MULTI-CRITERIA OPTIMIZATION OF DRESSING PARAMETERS IN INTERNAL GRINDING OF SKD11 TOOL STEEL USING AHP TECHNIQUE

TỐI ƯU HÓA ĐA MỤC TIÊU CÁC THÔNG SỐ SỬA ĐÁ KHI MÀI LỖ THÉP DỤNG CỤ SKD11 BẰNG PHƯƠNG PHÁP AHP

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ABSTRACT

This study applies the Analytic Hierarchy Process (AHP) to optimize dressing parameters in the surface grinding of SKD11 tool steel. Two key performance criteria surface roughness (Ra) and grinding wheel life (Tw) were simultaneously considered. Based on experimental data from 16 dressing trials, the AHP method was used to calculate composite performance scores and rank configurations. The best combination achieved a balanced trade-off between low Ra and long Tw. The results demonstrate that AHP is an effective tool for multi-criteria decision making in precision grinding.

Keywords: *AHP; Dressing parameters; SKD11 tool steel; Internal grinding; Multi-criteria decision making; Surface roughness; Tool life.*

TÓM TẮT

Nghiên cứu này áp dụng phương pháp AHP để tối ưu hóa các thông số gia công trong quá trình mài bề mặt thép công cụ SKD11. Hai hàm đơn mục tiêu bao gồm nhám bề mặt Ra nhỏ nhất và tuổi thọ đá mài Tw lớn nhất được xem xét đồng thời. Dựa trên dữ liệu thực nghiệm từ 16 lần gia công thử, phương pháp AHP đã được sử dụng để tính điểm hiệu suất tổng hợp và cấu hình thứ hạng. Sự kết hợp tốt nhất đạt được sự cân bằng giữa Ra thấp và Tw lâu. Kết quả chứng minh rằng AHP là một công cụ hiệu quả để đưa ra quyết định đa tiêu chí trong quá trình mài.

Từ khóa: *AHP; Thông số sửa đá; Thép công cụ SKD11; Mài lỗ; Ra quyết định đa tiêu chí; Nhám bề mặt; Tuổi thọ đá mài.*

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1. INTRODUCTION

In grinding operations, particularly for hard-to-machine tool steels such as SKD11 and 9CrSi, dressing is a crucial process to maintain the effectiveness and precision of grinding wheels. Dressing parameters strongly affect the wheel surface topography, which in turn influences the material removal rate, surface roughness, and overall efficiency of the grinding process.

Liu et al. [1] conducted kinematic simulations to analyze the effect of different grain shapes and dressing methods on surface roughness. The study showed that grain morphology and dressing strategies significantly affect the Ra values. Hong et al. [2] used the Taguchi method and Grey Relational Analysis (GRA) to optimize dressing parameters in the surface grinding of 90CrSi tool steel, successfully identifying parameter settings that minimized Ra and enhanced performance.

Klocke and Linke [3] explored the fundamental mechanisms behind grinding wheel topography formation during dressing, emphasizing its critical role in grinding performance. Walter et al. [4] proposed the use of short-pulsed fiber lasers for dressing hybrid bonded CBN wheels, achieving precise topography control and improved tool efficiency.

Tu et al. [5] investigated the influence of dressing parameters on surface roughness when grinding hardened 9XC tool steel and identified significant correlations between the dressing depth, number of passes, and surface quality. In a similar context, Tung et al. [6] optimized dressing conditions for 9CrSi tool steel using the Taguchi-GRA hybrid method, confirming its effectiveness in multi-objective optimization.

Daneshi et al. [7] examined the effects of dressing in internal cylindrical grinding and highlighted its influence on dimensional accuracy and surface finish. Hong et al. [8] focused on SKD11 tool steel and applied the Taguchi method to optimize dressing parameters, achieving improvements in both Ra and grinding consistency.

Kozuro et al. [9] provided foundational knowledge in their handbook on grinding, presenting empirical and theoretical insights into dressing practices. Hung et al. [10] applied multi-objective optimization using Taguchi and GRA for internal grinding of 9CrSi alloy steel and reported enhanced surface finish and tool life.

Prusak et al. [11] evaluated the grinding performance of CBN/Seeded Gel hybrid wheels and demonstrated that dressing conditions directly impact grinding forces and surface quality. Aleksandrova [12] introduced a generalized utility function for optimizing dressing parameters in cylindrical grinding, offering a flexible approach to balance conflicting criteria.

