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MULTI-RESPONSE OPTIMIZATION OF MACHINING PERFORMANCE UNDER DRY AND CASTOR OIL–BASED MQL CONDITIONS USING GREY RELATIONAL ANALYSIS

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ABSTRACT

This study evaluates the combined machining performance of hardened martensitic stainless steel under dry and castor oil–based minimum quantity lubrication (MQL) conditions using grey relational analysis (GRA). Twelve experimental runs were evaluated at cutting speeds of 100–170 m/min and feed rates of 0.16–0.24 mm/rev, while maintaining a constant depth of cut of 0.2 mm. Tool life and surface roughness were selected as the performance responses. The responses were normalized using the larger-the-better criterion for tool life and the smaller-the-better criterion for surface roughness. Grey relational grades (GRGs) were calculated using equal response weights and a distinguishing coefficient of 0.5. Dry machining at 170 m/min and 0.24 mm/rev achieved the highest GRG of 1.0000, corresponding to a tool life of 33.70 min and a surface roughness of 0.380 µm. MQL at the same cutting parameters ranked second, with a GRG of 0.8466, a tool life of 26.44 min, and an identical surface roughness. The relative performance of the two lubrication conditions varied with the cutting parameters, indicating that castor oil–based MQL did not consistently outperform dry machining. Within the investigated dataset, dry machining at 170 m/min and 0.24 mm/rev provided the best observed combination of tool life and surface finish. Independent confirmation experiments are required to establish the repeatability of this result and support broader process recommendations

Keywords: Grey Relational Analysis; Minimum Quantity Lubrication; Castor Oil; Dry Machining; Tool Life; Surface Roughness

1 INTRODUCTION

Machining involves cutting action in separating the chip from the bulk (machined workpiece) as well as friction in the regions of contact, viz. between cutting tool and chip and between cutting tool and workpiece. These interactions induce high temperature in the cutting region as well as high cutting forces, particularly in high production machining. These might lead to rapid wear of the cutting tool, dimensional deviation of the machined parts and inferior surface integrity [1]. In order to overcome the negative effects of high cutting temperature and forces, cutting fluids are commonly used. Using cutting fluids in machining process has significant effect in the reduction of temperature and lubrication to tool and workpiece, which in turn results in longer tool life and improved surface quality. Minimum Quantity Lubrication (MQL) is a technique which sprays small amount of lubricant to the cutting zone area with the aid of compressed air. MQL has become an attractive option to conventional flood cooling and shows better results in terms of being able to increase tool life and reduce cost of the product, in addition to its green image and economic benefit. MQL technique

consumes oil in the range of approximately 10–100 ml/h (Dhar et al., 2006a; Weinert et al., 2004). It was used in machining various workpiece materials, including steels, aluminum alloys, and inconel, using carbide tools [2, 3, 4, 5, 6, 7]. Using MQL, cutting fluids can penetrate deep into the tool-chip and tool workpiece interface thus obtaining positive results. The overall performance resulted was better than dry and conventional wet turning in terms of being able to increase tool life, reduce cutting forces and temperature and enhance surface quality, which is beneficial environmentally and also economically [8]. Cutting fluid is another factor to be considered in machining. Weinert investigated the use of different cutting fluids (two emulsions and one synthetic) compared to dry cutting when turning hardened steel (49 HRC) using mixed alumina tools and found that the emulsions fluids (no mineral oil) and dry cutting produce better result than synthetic fluids and emulsions with mineral oil [9]. Vegetable oils are often proposed as alternative cutting fluids to the mineral-based oils, including for use in MQL. Of interest among available cutting fluids are those of vegetable oils, especially non edible ones. Khan and Dhar (2006) reported that applying MQL technique using vegetable oil offers better performance than dry cutting where cutting forces were reduced by 5 – 15%. Vegetable oil has proven to be a multi-purpose fluid which can be used as the cutting fluid as base oil with MQL in turning, drilling and other machining methods of metal and perform good lubricant and cooling effect [2]. This has been successful demonstrated by various researchers by Chinchanikar and Choudhury and Noordin [10,11]. However, up to the present, no work has been done on turning hardened stainless steel with coated carbide tools under MQL castor oil condition. Varadarajan turned hardened steel (AISI 4340) of 46 HRC with speed of up to 120 m/min and feed of 0.1 mm/rev using mineral oil [6].

This study explores the use of vegetable oil (castor oil) as the cutting fluids for turning of hardened martestic stainless steel under MQL condition. Different machining input parameters (cutting speed and feed) are varied to evaluate the MQL technique's performance. Tool life, surface roughness, and cutting forces are the machining responses to be evaluated. Experimental setup, procedure and equipment

2 EXPERIMENTAL METHOD

Two factors were investigated, viz. cutting speed and feed rate, for each test performed. The response variables were tool life and surface roughness. Three experiments of comparison were conducted for each condition of dry cutting and MQL for comparisons (Table 1).

