Optimization on orthogonal cutting force and temperature for Gcr15 hardened steel

Changlong Zhao¹, Jun Liu, Kuo Wang and Shihang Yao

College of Mechanical and Vehicle Engineering, Changchun University, 130022, China

¹E-mail: zhao19790204@126.com

Abstract. In the text, the process of dry turning of Gcr15 hardened steel is analyzed by the software of the 3D finite element with the design of orthogonal test. The finite element simulation and orthogonal test are combined to ensure the optimal cutting parameters with the assistance of analysis of signal to noise ratio and range. The optimal combination of cutting parameters for cutting force are cutting speed at level 3(120 m/min), feed rate at level 1(0.05 mm/rev) and the depth of cut at level 1(0.1 mm). The optimal combination of cutting parameters for tool temperature are cutting speed at level 1(80 m/min), feed rate at level 1(0.05 mm/rev) and the depth of cut at level 1(0.1 mm). In addition, the contribution of three cutting parameters to cutting force and tool temperature are analyzed with the assistance of ANOVA analysis.

1. Introduction

The demand for ultra hard materials become increasing with the development of social industry, which profits from the benefits of excellent wear resistance and hot working performance of ultrahard materials. Even though, large cutting force and high cutting temperature will come into being due to high hardness of ultrahard materials during the cutting process.

A lot of research about analysis of parameter optimization has been done in terms of tool aggravation caused by large cutting force and high cutting temperature, which provides experience and convenience for the follow-up metal cutting research. Y. J. Liu et al. [1] have made a research on the analysis and optimization of parameters during the cutting process of 45 steel with the assistance of analysis of variance and signal to noise ratio based on the method of Taguchi. It has made a conclusion that the depth of cut has a dominant influence on cutting force, then the parameter of feed rate has the greater influence than cutting speed on cutting force. J. Du et al. [2] have studied the dry turning of hardened H13 steel with the TiN coated tool to research the machinability. It has been reported that the optimal combination of the value of cutting parameters are 113.6 m/min, 0.153 mm/rev and 0.2 mm, at which the cutting force and tool temperature are lower than other combinations of cutting parameters. D. Philip Selvaraj et al. [3] optimized cutting parameters during dry turning process of nitrogen alloyed duplex stainless steel with the analysis of signal to noise ratio and variance. The optimal combination of cutting parameters: cutting speed is 120 m/min, feed rate is 0.04 mm/rev, the depth of cut is 0.5 mm.
2. Orthogonal test
The orthogonal test is designed to study multiple factors and levels of different cutting parameters, which combines the benefits of being efficient, rapid and thrifty in terms of reducing the number of trials and saving resources. The cutting parameters of orthogonal test are respectively divided into four levels, which are selected as cutting speed, feed rate and the depth of cut. The grades of cutting speed are divided into 80 m/min, 100 m/min, 120 m/min and 140 m/min. The grades of feed rate are divided into 0.05 mm/rev, 0.1 mm/rev, 0.15 mm/rev and 0.2 mm/rev. The grades of the depth of cut are divided into 0.1 mm, 0.2 mm, 0.3 mm and 0.4 mm. Tables for orthogonal factor level and orthogonal test are shown as Table 1-2.

| Symbol | Cutting parameter | Level 1 | Level 2 | Level 3 | Level 4 |
|--------|-------------------|---------|---------|---------|---------|
| V      | Cutting speed(m/min) | 80      | 100     | 120     | 140     |
| F      | Feed rate(mm/rev)  | 0.05    | 0.1     | 0.15    | 0.2     |
| \(a_p\) | The depth of cut(mm) | 0.1     | 0.2     | 0.3     | 0.4     |

| No | Cutting speed(m/min) | Feed rate(mm/rev) | The depth of cut(mm) |
|----|----------------------|-------------------|----------------------|
| 1  | 1                    | 1                 | 1                    |
| 2  | 1                    | 2                 | 2                    |
| 3  | 1                    | 3                 | 3                    |
| 4  | 1                    | 4                 | 4                    |
| 5  | 2                    | 1                 | 2                    |
| 6  | 2                    | 2                 | 3                    |
| 7  | 2                    | 3                 | 4                    |
| 8  | 2                    | 4                 | 1                    |
| 9  | 3                    | 1                 | 3                    |
| 10 | 3                    | 2                 | 4                    |
| 11 | 3                    | 3                 | 1                    |
| 12 | 3                    | 4                 | 2                    |
| 13 | 4                    | 1                 | 4                    |
| 14 | 4                    | 2                 | 1                    |
| 15 | 4                    | 3                 | 2                    |
| 16 | 4                    | 4                 | 3                    |