Hung et al. [13] focused on maximizing material removal rate (MRR) during internal cylindrical grinding of SKD11 while maintaining acceptable surface finish. In another study, Hung et al. [14] aimed to minimize surface roughness through the optimal selection of dressing parameters for SKD11 steel, confirming the sensitivity of Ra to parameter changes.

Tran et al. [15] optimized dressing conditions to minimize flatness deviation in SKD11 grinding, contributing to better geometric accuracy. To handle multi-criteria decision-making problems in manufacturing, Sri et al. [16] proposed the Fuzzy Multi-Attribute Decision Making (Fuzzy MADM) approach. Keshavarz-Ghorabaee [17] extended decision-making models through a hybrid subjective-objective method involving multi-expert input, emphasizing the robustness of integrated evaluation techniques.

Despite these efforts, studies that integrate analytical hierarchy process (AHP) for dressing parameter selection in SKD11 grinding remain limited. This research addresses that gap by employing AHP to evaluate combinations of dressing parameters considering two conflicting criteria: minimizing surface roughness (Ra) and maximizing grinding wheel life (Tw).

2. METHODOLOGY

This study proposes a multi-criteria decision-making approach using the Analytic Hierarchy Process (AHP) to evaluate and rank combinations of dressing parameters in the surface grinding of SKD11 tool steel. The methodology focuses on balancing two conflicting performance criteria: minimizing surface roughness (Ra) and maximizing grinding wheel life (Tw).

2.1. Experimental Data and Parameters

The experimental dataset includes dressing trials performed on SKD11 tool steel. Six dressing input variables are considered: fine dressing depth (mm) a_f, number of fine dressing passes n_f, non-feeding dressing (times) n_0, number of rough dressing passes n_r, rough dressing depth (mm) a_r, dressing feed rate (mm/min) S_d. The measured outputs include: surface roughness Ra (µm), to be minimized, grinding wheel life Tw (min), to be maximized.

All dressing trials were conducted under controlled conditions, and the output responses were recorded for each combination of the above parameters.

2.2. Multi-Criteria Decision Making via AHP

AHP is employed to evaluate and rank the dressing parameter sets based on the performance criteria (Ra, Tw). The methodology consists of the following steps:

1) Construction of the Pairwise Comparison Matrix

A pairwise comparison matrix is built to reflect the relative importance of each criterion. In this study, Tw is considered three times more important than Ra, based on practical judgment. The resulting matrix is:

$$\begin{bmatrix} 1 & 1/3 \\ 3 & 1 \end{bmatrix} \quad (1)$$

This matrix is used to calculate the priority weights of the criteria.

2) Consistency Check

The consistency of the pairwise matrix is verified using the Consistency Index (CI) and Consistency Ratio (CR) to ensure logical coherence in the judgment matrix. A CR less than 0.1 is considered acceptable.

3) Normalization of Criteria

• Ra is treated as a cost-type criterion (lower is better), and normalized as:

$$R_{anorm} = \frac{R_{amax}}{R_{ai}} \quad (2)$$

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• Tw is a benefit-type criterion (higher is better), normalized as:

$$T_{wnorm} = \frac{T_{wi}}{T_{wmax}} \quad (3)$$

4) Calculation of AHP Score

The normalized values are multiplied by their corresponding weights derived from the AHP process to calculate a composite score:

$$AHP\_Score_i = w_{Ra} \cdot R_{anorm,i} + w_{Tw} \cdot T_{wnorm,i} \quad (4)$$

5) Ranking of Alternatives

Each dressing parameter set is ranked based on the computed AHP score. The higher the score, the better the overall performance considering both criteria.

3. EXPERIMENTAL WORK

An experiment was conducted to generate input data for the multi-criteria decision-making (MCDM) analysis. The experimental design followed the Taguchi method with an L16 ($4^4 \times 2^2$) orthogonal array. Table 1 lists the input parameters along with their respective levels.

