# A Study on Optimization of Surface Roughness in Surface Grinding 9CrSi Tool Steel by Using Taguchi Method

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**Abstract.** In this study, the Taguchi method was utilized to find the optional surface roughness in fine surface grinding of 9CrSi annealing tool steel using Hai Duong grinding wheels. Minitab 17 software was used to determine the number of experiments L16 of the Taguchi method including five cutting parameter factors namely cooling concentration (CC), cooling flow (F), cross feed (CF), table speed ($V_w$), and depth of cut (DOC). From the analysis results of a Signal to Noise ratio (S/N), the optimum process parameters for minimum surface roughness were proposed. In addition, it was found that the factor having the largest effect on surface roughness is the coolant concentration, followed by the cross feed, the table speed, the coolant flow and the depth of cut ranking the last. Besides, a model for determination of the surface roughness was recommended.

**Keywords:** Surface grinding · Surface roughness · Optimization
Taguchi method · Hai Duong grinding wheel

## 1 Introduction

Grinding is an abrasive machining type which is commonly used for finishing operations. It is known that this type of machining accounts for more than 20% of the total expenditures on machining operations in industries. Therefore, optimization of grinding process has been subjected to numerous studies.

Fredj et al. [1] have investigated the surface grinding of the austenitic stainless steel AISI 304 under three different environmental modes: dry, soluble oil and cryogenic cooling. It was noted that the cryogenic cooling generates the lowest grinding temperature. In addition, the surfaces with lower roughness could be generated when grinding eight types of steels under this mode. Another test has been carried out to compare the surface roughness of the ground parts obtained under the wet mode and that under the cryogenic cooling mode using high work speed and low cut depth values. In this case, the cryogenic cooling mode gave better effect than the wet mode. Also, the grinding temperature, the force components and the surface roughness were reduced by those grinding conditions.


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Mandal et al. introduced a study [2] on flood cooling with pneumatic barrier setup to break the stiff air layer around the grinding wheel which raises the effective flow of cutting fluid. Grinding experiments were performed under dry, flood cooling and flood cooling with pneumatic barrier setup. From this research, the reduction of the grinding forces and the surface roughness were clearly observed with the use of pneumatic barrier setup, and hence, its applicability.

da Silva et al. [3] have conducted a study to evaluate the influence of different types of cutting fluids in the wear of a vitrified CBN wheel in high speed grinding with the amount of removed material in the grinding tests (6764 $mm^3$/mm). Different cutting fluids types (cutting oil, synthetic fluid in the concentration of 3 and 20 ° Brix and water) were tested to estimate the radial wheel wear and the surface roughness when grinding AISI 52100 steel.

Beside using a suitable coolant, in [4] the researchers suggested an active coolant cooling system utilizing a commonly used air conditioner that can reduce both the grinding temperatures and the grinding cost when surface grinding. It was revealed that the coolant temperature can be reduced to approximately 20 °C under no load condition, and to approximately 30 °C under loaded condition.

There have been several studies on using a hybrid Minimum Quantity of Lubricant [5, 6] and on the influence of two cooling modes (oil-based grinding fluid and cryogenic cooling) on the ground surface integrity of hardened AISI D2 when using aluminum oxide and SG grinding wheels [7]. A review of optimization of fluid application in grinding can be found in [8]. Besides, Pande et al. [9] carried out a research on surface grinding under dry plunge-cut conditions for evaluation of the performance when grinding steels.

In [10] there was a discussion on discussed about factors involved in the mechanical grinding of odd-profiled pyroceramic components and their effect on the quality of product. An experimental investigation [11] was carried out to evaluate the effect of CBN crystal characteristics and plating thickness on the performance of electroplated CBN wheelst.

The authors in [12] carried out an optimization study on surface roughness in surface grinding silicon carbide. Asokan et al [13] concentrated on the optimum process parameters for both rough and finish grinding by using the genetic algorithm, quadratic programming, and particle swarm optimizer. A multi-objective optimization study for surface grinding to minimize the production cost and the surface roughness was presented in [14]. Taguchi method was used in [15] and [16] for the optimization of the grinding parameters to gain the minimum surface roughness.

