

Surface Roughness Evaluation of Copper Material Processed by SPMAF - Literature Review

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ABSTRACT

This comprehensive literature review examines the surface roughness evaluation of copper materials processed through magnetic abrasive finishing techniques, with emphasis on statistical factorial design methodologies. The review synthesizes current research on magnetically assisted abrasive finishing processes, surface characterization methods, and statistical optimization techniques employed in precision manufacturing. Key aspects including process parameters, experimental design approaches, surface quality assessment, and optimization strategies are critically analyzed to provide insights into the state-of-the-art in this emerging field.

Keywords: Magnetic abrasive finishing, surface roughness, copper materials, factorial design, ANOVA, response surface methodology, process optimization, SPMAF

1. INTRODUCTION

The demand for high-quality surface finishes in manufacturing industries has driven the development of advanced finishing processes. Magnetically assisted abrasive finishing (MAAF) has emerged as a precision material removal technique capable of achieving superior surface quality on various materials. These processes rely on unique smart fluids known as magnetorheological fluids, which are suspensions of micron-sized magnetizable particles such as carbonyl iron dispersed in non-magnetic carrier mediums like silicone oil, mineral oil, or water [1]. The MAAF process overcomes limitations of conventional flow machining by deterministically controlling abrading forces through the application of magnetic fields around the workpiece. Copper and its alloys have gained significant attention in various industrial applications due to their excellent electrical and thermal conductivity properties. However, achieving optimal surface quality on copper materials remains challenging due to their inherent softness and tendency for material adhesion during processing. This necessitates the development of specialized finishing techniques and rigorous experimental methodologies to optimize process parameters.

2. MAGNETIC ABRASIVE FINISHING PROCESSES

2.1 Process Fundamentals

Magnetically assisted abrasive finishing processes are precision material removal techniques that have been successfully applied to a large variety of materials, from brittle to ductile and magnetic to non-magnetic [1]. The MAAF process is divided into two main categories: magnetorheological finishing (MRF) and magnetorheological abrasive flow finishing (MRAFF), with MRAFF demonstrating superior results compared to MRF due to its additional reciprocating motion.

The magnetic abrasive finishing process utilizes magnetic fields to force abrasive particles against the workpiece surface to remove material as microchips [2]. The process parameters that influence the finishing performance include rotational speed, abrasive quantity, mesh number, and processing time. Research has shown that by controlling these parameters, significant improvements in surface quality can be achieved.

2.2 Applications to Copper Materials

Several studies have investigated the application of magnetic field-assisted finishing processes for copper materials. A novel magnetic field-assisted polishing method using magnetic compound slurry demonstrated excellent performance in mirror surface finishing, achieving work-surface roughness decreased more than 6 times compared to the original after polishing on oxygen-free high conductivity copper workpieces [3]. The

study found that groove form accuracy varied at different locations, with retention rates greater than 99.4% even after processing.

Chemo-ultrasonic assisted magnetic abrasive finishing (CUMAF) has been developed as a compound process integrating chemo-mechanical polishing, ultrasonic vibrations, and magnetic abrasive finishing to achieve nanometer-order surface finishes within a short time span [4]. Experimental investigations on copper alloy pieces demonstrated the process's capability to achieve significant percentage changes in average surface roughness values through optimization of five critical process parameters.

The internal magnetic field assisted finishing with magnetorheological fluid-based slurry has been successfully applied to copper tubes [5]. The process created smooth mirror finished surfaces with few directional cutting marks, with the exciting current and abrasive size identified as key factors affecting the characteristics of the MRF-based slurry.

2.3 Process Parameters and Performance

Ultrasonic-assisted double-disk magnetic abrasive finishing has been evaluated on copper alloy and stainless steel with different mechanical properties [6]. The experiments revealed that working gap, rotational speed, and pulse-on time of ultrasonic vibration significantly affect the finishing performance. Scanning electron microscopy and atomic force microscopy analyses were employed to understand the material removal mechanism and surface morphology produced by the process.