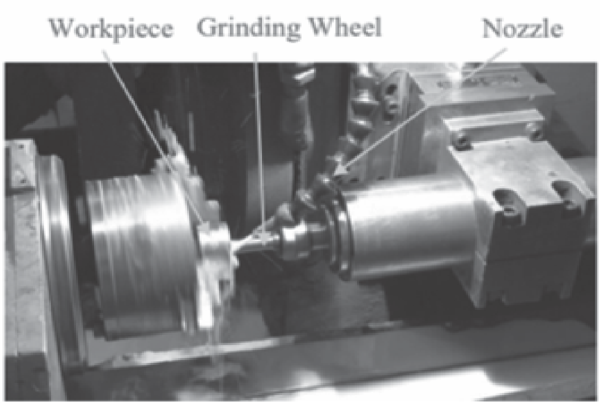

Figure 1. Experimental setup

Figure 1 illustrates the experimental setup, which includes the following equipment: A MACHT-701 surface grinding machine (Japan) was used to grind SKD11 tool steel workpieces with dimensions Ø25 × Ø36 × 22 mm and a hardness of 58-60 HRC. The grinding wheel employed was a 19A 120L 8 ASI T S 1A (Japan) with dimensions 23 × 25 × 8 mm. Surface roughness was measured using a Mitutoyo SV-3100 tester, while a DKB3E002110 diamond dresser and Caltex Aquatex 3180 oil were used for dressing and lubrication, respectively.

The experimental procedure was carried out as follows: Each sample was ground until its surface roughness (Ra) exceeded 0.4 µm, at which point both wheel life (Lw) and material removal rate (MRR) were evaluated. The processing time was recorded for each trial to determine Lw, while MRR was calculated by measuring the workpiece diameter before and after grinding. The MRR for the ith trial was computed using Equation (5):

$$MRR_i = \frac{\pi \cdot \left(d_{pbi}^2 - d_{pai}^2\right) \cdot l_{pi}}{4 \cdot T_{wi}} \quad (5)$$

Where d_{pbi} and d_{paid} are the inner diameters of the i_{th} workpiece before and after grinding (mm), l_{pi} is the workpiece length (mm), T_{wi} is the grinding time or wheel life (min).

Table 1 presents the complete experimental plan along with the measured output responses, including surface roughness (Ra), material removal rate (MRR), and wheel life (Lw).

Table 1. Experimental matrix and output results

No.	a_f	n_f	n_0	n_r	a_r	S_d	Ra (µm)	Lw (min.)
1	0.005	0	0	1	0.03	1	0.365	11.267
2	0.005	1	1	2	0.03	1.5	0.214	12.733
3	0.005	2	2	3	0.04	1	0.195	12.697
4	0.005	3	3	4	0.04	1.5	0.242	11.423
5	0.01	0	1	3	0.04	1.5	0.185	11.803
6	0.01	1	0	4	0.04	1	0.248	12.430
7	0.01	2	3	1	0.03	1.5	0.252	11.147
8	0.01	3	2	2	0.03	1	0.217	12.077
9	0.015	0	2	4	0.03	1.5	0.306	12.547
10	0.015	1	3	3	0.03	1	0.324	12.077
11	0.015	2	0	2	0.04	1.5	0.341	12.027
12	0.015	3	1	1	0.04	1	0.354	12.503
13	0.02	0	3	2	0.04	1	0.318	12.177
14	0.02	1	2	1	0.04	1.5	0.313	10.620
15	0.02	2	1	4	0.03	1	0.326	13.153
16	0.02	3	0	3	0.03	1.5	0.363	12.230

4. RESULTS AND DISCUSSION

This section presents the analytical results from the AHP-based evaluation of dressing parameter combinations in the grinding of SKD11 steel. The focus is placed on interpreting the ranking outcomes, visual patterns, and implications for dressing optimization in surface grinding.

4.1. AHP Ranking Results

Based on the computed AHP weights (Ra = 0.25, Tw ≥ 0.75), all 16 dressing parameter combinations were evaluated. The normalized values of Ra and Tw were combined to produce a unified AHP Score for each trial. The top five results, ranked in descending order of AHP Score, are presented in Table 2.

The highest AHP score was achieved by Trial No. 3, with an Ra value of 0.195 µm and a Tw of 12.70 minutes. This suggests that an optimal trade-off between low surface roughness and high tool life can be achieved with this parameter combination, making it the most desirable configuration among all alternatives evaluated. ☞

Table 2. Top five dressing trials ranked by AHP Score.

Trial No.	a_f (mm)	n_f	n_0	n_r	a_r (mm)	S_d	Ra (μm)	Tw (min)	AHP Score	Rank
3	0.005	2	2	3	0.04	1.0	0.195	12.70	1.193	1
5	0.010	0	1	3	0.04	1.5	0.185	11.80	1.167	2
2	0.005	1	1	2	0.03	1.5	0.214	12.73	1.153	3
8	0.010	3	2	2	0.03	1.0	0.217	12.08	1.110	4
6	0.010	1	0	4	0.04	1.0	0.248	12.43	1.077	5

4.2. Visualization of AHP Scores

To provide a clear overview of all experimental results, Figure 2 illustrates the AHP Score for each experiment, with the best-performing configuration (Rank 1) highlighted in red.

