Optimization of Dressing Parameters for Minimum Surface Roughness and Maximum Material Removal Rate in Internal Grinding of SKD11 Tool Steel

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Abstract. This paper introduces a study on multi-objective optimization of dressing parameters in internal grinding of SKD 11 tool steel using Grey based Taguchi method. The L27 orthogonal array of the Taguchi method was selected to design the experiments. The input parameters of the dressing process are the depth of fine, the time of fine dressing, the depth of coarse dressing, the time of coarse dressing, non-feeding dressing, and dressing feed rate. The output factors are surface roughness (SR) and material removal rate (MRR). A grey relation grade was determined by using the signal-to-noise ratio. The ANOVA was applied to find out the effect of input factors on the grey relation grade. In conclusion, the fine dressing times is the parameter that has the strongest impact on multiple performance characteristics, followed by the coarse dressing times. Also, the optimum dressing parameters to get minimum SR and maximum MRR is the depth of coarse dressing of 0.03mm, the time of coarse dressing of 2 times, the depth of fine dressing of 0.01 mm, the time of fine dressing of 2 times, non-feeding dressing of 2 times, and dressing feed rate of 1.2mm/min.

Keywords: Internal grinding, dressing parameters, multi-objective optimization, SKD11.

1. Introduction

The achievement of two requirements at the same time, which is to ensure the quality of processing and to achieve the highest processing capacity, has attracted researchers and manufacturers around the world. However, quality and productivity in machining are often two opposing requirements. Optimizing to achieving the best quality while also achieving the highest productivity is called multi-objective optimization. To solve the single-objective optimization problem in experimental research, researchers often use Taguchi method. This is a simple yet very powerful method to use[1, 2]. This optimal method is especially suitable for experimental studies that need to ensure evaluation efficiency and economic criteria with a small number of experiments. However, Taguchi cannot be applied to solve the multi-objective optimization problem[3]. To solve this problem, a method combining Taguchi and Gray relational analysis was proposed by J. Deng [4]. The Grey based Taguchi method has been applied and obtained positive results in many researches in metal cutting such as milling[5, 6], drilling[7], turning[8-10], grinding[11-14], EDM[3], and so on.

SKD11 alloy steel is widely used in industry because of its characteristics such as good purity, high toughness, uniform structure, high temperature strength, good fatigue resistance. In addition, SKD11 steel can endure sudden temperature changes and works long-time at high temperature [15]. Therefore, it is a popular research object in metalworking. In metal grinding, internal grinding is one of the most

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complex grinding processes. In internal grinding, the working space is limited by the size of the hole, the diameter of the grinding wheel. The temperature in the machining zone can reach over 1000ºC [16]. By working in such harsh conditions, the performance of the grinding wheel will decrease rapidly. A process that is requested to return the performance of the grinding wheel to its original state is dressing process [17]. Many conclusions have been drawn that that applying the right dressing mode can improve roughness [18-20] as well as improve MRR [21, 22].

In metal cutting, surface roughness characterizes the quality of the machining process. In contrast, MRR is specific for machining productivity. Simultaneously achieving the minimum roughness and the highest MRR is always attractive to researchers. In the study, Grey based Taguchi method was applied to optimize the dressing parameters for minimizing roughness and maximizing MRR in internal grinding of hardened SKD 11 alloy steels. The input factors including coarse dressing depth, coarse dressing times, fine dressing depth, fine dressing times, non-feeding dressing, and dressing feed rate were selected to investigate their impact on multiple performance characteristics.

2. Experimental design

No.	Input factors	symbol	unit	levels			
				1	2	3	4
1	Coarse dressing depth	a_r	mm	0.025	0.03	-	-
2	Coarse dressing times	n_r	time	1	2	3	4
3	Fine dressing depth	a_f	mm	0.005	0.01	0.015	0.02
4	Fine dressing times	n_f	time	0	1	2	3
5	Non-feeding dressing	n_0	time	0	1	2	3
6	Dressing feed rate	S_d	m/min	1	1.2	-	-

In the study, a MACHT-701 (Japan) grinding machine was used for all experiments. The SKD11 steel workpieces with a dimension of ϕ25 ×ϕ36 × 22 mm were heat treated to a hardness of 60HRC. In each experiment, a new 19A 120L 8 ASI T S 1A (Japan) with a dimension of 23×25×8 mm was used. The surface roughness was measured via Mitutoyo SV-3100. The material removal rate (MMR) is determined by using a high precision scale. Diamond dresser is DKB3E002110. Caltex Aquatex 3180 with concentration of 2% - 5% was cooling oil used in the experiment. Table 1 shows the input factors selected in the study.