From the above analyses, it is evident that until now there have been a number of researches on the optimization of grinding process as well as the surface grinding process. However, there is still a lack in research on the optimization of the surface roughness in surface grinding 9CrSi tool steel by Hai Duong grinding wheel. In this study, the input process parameters included the coolant concentration (CC), the coolant flow (F)), the cross feed (CF), the table speed ($V_w$), and the depth of cut (DOC). They were investigated for evaluating their influence on the surface roughness as well as for finding the minimum surface roughness when surface grinding 9CrSi steel with Hai Duong grinding wheel by using Taguchi method.

## 2 Experimental Setup

To optimize the surface roughness when surface grinding 9CrSi tool steel, an experiment was designed by using Taguchi method. This method was chosen as it can effectively reduce the number of tests required for the experiment. The grinding conditions for the experiment are presented in Table 1. The work material is 9CrSi tool steel which was hardened and tempered to 56–58 HRC. The dimensions of specimens are 100 × 60 × 25 (mm). Also, the chemical composition of the material is described in the Table 2. Moreover, the schema of experimental setup is shown in Fig. 1.

In this study, the coolant concentration (%), coolant flow (lit/min), the cross feed (mm/path), the table speed (m/min) and the depth of cut (mm) were selected as input process parameters. The level of this input parameters are shown in Table 3. An orthogonal array L16 ($5^4$) was adopted (Table 4).

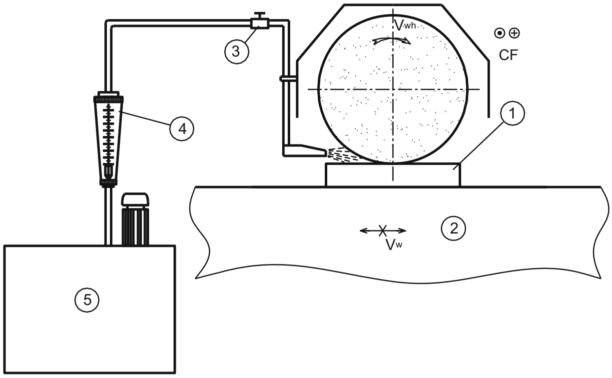


**Fig. 1.** Experimental setup: 1 - Workpiece; 2 - Magnetic table; 3 - Flow control valve; 4 - Flow measurement device; 5 - Coolant reservoir

**Table 1.** Grinding conditions for the experiment.

| Grinding machine | Moto – Yokohama (from Japan) |
|---|---|
| Grinding wheels | Cn46TB2GV1.300.32.127.30 m/s (Hai Duong, Vietnam) |
| Wheel speed (m/s) | 26,7 |
| Cooling modes | Caltex Aquatex 3180 |
| Environment | Flood |
| Dresser | Multi diamond dresser, 3908-0088C type 2 (from Russia) |
| Dressing depth (mm) | 0.02 × 3 + 0.01 × 2 |
| Crossing feed (m/min.) | 1.6 |
| Flow measurement device | Z-5615 Panel Flowmeter (from Thailand) |
| Surface roughness measuring instrument | SJ201 – Mitutoyo (from Japan) |

**Table 2.** Chemical composition of 9CrSi tool steel.

| C | Si | Mn | P ≤ | S ≤ | Cr ≤ | Mo ≤ | Ni ≤ | V ≤ | W ≤ | Other |
|---|---|---|---|---|---|---|---|---|---|---|
| 0.85–0.95 | 1.2–1.6 | 0.3–0.6 | 0.03 | 0.03 | 0.95–1.25 | 0.2 | 0.35 | 0.15 | 0.2 | Cu ≤ 0.3; Ti ≤ 0.03 |

**Table 3.** Input process parameters and design levels.

| Input parameters | Lable | Levels | | | |
|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 |
| Coolant concentration (%) | CC | 1 | 2 | 3 | 4 |
| Coolant flow (lit/min) | F | 5 | 10 | 15 | 20 |
| Cross feed (mm/path) | CF | 6 | 8 | 10 | 12 |
| Table speed (m/min) | Vw | 6 | 8 | 10 | 12 |
| Depth of cut (mm) | DOC | 0.005 | 0.01 | 0.015 | 0.02 |