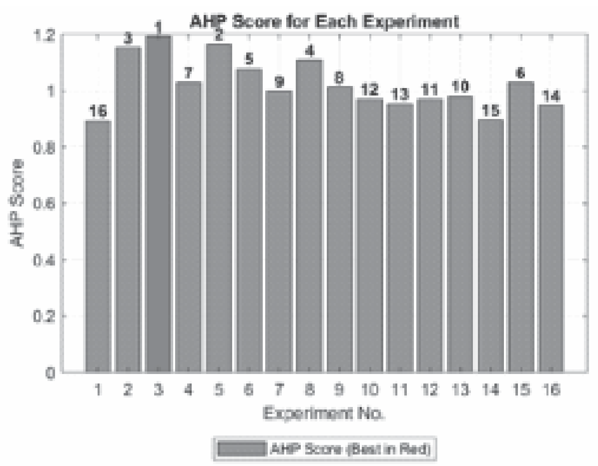

Figure 2. AHP Score for each dressing trial.

As seen in Figure 1, AHP scores range from approximately 0.90 to 1.19. Trial 3 stands out clearly above the rest, validating its dominant performance. The distribution also shows that several other trials - namely Trials 5, 2, and 8 - achieved high scores, indicating acceptable trade-offs between Ra and Tw.

4.3. Normalized Criteria Comparison

Figure 3 compares the normalized values of Ra (cost-type, inverted) and Tw (benefit-type) across all experiments. This visual highlight the trade-off effect that often occurs between surface quality and tool wear resistance.

From Figure 3, it can be observed that although some trials (e.g., Trial 5) had extremely low Ra values (leading to high R_{anorm}), their T_{wnorm} values were slightly lower than others. Trial 3, however, maintained a strong balance between both criteria ranking among the top in both normalized Ra and Tw thus explaining its dominance in the AHP ranking.

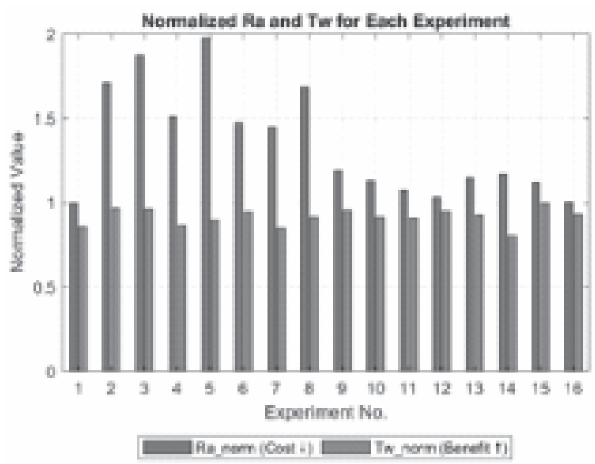

Figure 2. Normalized surface roughness (Ra) and tool life (T_{wnorm}) for all dressing configurations.

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4.4. Discussion and Practical Implications

The results reveal that neither the lowest Ra nor the highest Tw alone determines the best dressing configuration. Instead, a weighted combination of both is needed. The use of AHP enables such multi-criteria integration in a transparent and structured way.

In practical terms, this approach aids process engineers in identifying dressing settings that deliver consistent surface quality without compromising wheel life - an essential requirement in industrial grinding of hardened steels like SKD11.

5. CONCLUSION

This study presented a structured multi-criteria decision-making approach using the Analytic Hierarchy Process (AHP) to evaluate dressing parameter combinations in the surface grinding of SKD11 tool steel. Two critical and conflicting performance indicators surface roughness (Ra) and grinding wheel life (Tw) were considered simultaneously.

Based on experimental data from 16 dressing configurations, the AHP method successfully integrated expert preferences (with Tw weighted three times more than Ra) to compute composite performance scores. The results revealed that the best-performing configuration (Trial 3) offered an optimal trade-off between minimal surface roughness and prolonged wheel life, achieving the highest AHP Score of 1.193.

Visualization of AHP Scores and normalized criteria further confirmed the effectiveness of the proposed method in identifying balanced solutions, highlighting the limitations of single-objective optimization in complex grinding processes. The use of AHP provided a transparent and rational basis for decision-making in parameter selection.

The findings demonstrate that AHP is a viable and practical tool for optimizing dressing strategies in grinding operations, particularly when dealing with hard materials such as SKD11. Future work may extend this approach by incorporating more criteria such as grinding force, energy consumption, or economic cost, and integrating it with machine learning-based prediction models for real-time optimization.

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