1 Results and discussions

After the experiment, the data was collected and presented in Table 2.

Table 1. The result of the experiment

No.	a_r	n_r	a_f	n_f	n_0	S_d	Ra (μm)			MRR (mm³/s)		
							Trial 1	Trial 2	Trial 3	Trial 1	Trial 2	Trial 3
1	0.025	1	0.005	0	0	1.0	0.365	0.367	0.364	0.919	0.922	0.915
2	0.030	1	0.010	1	1	1.0	0.214	0.212	0.215	1.035	1.040	1.049
3	0.025	1	0.015	2	2	1.2	0.198	0.194	0.192	1.117	1.122	1.125
4	0.030	1	0.020	3	3	1.2	0.242	0.240	0.243	1.102	1.114	1.117
5	0.030	2	0.005	1	2	1.2	0.185	0.187	0.183	1.248	1.252	1.238
6	0.025	2	0.010	0	3	1.2	0.249	0.248	0.246	1.275	1.265	1.260
7	0.030	2	0.015	3	0	1.0	0.252	0.250	0.254	1.174	1.182	1.179
8	0.025	2	0.020	2	1	1.0	0.217	0.214	0.219	1.219	1.230	1.226
9	0.030	3	0.005	2	3	1.0	0.307	0.305	0.307	1.488	1.492	1.484
10	0.025	3	0.010	3	2	1.0	0.324	0.322	0.326	1.366	1.372	1.379
11	0.030	3	0.015	0	1	1.2	0.343	0.340	0.339	1.268	1.275	1.270
12	0.025	3	0.020	1	0	1.2	0.354	0.356	0.352	1.193	1.195	1.208
13	0.025	4	0.005	3	1	1.2	0.320	0.318	0.316	1.227	1.220	1.235
14	0.030	4	0.010	2	0	1.2	0.313	0.310	0.315	1.268	1.264	1.262
15	0.025	4	0.015	1	3	1.0	0.327	0.325	0.326	1.124	1.129	1.121
16	0.030	4	0.020	0	2	1.0	0.363	0.365	0.362	1.183	1.189	1.198

After the experiment, the simultaneous optimization is carried out by using Grey-based Taguchi method. The main steps of this optimization process are given with the steps as follows:

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In the first step, the signal to noise (S/N) is determined for corresponding responses. The object of this study is to reduce the surface roughness and increase the *MRR*. Thus, the-smaller-is-the-better S/N determined by formula (1) is the suitable type for the roughness and the-larger-is-the-better S/N determined by formula (2) is the suitable type for the *MRR*:

The-smaller-is-the-better S/N:

$$SN = -10log_{10}(\frac{1}{n}\sum_{i=1}^{n} y_i^2) \quad (1)$$

The-larger-is-the-better S/N:

$$SN = -10log_{10}(\frac{1}{n}\sum_{i=1}^{n} \frac{1}{y_i^2}) \quad (2)$$

Where: y_i is the data of the experiment, n is number of repetitions of an experiment.