**Table 4.** Standard L16 ($5^4$) orthogonal matrix.

| No. Test | CC | F | CF | Vw | DOC |
|---|---|---|---|---|---|
| 1 | 1 | 1 | 1 | 1 | 1 |
| 2 | 1 | 2 | 2 | 2 | 2 |
| 3 | 1 | 3 | 3 | 3 | 3 |
| 4 | 1 | 4 | 4 | 4 | 4 |
| 5 | 2 | 1 | 2 | 3 | 4 |
| 6 | 2 | 2 | 1 | 4 | 3 |
| 7 | 2 | 3 | 4 | 1 | 2 |
| 8 | 2 | 4 | 3 | 2 | 1 |
| 9 | 3 | 1 | 3 | 4 | 2 |
| 10 | 3 | 2 | 4 | 3 | 1 |
| 11 | 3 | 3 | 1 | 2 | 4 |
| 12 | 3 | 4 | 2 | 1 | 3 |
| 13 | 4 | 1 | 4 | 2 | 3 |
| 14 | 4 | 2 | 3 | 1 | 4 |
| 15 | 4 | 3 | 2 | 4 | 1 |
| 16 | 4 | 4 | 1 | 3 | 2 |

## 3 Results and Discussion

After processing, the surface roughness was measured by a strain gage transducer contact SJ-201 (Mitutoyo, Japan). The different levels of the input parameters and the results of the output response (the surface roughness Ra) are presented in Table 5.

**Table 5.** Experimental results of L16 ($5^4$) for surface roughness and their corresponding S/N ratios.

| Exp no. | Factor and their levels | | | | | Surface roughness (Ra) for repeated tests | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | CC | F | CF | $V_w$ | DOC | $Ra_1$ | $Ra_2$ | $Ra_3$ | Mean | S/N |
| 1 | 1 | 5 | 6 | 6 | 0.005 | 0.784 | 0.747 | 0.805 | 0.779 | 2.169 |
| 2 | 1 | 10 | 8 | 8 | 0.01 | 0.834 | 0.742 | 0.747 | 0.774 | 2.209 |
| 3 | 1 | 15 | 10 | 10 | 0.015 | 1.003 | 1.05 | 1.09 | 1.048 | -0.409 |
| 4 | 1 | 20 | 12 | 12 | 0.02 | 0.858 | 0.888 | 0.877 | 0.874 | 1.166 |
| 5 | 2 | 5 | 8 | 10 | 0.02 | 0.571 | 0.587 | 0.616 | 0.591 | 4.559 |
| … | | | | | | | | | | |
| 15 | 4 | 15 | 8 | 12 | 0.005 | 0.478 | 0.474 | 0.436 | 0.463 | 6.687 |
| 16 | 4 | 20 | 6 | 10 | 0.01 | 0.475 | 0.415 | 0.459 | 0.45 | 6.928 |

To evaluate the impact of the input factors on the surface roughness and to determine the optimum factors, the orthogonal arrays of Taguchi, the signal-to-noise (S/N) ratio and the analysis of variance (ANOVA) were conducted. The criterion "lower is better" was selected for the Signal to Noise ratio as the surface roughness is the factor of consideration, and it is described by the following equation [17]:

$$\mu = (S/N)i = -10log_{10}\left(\frac{1}{n}\sum\nolimits_{i=1}^{n} y_{ij}^2\right) \tag{1}$$

Where, $\mu$ represents S/N ratio for "lower is better"; n is the number of repetitions in each experiment; $y_{ij}$ is the measured value of quality characteristic for the $i^{th}$ (i = 1, 2, 3, … n) of the $j^{th}$ experiment (j = 1, 2, 3 … 16). Therefore, S/N ratio is used to optimize the level of input parameter. The experimental results and corresponding S/N ratios are given in Table 5.

The average value and S/N ratio for each level of the input parameters are described in Table 6. From this table, the order effect of the input parameters on the surface roughness Ra are shown as follows: CC, CF, $V_w$, F, DOC (Table 6).