Tool life was determined by measuring the tool wear using an optical microscope (Zeiss, type Stemi 200-C) (Figure 1). The worn tools were cleaned using hydrochloric acid (HCI) followed by acetone to remove oil stains and dirt particles before their images were captured at high magnification for tool mode failure studies and element identification using field emission scanning electron microscope (FESEM) (Figure 2).

Three experiments were conducted for each condition of dry and MQL castor oil at various cutting speeds and feed rates (100 m/min, 016 mm/rev), (135 m/min, 0.20 mm/rev), and (170 m/min, 0.24 mm/rev) and constant depth of cut of 0.2 mm.



Figure 1: FESEM



Figure 2: Optical

Table 1: Results of tool life and Surfaceroughness under dry and MQL castor oil conditions

Condition	Cutting speed (m/min)	Feed rate (mm/rev)	Tool life (Min)	Surface roughness (µm)
Dry	100	0.16	17.7	0.41
Dry	170	0.16	5.5	0.44
Dry	100	0.24	0.9	0.55
Dry	170	0.24	33.7	0.38
MQL	100	0.16	8.3	0.38
MQL	170	0.16	1.5	0.43
MQL	100	0.24	14.21	0.419
MQL	170	0.24	26.44	0.38
Dry	135	0.2	3.53	0.487
Dry	135	0.2	5.39	0.401
MQL	135	0.2	4.23	0.382
MQL	135	0.2	5.78	0.498

3 ANALYSIS METHOD

1.1. Grey rational analysis

During normalization, all output parameters are converted into dimensionless values. Furthermore, the range of the parameters is restricted to 0–1, where "0" indicates the lowest value and "1" the highest value. This standard ensures comparison of the various parameters is easy. Moreover, the risk of errors in the normalized values is low. Typically, the normalization process involves two concepts into the Taguchi's technique (nominal the smaller is the better and higher is the better). The "higher is the better" concept is used for normalizing the tool life. In principle, the formula for the normalization process is presented in Eq 1, However, the lower is the better concept is used for normalizing the variables surface roughness by the next Eq 2

$$x_i^*(k) = \frac{x_i(k) - min\ x_i(k)}{max\ x_i(k) - min\ x_i(k)} \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

$$x_i^*(k) = \frac{max\ x_i(k) - x_i(k)}{max\ x_i(k) - min\ x_i(k)} \ldots\ldots\ldots\ldots\ldots\ldots (2)$$

The terms x_i (k) is the i^{th} series in the original value of k; order $x_i^*(k)$ is the i^{th} series and k order after normalization, $minx_i(k)$ is the minimum value in the i^{th} series, $max\ x_i(k)$ is the maximum value in the i^{th} series**.** Table 3 shows the normalized results of experimental results obtained for performances.

Table 2: Sequence values for responses

Exp no	Tool life	SR
Reference sequence	1	1
1	0.512195	0.823529
2	0.140244	0.647059
3	0	0
4	1	1
5	0.22561	1
6	0.018293	0.705882
7	0.405793	0.770588
8	0.778659	1
9	0.080183	0.370588
10	0.13689	0.876471
11	0.101524	0.988235
12	0.14878	0.305882

Table 3: Deviation sequence values

Exp no	Tool life	SR
1	0.487805	0.176471
2	0.859756	0.352941
3	1	1
4	0	0
5	0.77439	0
6	0.981707	0.294118
7	0.594207	0.229412
8	0.221341	0
9	0.919817	0.629412
10	0.86311	0.123529
11	0.898476	0.011765
12	0.85122	0.694118

1.2. Grey rational coefficients (GRC)

Normalization creates a new matrix of difference vectors. From this matrix, a GRC is calculated, expressed as:

$$\vartheta_i(k) = \frac{(\Delta min \; + \; \xi \Delta max)}{(\Delta_{0i}(\mathrm{k}) \; + \; \xi \Delta max \,)} \quad (3)$$

The term $\vartheta i(k)$ denotes GRC for the *k* output parameter and $\Delta_{0i}(k) = | x_0^*(k) - xi^*(k) |$ is the deviation sequence. Lastly, $\Delta min = min| x_0^*(k) - x_i^*(k)|$ whereas $\Delta max = max |x_0^*(k) - x_i^*(k)|$ and **ζ**= weighting coefficient that is 0.5.

1.3. Grey Relational Grades (GRG)

Table 4: GRG for each experimental run

Expt. no	Grey Relational Coefficient		Grey relational grade (γ)	Rank
	Tool life $\vartheta i(1)$	SR $\vartheta i(2)$		
1	0.506173	0.73913	0.62265164	5
2	0.367713	0.586207	0.47695995	9
3	0.333333	0.333333	0.33333333	12
4	1	1	1	1
5	0.392344	1	0.69617225	3
6	0.337449	0.62963	0.48353909	8
7	0.456952	0.685484	0.57121783	7
8	0.693153	1	0.8465765	2
9	0.352158	0.442708	0.39743319	10
10	0.366808	0.801887	0.58434756	6
11	0.357532	0.977011	0.66727183	4
12	0.370036	0.418719	0.39437766	11

Finally, the GRG is obtained by averaging the GRC corresponding to each performance measures. Thus by applying (Eq 4), all GRGs can be computed

$$(\gamma)i = \frac{1}{n}\sum_{1}^{n} \vartheta_i(k) \quad (4)$$

The term γ denotes the Grey Relational Grade (GRG) while ,*n,* is the number of output parameters. Table 4 presents the grey rational coefficients and grades for each response.