Table 2. The result of Grey-based Taguchi method

Exp. No	S/N		Zi		Δj(k)		Grey relational co-efficient γi		$\bar{\gamma}$
	Ra	MRR	$\overline{Ra}$	$\overline{MRR}$	$\overline{Ra}$	$\overline{MRR}$	$\overline{Ra}$	$\overline{MRR}$	
			Z0(k)						
			1.000	1.000					
1	8.7488	-0.7372	0.000	0.000	1.000	1.000	0.333	0.333	0.3333
2	13.4051	0.3511	0.788	0.260	0.212	0.740	0.702	0.403	0.5553
3	14.2084	0.9958	0.924	0.414	0.076	0.586	0.868	0.460	0.6664
4	12.3355	0.9143	0.607	0.394	0.393	0.606	0.560	0.452	0.5006
5	14.6562	1.9091	1.000	0.632	0.000	0.368	1.000	0.576	0.788
6	12.1225	2.0528	0.571	0.666	0.429	0.334	0.538	0.600	0.569
7	11.9718	1.4244	0.546	0.516	0.454	0.484	0.524	0.508	0.516
8	13.2838	1.7630	0.768	0.597	0.232	0.403	0.683	0.554	0.618
9	10.2729	3.4510	0.258	1.000	0.742	0.000	0.403	1.000	0.701
10	9.7920	2.7494	0.177	0.832	0.823	0.168	0.378	0.749	0.563
11	9.3562	2.0825	0.103	0.673	0.897	0.327	0.358	0.605	0.481
12	9.0171	1.5744	0.045	0.552	0.955	0.448	0.344	0.527	0.436
13	9.9544	1.7788	0.204	0.601	0.796	0.399	0.386	0.556	0.471
14	10.1013	2.0400	0.229	0.663	0.771	0.337	0.393	0.597	0.495
15	9.7386	1.0204	0.168	0.420	0.832	0.580	0.375	0.463	0.419
16	8.7912	1.5094	0.007	0.536	0.993	0.464	0.335	0.519	0.4

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In second step, normalization of data preprocessing for raw data (S/N data) is performed. The linear normalization of the S/N ratio is conducted by applying the grey relational generating (a range between zero and unity). The normalized S/N ratio Zij for the i^{th} performance characteristic in the j^{th} experiment is determined by equation (3).

$$Z_{ij} = \frac{SN_{ij} - \min(SN_{ij}, j=1,2,..k)}{\max(SN_{ij}, j=1,2,..n) - \min(SN_{ij}, j=1,2,..n)} \quad (3)$$

In next step, the grey relation coefficient is calculated by (4)

$$\gamma(k) = \frac{\Delta min + \zeta \Delta max}{\Delta_j(k) + \zeta \Delta max} \quad (4)$$

Where:

j=1, 2…n; k=1, 2…m, n is the number of experiments, k is the number of objects.

Δj(k) is the deviation sequence and determined as the equation:

$$\Delta_{j(k)} = \|Z_0(k) - Z_j(k)\|.$$

$$\Delta\text{min} = \min_{\forall j \in i} \min_{\forall k} \|Z_0(k) - Z_j(k)\| ;$$

$$\Delta\text{max} = \max_{\forall j \in i} \max_{\forall k} \|Z_0(k) - Z_j(k)\|.$$

ζ is the distinguishing coefficient $0 \le \zeta \le 1$. In this case, $\zeta = 0.5$.

After the third step, the grey relational grade γ_i is calculated as equation (5).

$$\overline{\gamma_j} = \frac{1}{k}\sum_{i=1}^{m} \gamma_{ij} \quad (5)$$

Where γ_j is the grey relational grade for the j^{th} experiment; k is the number of objectives (in this study, k=2).

Table 3 shows the result of steps of Grey-based Taguchi method.

In the next step, Taguchi will be used to determine the influence of the inputs on the grey relational grade. The Table 4 shows the response for S/N ratio. As shown in this table, it can be seen that the fine dressing times is the most influential factor on the grey relational grade with the 1st rank, followed by the coarse dressing times.

Level	n_r	a_f	n_f	n_0	a_r	S_d
1	-6.040	-5.309	-7.046	-7.152	-6.059	-5.954
2	-4.223	-5.283	-5.498	-5.555	-5.226	-5.331
3	-5.409	-5.801	-4.228	-4.500	-	-
4	-6.898	-6.176	-5.797	-5.363	-	-
Delta	2.675	0.893	2.818	2.652	0.833	0.623
Rank	2	4	1	3	5	6
Larger is better						

Figure 1 shows the main effects plot for the grey relational grade. Figure 1 shows the optimal levels of each input to achieve the goal set out in this study. That means, to achieve minimum roughness and maximum material removal rate, dressing mode needs to be done with the coarse dressing depth of 0.03mm, the coarse dressing times of 2 times, the fine dressing depth of 0.01mm, the fine dressing times of 2 times, the non-feeding dressing of 2 time, and the dressing feed rate of 1.2m/min.