**Table 6.** Response table for surface roughness (means and S/N ratios).

| Level | S/N ratios (Smaller is better) | | | | | Means of surface roughness (μm) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | CC | F | CF | $V_w$ | DOC | CC | F | CF | $V_w$ | DOC |
| 1 | 1.283 | 5.176 | 5.237 | 4.129 | 4.326 | 0.8687 | 0.5664 | 0.5617 | 0.628 | 0.6184 |
| 2 | 4.193 | 4.299 | 4.684 | 5.097 | 4.828 | 0.618 | 0.6151 | 0.5932 | 0.575 | 0.587 |
| 3 | 5.885 | 4.279 | 3.679 | 3.996 | 4.335 | 0.5097 | 0.6498 | 0.6849 | 0.664 | 0.6448 |
| 4 | 6.621 | 4.229 | 4.383 | 4.76 | 4.493 | 0.4683 | 0.6333 | 0.6248 | 0.598 | 0.6144 |
| Delta | 5.338 | 0.948 | 1.557 | 1.101 | 0.502 | 0.4005 | 0.0834 | 0.1232 | 0.089 | 0.0578 |
| Rank | 1 | 4 | 2 | 3 | 5 | 1 | 4 | 2 | 3 | 5 |
| The average S/N ratio: 4.496 | | | | | | Mean of surface roughness: 0.616 μm | | | | |

The result of ANOVA for S/N ratio is presented in Table 7. It can be found that coolant concentration had the largest effect on S/N ratio on the surface roughness (84.64%), while the contribution of other parameters was found to be as follows: the coolant flow (2.31%), the cross feed (5.57%), the table speed and the depth of cut (3.3%). The depth of cut during finish grinding which had the least significant effect was used to analyze error.

**Table 7.** ANOVA table for S/N for surface roughness.

| Source | DF | Seq SS | Adj MS | Seq SS' | F | p | Pc (%) |
|---|---|---|---|---|---|---|---|
| CC | 3 | 67.4361 | 22.4787 | 66.7763 | 102.2 | 0.002 | 84.64 |
| F | 3 | 2.4824 | 0.82747 | 1.8226 | 3.76 | 0.153 | 2.31 |
| CF | 3 | 5.053 | 1.68433 | 4.3932 | 7.66 | 0.064 | 5.57 |
| Vw | 3 | 3.2648 | 1.08827 | 2.6050 | 4.95 | 0.111 | 3.30 |
| DOC | (3) | (0.6598) | -pooled- | – | – | – | – |
| Residual error | 3 | 0.6598 | 0.21993 | | | | 4.18 |
| Total | 15 | 78.8962 | | | | | 100,00 |

The linear model analysis in the Taguchi method of S/N ratio for surface roughness was carried out with the criteria "higher is better". The S/N ratio which was calculated for five factors: CC, F, CF, $V_w$ and DOC in different levels is listed in Table 6 and plot about the main effects is illustrated in Fig. 2. From this figure, it can be seen that when the coolant concentration increases, the S/N ratio for the surface roughness will increase and get the highest value at level 4 (CC4). As the coolant flow increases, the S/N ratio for surface roughness decreases and the S/N ratio hits a peak at level 1 (F1). When the cross feed rises, the S/N ratio for surface roughness falls to the lowest value at level 3. After that, it will increase and the S/N ratio is maximum at level 1 (F1). As the table velocity increases, the S/N ratio of the surface roughness decreases and then increases but it reaches the maximum value when the velocity of the table is in level 2 ($V_w$2). With the increase of the cutting depth, the S/N ratio of the surface roughness decreases and then increases but the maximum S/N value when cutting depth was 2 (DOC2). Therefore, the optimum process parameters for getting the minimum surface roughness are CC4/C1/CF1/$V_w$2/DOC2, respectively with CC = 4%, C = 5 l/min, CF = 6 mm/path, $V_w$ = 8 m/min and DOC = 0.01 mm.

