEURISTIC ALGORITHMS - A COMPARATIVE ANALYSIS

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Abstract

The machining and manufacturing industry has rapidly evolved with the integration of advanced optimization techniques aimed at improving machining efficiency, reducing costs, minimizing environmental impact and enhancing product quality. Increasing demands for precision, productivity and sustainability have intensified research interest in both conventional machining and non-traditional machining (NTM) processes. Traditional optimization approaches, such as gradient-based methods and trial-and-error strategies, often fail to locate globally optimal solutions for complex multi-objective machining problems involving conflicting responses such as material removal rate (MRR), surface roughness (SR), tool wear rate (TWR) and specific cutting energy consumption (SCEC). These limitations highlight the need for flexible, robust and adaptive computational tools capable of addressing nonlinear, multi-parameter interactions found in machining operations. Metaheuristic algorithms, inspired by natural evolutionary processes, swarm intelligence, biological interactions and physical laws, have emerged as powerful tools for navigating complex search spaces to achieve near-global optimal solutions. Their ability to balance exploration and exploitation makes them particularly well-suited for machining optimization. This research presents a comprehensive investigation into parametric optimization across five distinct machining processes i.e. turning, milling, laser beam machining (LBM), abrasive water jet machining (AWJM) and plasma arc cutting (PAC) using five categories of nature-inspired metaheuristic algorithms like human-inspired, mating behavior-based, preying behavior-based, foraging behavior-based and physics-based algorithms. A structured methodological framework is developed consisting of selection of machining processes, application of 25 metaheuristic algorithms across five categories, optimization of machining parameters such as cutting speed, feed rate, depth of cut, SCEC, TWR and MRR, performance assessment based on solution accuracy, variability, computation time and convergence speed and statistical validation using Friedman's mean rank test and Wilcoxon rank sum test. The study emphasizes sustainability by minimizing energy consumption, reducing carbon footprint and improving occupational health and

safety, thereby supporting greener and resource-efficient manufacturing practices. For the turning process on AISI 6061-T6 aluminum, five human-inspired algorithms i.e. TLBO, SAR, TOA, HCO and QSA are evaluated. TLBO consistently performs best, providing optimal improvements in MRR, SR and SCEC. Pareto fronts and quality metrics such as spacing (SP) and hypervolume (HV) validate its superiority. In green machining, particularly dry milling of stainless steel 304, five mating behavior-based algorithms, FMA, NMR, BOA, BMOA and AZOA are examined. FMA outperforms others by achieving superior SR, SCEC and power consumption reduction. Its strong exploration–exploitation capability and statistical validation against widely used algorithms such as GA, PSO, ACO and ABC confirm its dominance. Laser beam drilling (LBD) on polycarbonate is optimized using five preying behavior-based algorithms i.e. SFO, HHO, AO, BA and GWO. GWO emerges as the most effective, achieving high-quality holes with minimal heat-affected zone (HAZ) and demonstrating fast convergence and high accuracy. For AWJM, five foraging behavior-based algorithms including DOA, AVOA, GOA, FOA and BSA are applied. AVOA provides the best optimization of stand-off distance and traverse speed, yielding improved surface quality and machining consistency. Similarly, PAC is optimized using five physics-based algorithms, like AOA, ASO, NRO, EFO and GSA. EFO outperforms others in optimizing kerf taper, MRR and HAZ while balancing computational effort and convergence characteristics. The top-performing algorithms from each category i.e. TLBO, FMA, GWO, AVOA and EFO are further applied to optimize end milling of an Al7075/SiC/Gr hybrid composite. GWO consistently outperforms the others in both single- and multi-objective optimization, achieving optimal MRR, SR and microhardness with favorable parametric combinations of spindle speed, feed rate, depth of cut and reinforcement percentage. Although the study provides strong computational evidence, its main limitation lies in the absence of real-time experimental validation. Future work should incorporate experimental confirmation, algorithm–ML hybridization, real-time adaptive control and extension to additive and hybrid machining processes. Overall, this research establishes a unified and robust framework for applying metaheuristic algorithms to diverse machining processes, providing valuable insights for researchers and practitioners in selecting appropriate optimization strategies to improve machining performance, sustainability and cost-effectiveness.

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