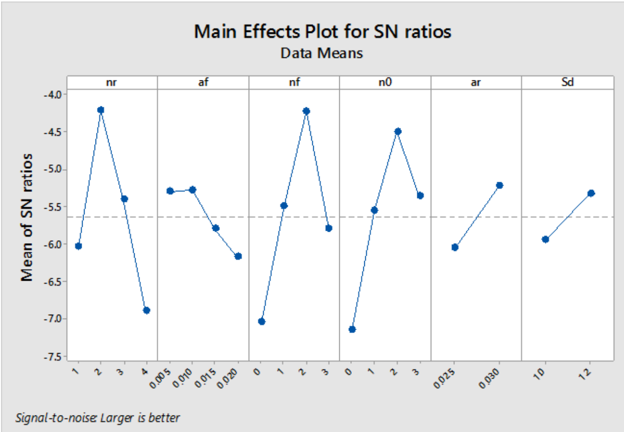

Fig. 1. Main effects plot

The table of variance analysis is shown in Table 5. Table 5 shows that the factor with the greatest influence on the grey relational grade is the fine dressing times. The impact percentage of the fine dressing times is 30.26%. The second biggest influencing factor is the coarse dressing times with 28.65%. The third biggest impact factor is the non-feeding dressing with 27.66%. The other factors have a weak impact with less than 10%.

Table 3. Analysis of Variance for SN ratios

Source	DF	Seq SS	Adj SS	Adj MS	F	P	C(%)
n_r	3	15.2095	15.2095	5.0698	8.36	0.248	28.65
a_f	3	2.2028	2.2028	0.7343	1.21	0.569	4.15
n_f	3	16.0643	16.0643	5.3548	8.83	0.241	30.26
n_0	3	14.6847	14.6847	4.8949	8.08	0.252	27.66
a_r	1	2.7735	2.7735	2.7735	4.58	0.278	5.22
S_d	1	1.5500	1.5500	1.5500	2.56	0.356	2.92
Residual Error	1	0.6061	0.6061	0.6061			1.14
Total	15	53.0910					

Finally, the predictive value of the output responses when applying the optimal conditions of the dressing process is given in Table 6 by Minitab v18 software. As shown in the table, the predicted value of roughness is 0,149910 µm and the predicted value of MRR is 1,39548mm3/s

Table 6. The results of predicted values

Response	S/N Ratio	Mean	StDev	Ln(StDev)
Ra	15.4739	0.149910	0.0030112	-5.68838
MRR	3.04296	1.39548	0.0057677	-5.20265

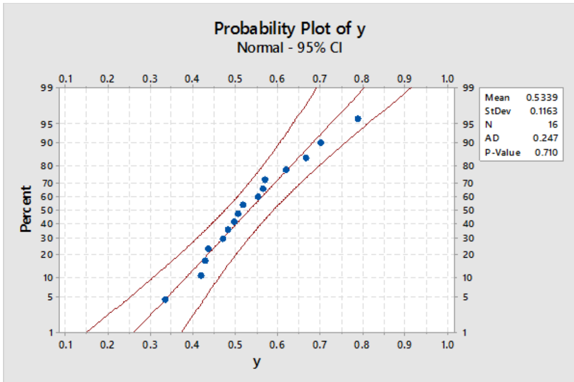

Fig. 2. The graph of the probability distribution

To evaluate the fit of the model with the data obtained from the experiment, the Anderson-Darling method is used. The results of this evaluation are shown in Figure 2. It can be seen that the data corresponding to the experimental points (blue dots) are in the region bounded by 2 upper and lower lines with the limit standard deviation of 95%. This indicates that the applied empirical model is reliable.

2 Conclusion

In the study, a simultaneous optimization on the dressing process for minimizing the SR and maximizing MRR in internal grinding of hardened SKD 11 tool steel was introduced. In the study, the grey-based Taguchi method was applied. From the study results, several main results are suggested as follows:

- To achieve minimum SR and maximum MRR, dressing process needs to be carried out with the coarse dressing depth of 0.03mm, the coarse dressing times of 2 times, the fine dressing depth of 0.01mm, the fine dressing times of 2 times, the non-feeding dressing of 2 time, and the dressing feed rate of 1.2m/min.

- The factor with the greatest influence on the grey relational grade is the fine dressing times with 30.26% total effects. The second biggest influencing factor is the coarse dressing times with 28.65%. The third biggest impact factor is the non-feeding dressing with 27.66%. The other factors have a weak impact with less than 10%.

- The results of the evaluation of the fit of the empirical model show that the model is completely reliable.

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