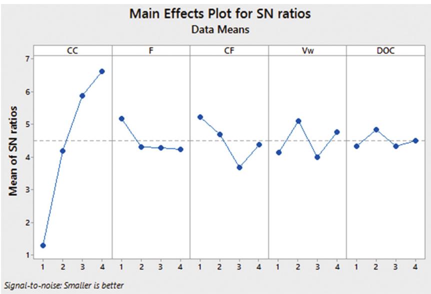


**Fig. 2.** Main effects plot for S/N ratios (for surface roughness).

**Table 8.** ANOVA table of means for surface roughness.

| Source | DF | Seq SS | Adj MS | Seq SS' | F | p | P (%) |
|---|---|---|---|---|---|---|---|
| CC | 3 | 0.38809 | 0.12936 | 0.38137 | 57.73 | 0.004 | 82.64 |
| F | 3 | 0.01562 | 0.00521 | 0.0089 | 2.32 | 0.253 | 1.93 |
| CF | 3 | 0.03317 | 0.01106 | 0.02645 | 4.93 | 0.111 | 5.73 |
| Vw | 3 | 0.01786 | 0.00595 | 0.01114 | 2.66 | 0.222 | 2.41 |
| DOC | (3) | (0.00672) | -pooled- | – | – | | – |
| Residual error | 3 | 0.00672 | 0.00224 | | | | 7.28 |
| Total | 15 | 0.46146 | | | | | 100,00 |

The analysis of means for the surface roughness is reported in Table 8 and Fig. 3. It was found that the depth of cut which has very minimal effect on the surface roughness is used to analyze error. In Table 8, the coolant concentration CC has the largest effect on the surface roughness (82.64%), followed by cross feed CF (5.73%), table speed $V_w$ (2.41%), cooling flow (1.93%) and the depth of cut with the least significant effect. This result is suitable with the result in analysis of S/N ratios for surface roughness.

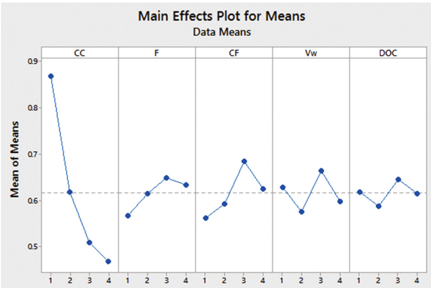


**Fig. 3.** Main effects plot for means (for surface roughness).

From the data of the experiment (Table 5), the following regression equation (the coefficient of determination was $R^2 = 0.89$) was found for determination of the surface roughness:

$$R_a = 0.5024.CC^{-0.4531}.CF^{0.1883}.DOC^{-0.0054}.F^{0.0793}.V_w^{-0.0429} \quad (2)$$

To verify the optimum input process parameters for the surface roughness (CC = 4%, C = 5 l/min, CF = 6 mm/path, $V_w$ = 8 m/min and DOC = 0.01 mm), a test using the optimum values was conducted. The predicted value of the surface roughness at optimum input parameters is calculated as follows [17]:

$$\overline{Ra}_{OP} = \overline{CC}_4 + \overline{F}_1 + \overline{CF}_1 + \overline{Vw}_2 - 3 * \overline{T}_g \quad (3)$$

In which, $\overline{CC}_4, \overline{F}_1, \overline{CF}_1, \overline{Vw}_2$ is total mean value of surface roughness for every parameter; $\overline{T}_g$ is the mean of surface roughness (Table 6).

By applying Eq. (3), the predicted optimum value of the surface roughness is determined as $\overline{Ra}_{OP} = 0.323\,(\mu\text{m})$ with the ratio S/N = 8.6445. It was identified that the predicted surface roughness (0.323 µm) fit quite well with the surface roughness of the verified test (0.348 µm) (the error between experimental and predict values is 7.18%).

## 4 Conclusions

A study on optimization of the surface roughness when surface grinding tool steel 9CrSi by Hai Duong grinding wheels was conducted. From the results of the study, the following conclusions can be drawn:

The influence of input process parameters on the surface roughness was investigated. Also, it was found that the factor having the largest effect on the surface roughness is the coolant concentration, followed by cross feed, table speed, cooling flow and depth of cut ranking the last.

The optimum process parameters for getting the minimum surface roughness are the coolant concentration 4%, the coolant flow 5 l/min, the cross feed 6 mm/path, the table speed 8 m/min, and the depth of cut 0.01 mm.

A regression equation for determination of the surface roughness was proposed.

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