Experimental study on magnetorheological finishing of oxygen-free high conductivity copper investigated the influence function by studying the flow behavior of MR fluid [7]. The research demonstrated that depth and area of material removal increase with spindle speed while reducing the working gap. The study confirmed that spot size decides normal force, whereas contact length removes material proportional to tangential force.

3. SURFACE ROUGHNESS EVALUATION AND MEASUREMENT

3.1 Surface Roughness Parameters

Surface roughness is a critical indicator of surface quality and is among the most specified customer requirements in machining operations. Various roughness parameters are employed to characterize surface quality, with Ra (arithmetic average roughness) being the most commonly used parameter. Additional parameters such as Rq (root mean square roughness), Rt (total roughness), Rz (average maximum height), and Rp are employed for comprehensive surface characterization [8].

Research on ball end milling of oxygen-free high conductivity copper developed statistical models to predict surface roughness components including Ra and Rz using response surface methodology [9]. The study revealed that step over and axial depth of cut have higher contribution (45.81%) to surface roughness, indicating their significant influence on the milled OFHC copper surface quality.

3.2 Measurement Techniques and Instrumentation

Modern surface roughness evaluation employs both contact and non-contact measurement techniques. Three-dimensional profilometry has been utilized to characterize surface morphology and quantify roughness parameters [10]. The use of metallographic microscopes and digital Vickers testers allows for comprehensive analysis of surface characteristics and microhardness variations.

Advanced characterization methods include scanning electron microscopy (SEM) for morphological analysis and atomic force microscopy (AFM) for nanoscale surface topography evaluation. These techniques provide detailed insights into the material removal mechanisms and surface integrity achieved through finishing processes [6].

4. STATISTICAL FACTORIAL DESIGN METHODOLOGY

4.1 Design of Experiments Approaches

Statistical factorial design has become an essential tool for optimizing manufacturing processes and understanding parameter interactions. Full factorial design allows for comprehensive investigation of all possible factor combinations, providing complete information about main effects and interactions [11]. The methodology is particularly suitable for analyzing machining results when multiple parameters need to be optimized simultaneously.

Experimental investigation of turning polymers employed full factorial design experiments to study the effect of process parameters on surface roughness, material removal rate, and chip formation [12]. The study demonstrated that full factorial design provides robust statistical analysis capabilities through ANOVA and 3D response surface plots, enabling identification of optimal parametric conditions.

Research on electric discharge machining utilized full factorial experiment design approach to prepare samples and observe surface roughness variations and dimensional stability [13]. The methodology enabled regression

analysis and ANOVA interpretation of results, confirming the significance of each operating parameter on output responses.

4.2 Analysis of Variance (ANOVA)

Analysis of variance is a powerful statistical method employed to examine the dependence of process responses on input parameters and their interactions [14]. ANOVA allows researchers to understand the contribution of various factors and their interactions at specified confidence levels, typically 95%. The technique has been extensively used to analyze surface roughness data and identify statistically significant parameters.

Studies on CNC slot milling of aluminum alloys demonstrated that fractional and full factorial design approaches, when analyzed through ANOVA, provide equally suitable methods for evaluating surface roughness characteristics [11]. Multiple statistical tools confirmed the appropriateness of factorial design for analyzing machining results.

4.3 Response Surface Methodology

Response surface methodology (RSM) represents an advanced statistical technique for developing mathematical models that correlate experimental results with process parameters [9]. RSM employs central composite designs and Box-Behnken designs to create quadratic models predicting surface roughness in terms of significant process parameters and their interactions.

Research on turning AISI 420 stainless steel employed full factorial design with RSM to develop quadratic regression models for surface roughness parameters [8]. The study found that feed rate exhibited the highest influence on roughness parameters when compared with cutting speed and depth of cut, with good agreement observed between predicted and experimental values.

Investigation of surface roughness in ball end milling of OFHC copper utilized RSM with full factorial rotatable central composite design [9]. Mathematical models were formulated for surface roughness components, and the predicted values from RSM were found to be close to actual values, demonstrating the effectiveness of this approach.