4 RESULTS AND DISCUSSION

Grey relational analysis (GRA) was applied to evaluate the combined performance of tool life and surface roughness under dry and castor-oil MQL conditions. Tool life was normalized using the larger-the-better criterion, whereas surface roughness was normalized using the smaller-the-better criterion. Equal weights were assigned to both responses, and a distinguishing coefficient of 0.5 was used to calculate the grey relational coefficients and the overall grey relational grade (GRG). Experiment 4, conducted under dry conditions at a cutting speed of 170 m/min and a feed rate of 0.24 mm/rev, achieved the highest GRG of 1.0000. This experiment provided the longest tool life of 33.7 min and the joint-lowest surface roughness of 0.380 µm. Its highest ranking therefore reflects simultaneous superiority in both responses within the investigated dataset, rather than a compromise between competing objectives. A GRG of unity indicates agreement with the reference sequence defined by the best observed values; it does not imply absolute process efficiency or optimality beyond the tested conditions. Experiment 8, performed under MQL at the same cutting speed and feed rate, ranked second with a GRG of 0.8466. Although it achieved the same surface roughness of 0.380 µm, its tool life was lower at 26.44 min. Consequently, the difference in GRG between these two experiments was attributable entirely to tool life. Experiment 5 ranked third with a GRG of 0.6962, combining a surface roughness of 0.380 µm with a tool life of 8.3 min. In contrast, Experiment 3 exhibited the lowest GRG of 0.3333 because it produced both the shortest tool life and the highest surface roughness. The results also indicate that the relative performance of dry machining and MQL depended on the cutting parameters. At 100 m/min and 0.16 mm/rev, MQL achieved a higher GRG than dry machining despite its shorter tool life, because of its improved surface finish. However, at 170 m/min and 0.24 mm/rev, dry machining achieved the higher GRG through longer tool life at an identical surface roughness. Thus, the ranking does not support a general claim that either lubrication condition consistently outperformed the other across all tested

settings. Overall, dry machining at 170 m/min and 0.24 mm/rev was identified as the best observed combination for the simultaneous improvement of tool life and surface roughness under the adopted GRA criteria. Independent confirmation experiments are required to assess the repeatability of this result. In addition, the GRA ranking alone does not establish the statistical significance of individual factors or their interactions

Table 5: Response table for GRG

Machining parameters	Grey Relational Grade			Main Effect Max-Min	Rank
	Level 1	Level 2	Level 3		
Cutting speed	0.555844	0.510858	0.701769	0.190911	2
Feed rate	0.569831	0.510858	0.649376	0.138519	1
Total mean value of the Grey relational grade (γ) = 0.589490069 * Levels for optimum GRG					

Total mean value of GRG = 0.58949; * Levels for optimum GRG

5 CONCLUSION

This study applied grey relational analysis to assess tool life and surface roughness simultaneously under dry and castor oil–based MQL machining conditions. Based on the investigated dataset, the following conclusions can be drawn

- Dry machining at a cutting speed of 170 m/min and a feed rate of 0.24 mm/rev produced the best observed overall performance, achieving the highest grey relational grade of 1.0000. This condition combined the longest tool life of 33.70 min with the joint-lowest surface roughness of 0.380 μm.
- Castor oil–based MQL at the same cutting speed and feed rate ranked second, with a grey relational grade of 0.8466. It achieved an identical surface roughness of 0.380 μm but a shorter tool life of 26.44 min. Thus, dry machining provided approximately 27.5% longer tool life than MQL at this particular setting.
- The relative performance of dry machining and MQL depended on the cutting parameters. At 100 m/min and 0.16 mm/rev, MQL achieved a higher overall grade despite its shorter tool life, reflecting the contribution of improved surface finish under equal response weighting. Consequently, neither lubrication condition demonstrated consistent superiority across all investigated settings.
- GRA provided a systematic means of combining the two machining responses into a single comparative index. However, a grey relational grade of unity represents agreement with the best observed response values within the dataset and does not establish a universal process optimum.
- The identified best-performing condition should be verified through independent confirmation experiments. Additional replication and statistical analysis are necessary to quantify experimental variability and determine the significance of cutting speed, feed rate, lubrication condition, and their interactions.

STATEMENTS ON COMPLIANCE WITH ETHICAL STANDARDS

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Disclosure of conflict of interest

The author declared that there was no conflict of interest during the cause of this study and producing and submitting this manuscript for publications.

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