4.4 Optimization Strategies

Multi-objective optimization techniques have been developed to simultaneously optimize multiple performance characteristics. Grey relational analysis combined with Taguchi methodology has been employed to convert multi-objective criteria into equivalent single objective functions [15]. This approach enables determination of optimal machining parameters for achieving minimum surface roughness and optimal chip thickness simultaneously.

Experimental study on magnetic abrasive finishing of flat brass plates investigated the effect of process parameters using full factorial experimental design [2]. ANOVA was employed to find optimal conditions for better surface roughness and material removal rate. Regression models developed using MINITAB software showed that rotational speed was the most important parameter affecting surface roughness, while processing time significantly influenced material removal rate.

5. COPPER MATERIAL PROCESSING CHARACTERISTICS

5.1 Machining Challenges

Copper and copper alloys present unique challenges during processing due to their high thermal conductivity and tendency for adhesion to cutting tools. Research on magnetorheological finishing of non-magnetic freeform work materials, including copper alloys, investigated the effects of various parameters such as MR fluid composition, rotational speed, and mesh size of abrasives on surface finish [16]. The process demonstrated capability to achieve nanometer-scale surface finishes on copper alloy components.

Studies on atomizing rapid solidification spherical abrasive finishing explored the effect of magnetic abrasive finishing on the surface quality of copper-nickel alloys [10]. When optimal process parameters were employed (spindle speed 1300 r/min, feeding rate 13 mm/min, processing distance 1.2 mm, filling amount 2.0 g), surface roughness decreased from 0.212 to 0.023 μm while surface hardness increased from 114 to 119.8 HV.

5.2 Surface Quality Enhancement

The application of advanced finishing techniques to copper materials has demonstrated significant potential for surface quality improvement. Experimental study on magneto-rheological abrasive flow finishing of copper workpieces showed that by decreasing mesh number, surface roughness decreased for all three materials tested [17]. The study also revealed that increasing magnetic field strength led to improved surface characteristics.

Research on diamond machining of advanced technology components highlighted that copper materials require specialized approaches to minimize surface layer damage while achieving ultra-precision finishes [18]. The tolerances achieved on workpieces reached 0.01 μm , demonstrating the potential for achieving exceptional surface quality on copper materials.

6. PROCESS OPTIMIZATION AND MODELING

6.1 Mathematical Modeling

Mathematical modeling of surface finishing processes enables prediction and optimization of surface roughness based on process parameters. Regression analysis has been extensively employed to develop predictive models for surface roughness [14]. First-order and second-order models have been developed using experimental data to establish relationships between cutting conditions and surface characteristics.

Studies on turning processes demonstrated that second-order regression models provide higher R^2 values and represent better fit compared to first-order models [19]. The models indicate good correlations between experimental and predicted results, enabling efficient process planning and optimization.

6.2 Artificial Intelligence Applications

Artificial neural networks (ANN) have emerged as powerful tools for predicting surface roughness in manufacturing processes [20]. Feed-forward back-propagation neural networks trained with experimental datasets demonstrate excellent predictive performance, often surpassing traditional regression models. Research comparing regression and ANN models for surface roughness prediction showed that ANN models with scaled conjugate gradient algorithms produced R^2 values of 0.999 for training data and 0.998 for test data [21].

Hybrid approaches combining RSM with genetic algorithms have been developed for multi-objective optimization [12]. These methodologies enable determination of optimal conditions for each response variable while considering multiple conflicting objectives simultaneously.

6.3 Multi-Response Optimization

Multi-criteria optimization has become essential in modern manufacturing to balance competing performance objectives. Grey relational analysis coupled with Taguchi methodology provides an effective framework for converting multi-objective problems into single-objective optimization [15]. This approach has been successfully applied to determine optimal combinations of process parameters for achieving minimum surface roughness and optimal material removal rates.

Desirability function approaches have been employed to optimize multiple performance characteristics simultaneously [22]. Research on wire electrical discharge machining demonstrated that optimal parameter combinations can be identified to achieve highest desirability values, ensuring balanced performance across multiple quality metrics.

7. CURRENT CHALLENGES AND FUTURE DIRECTIONS

7.1 Process Control and Monitoring

Despite significant advances in magnetic abrasive finishing technologies, several challenges remain in achieving consistent and predictable surface quality. The deterministic control of abrading forces through magnetic field manipulation requires further investigation to establish robust process models [1]. Real-time monitoring and adaptive control systems need development to maintain optimal processing conditions throughout the finishing operation.

7.2 Material-Specific Considerations

The processing of copper materials through magnetic finishing techniques requires consideration of material-specific characteristics such as thermal conductivity, work hardening behavior, and surface reactivity. Further research is needed to understand the fundamental mechanisms of material removal at the micro and nano scales for copper and its alloys.

7.3 Integration of Advanced Technologies

The integration of ultrasonic vibrations, chemical-mechanical effects, and magnetic fields presents opportunities for enhanced finishing performance [4]. Compound processes such as chemo-ultrasonic assisted magnetic abrasive finishing demonstrate the potential for achieving superior surface quality within reduced processing times. However, the complex interactions between these multiple energy sources require systematic investigation through advanced experimental design methodologies.

7.4 Sustainability Considerations

The development of environmentally friendly finishing processes aligns with global sustainability goals. Research on minimum quantity lubrication and eco-friendly cutting fluids in machining operations [23] provides insights applicable to magnetic abrasive finishing. The use of vegetable-oil-based fluids and biodegradable materials in magnetorheological composition warrants investigation.

8. CONCLUSIONS

This comprehensive literature review has examined the current state of knowledge regarding surface roughness evaluation of copper materials processed through magnetic abrasive finishing techniques using statistical factorial design methodologies. The review reveals that:

1. Magnetically assisted abrasive finishing processes offer significant advantages for achieving superior surface quality on copper materials, with demonstrated capability to reduce surface roughness by more than six-fold compared to initial conditions [3].
2. Statistical factorial design, particularly full factorial designs combined with ANOVA and response surface methodology, provides robust frameworks for optimizing process parameters and developing predictive models for surface roughness [11].
3. Process parameters including rotational speed, working gap, abrasive characteristics, and magnetic field strength significantly influence surface roughness outcomes, with their relative importance varying based on material properties and process configuration [2].
4. Advanced characterization techniques including SEM, AFM, and three-dimensional profilometry enable comprehensive evaluation of surface quality and material removal mechanisms [6].
5. Multi-objective optimization approaches combining statistical design with artificial intelligence techniques demonstrate superior capability for balancing competing performance objectives [15].

Future research should focus on developing deterministic process models, implementing real-time monitoring systems, and investigating compound processes that integrate multiple energy sources for enhanced finishing performance. The application of advanced experimental design methodologies will continue to play a crucial role in understanding and optimizing these complex manufacturing processes.

9. REFERENCES

- [1] C. Kumari and S. K. Chak, "A review on magnetically assisted abrasive finishing and their critical process parameters," *EDP Sciences*, 2018.
- [2] A. Babbar *et al.*, "Regression model and optimization of magnetic abrasive finishing of flat brass plate," *Indian Society for Education and Environment*, 2017.
- [3] Y. Wang, Y. Wu, and M. Nomura, "A novel magnetic field-assisted polishing method using magnetic compound slurry and its performance in mirror surface finishing of miniature v-grooves," *American Institute of Physics*, 2016.
- [4] N. Sihag, P. Kala, and P. M. Pandey, "Experimental investigations of chemo-ultrasonic assisted magnetic abrasive finishing process," *None*, 2015.
- [5] T. Sat, H. Yamaguchi, T. Shinmura, and T. OKAZAKI, "Study of internal magnetic field assisted finishing for copper tubes with MRF (magneto-rheological fluid)-based slurry," *Trans Tech Publications*, 2007.
- [6] P. Kala and P. M. Pandey, "Experimental investigations into ultrasonic-assisted double-disk magnetic abrasive finishing of two paramagnetic materials," *SAGE Publishing*, 2015.
- [7] N. K. Dubey and A. Sidpara, "Numerical and experimental study of influence function in magnetorheological finishing of oxygen-free high conductivity (OFHC) copper," *IOP Publishing*, 2020.
- [8] L. Bouzid, M. A. Yallese, S. Belhadi, T. Mabrouki, and L. Boulanouar, "RMS-based optimisation of surface roughness when turning AISI 420 stainless steel," *Inderscience Publishers*, 2014.
- [9] A. H. Seikh, B. B. Mandal, A. Sarkar, M. Baig, N. H. Alharthi, and B. Alzahrani, "Application of response surface methodology for prediction and modeling of surface roughness in ball end milling of OFHC copper," *Springer Nature*, 2019.
- [10] T. Cui, G. Zhang, Y. Cui, L. Jiang, P. Zhu, and J. Du, "Effect of atomizing rapid solidification spherical abrasive finishing on the surface quality of copper-nickel alloy," *SAGE Publishing*, 2021.
- [11] N. A. Fountas, K. -E. Aslani, J. D. Kechagias, P. Kyratsis, and N. M. Vaxevanidis, "Experimental and statistical study of surface roughness in CNC slot milling of AL 7075 alloy using full and fractional factorial design," *University of Kragujevac*, 2022.
- [12] A. I. Alateyah, Y. El-Taybany, S. ElSanabary, W. H. El-Garaihy, and H. Kouta, "Experimental investigation and optimization of turning polymers using RSM, GA, hybrid FFD-GA, and MOGA methods," *Multidisciplinary Digital Publishing Institute*, 2022.
- [13] F. Gillani, T. Zahid, S. Bibi, R. S. U. Khan, M. R. Bhutta, and U. Ghafoor, "Parametric optimization for quality of electric discharge machined profile by using multi-shape electrode," *Multidisciplinary Digital Publishing Institute*, 2022.
- [14] L. B. Abhang and M. Hameedullah, "Modeling and analysis for surface roughness in machining EN-31 steel using response surface methodology," *None*, 2011.

- [15] L. B. Abhang and M. Hameedullah, "Determination of optimum parameters for multi-performance characteristics in turning by using grey relational analysis," *Springer Science+Business Media*, 2012.
- [16] L. N. Pattanaik and H. Agarwal, "Magnetorheological finishing (MRF) of a freeform non-magnetic work material," *De Gruyter*, 2015.
- [17] A. D. Ghadikolaei and M. Vahdati, "Experimental study on the effect of finishing parameters on surface roughness in magneto-rheological abrasive flow finishing process," *SAGE Publishing*, 2014.
- [18] P. A. McKeown, "ULTRA-PRECISION DIAMOND MACHINING OF ADVANCED TECHNOLOGY COMPONENTS," *Taylor & Francis*, 1986.
- [19] A. Panda, A. K. Sahoo, and A. K. Rout, "Multi-attribute decision making parametric optimization and modeling in hard turning using ceramic insert through grey relational analysis: A case study," *Growing Science*, 2016.
- [20] M. I. Hossain, A. K. M. N. Amin, and M. A. U. Patwari, "Development of an artificial neural network algorithm for predicting the surface roughness in end milling of inconel 718 alloy," *None*, 2008.
- [21] M. Nalbant, H. Gkkaya, and hsan Tokta, "Comparison of regression and artificial neural network models for surface roughness prediction with the cutting parameters in CNC turning," *Hindawi Publishing Corporation*, 2007.
- [22] V. Kumar, V. Kumar, and K. Kumar, "An experimental analysis and optimization of machining rate and surface characteristics in WEDM of monel-400 using RSM and desirability approach," *Springer Nature*, 2015.
- [23] B. Sen, M. Mia, G. Krlczyk, U. K. Mandal, and S. P. Mondal, "Eco-friendly cutting fluids in minimum quantity lubrication assisted machining: A review on the perception of sustainable manufacturing," *Springer Science+Business Media*, 2019.