3. Finite element analysis
Advantedge (FEM) [4] is a powerful software of Computer Aided Engineering (CAE) in terms of combining the functions of designing, modeling and optimization of processing technology. The software helps users set processing parameters to complete the process of finite element analysis. The simulation process [5] contains the installing of simulation parameters, the analysis of solution procedure and the analysis of simulation results.

The work piece material is selected as 100Cr6 in the region of Germany, which corresponds to Gcr15 hardened steel in the region of China. The hardness of the material is 61-64HRC. The diameter and length of work piece respectively are 20 mm and 50 mm. The window of installing of the material of work piece is shown in Figure 1. The material of cutting tool is selected as Cubic Boron Nitride (CBN) during the process of finite element analysis, the shape of blade is square, the relief angle is 0, the length of cutting edge is 12 mm, the thickness of blade is 4.76 mm, the corner radius is 0.8 mm. The selection and installing of cutting parameters have a direct contact with the result of finite element analysis. As a result, it is necessary to properly install cutting parameters. The window of OD turning
process parameters is shown in Figure 2, in which the cutting parameters are installed according to the design of orthogonal test.

Figure 1. Library of work piece material.

Figure 2. Schematic diagram of OD turning process parameters.

4. Analysis of signal to noise ratio
Analysis of signal to noise ratio describes the ratio of signal to noise in an electronic system. The higher value of signal to noise ratio makes contribution to the stronger signal and lower noise. In another word, the higher value of signal to noise ratio means the smaller deviation of output value from desired value. The analysis of simulation result is to ensure the optimum combination of cutting parameters. The equation of signal to noise ratio is described \([6]\) as:

\[
S / N(\eta) = -10 \log \left( \frac{1}{n} \sum_{i=1}^{n} T_i^2 \right) \tag{1}
\]

\[
S / N(\eta) = -10 \log \left( \frac{1}{n} \sum_{i=1}^{n} F_i^2 \right) \tag{2}
\]
Where $T_i$ is the value of tool temperature, $F_i$ is the value of cutting force, n is the number of trials.

5. Results and discussions
The results of cutting force and tool temperature with their corresponding values of signal to noise ratio are indicated in Table 3-4. The results of range analysis for cutting force and tool temperature are shown in Table 5. The results of ANOVA analysis are shown in Table 6. As illustrated in Table 3, the higher value of signal to noise ratio for cutting force is available at the forth level of cutting speed(140 m/min), the second level of feed rate(0.1 mm/rev) and the first level of the depth of cut(0.1 mm). As illustrated in Table 4, the higher value of signal to noise ratio for tool temperature is available at the first level of cutting speed(80 m/min), the first level of feed rate(0.05 mm/rev) and the first level of the depth of cut(0.1 mm). As illustrated in Table 5, the higher mean S/N ratio of cutting speed, feed rate and the depth of cut for cutting force are 120 m/min, 0.05 mm/rev and 0.1 mm, respectively. The higher mean S/N ratio of cutting speed, feed rate and the depth of cut for tool temperature are 120 m/min, 0.05 mm/rev and 0.1 mm, respectively. Therefore, the optimal combination of cutting parameters for cutting force is cutting speed at level 3(120 m/min), feed rate at level 1(0.05 mm/rev) and the depth of cut at level 1(0.1 mm), the optimal combination of cutting parameters for tool temperature is cutting speed at level 1(80 m/min), feed rate at level 1(0.05 mm/rev) and the depth of cut at level 1(0.1 mm).

Table 6 shows the results of ANOVA analysis for cutting force and tool temperature. It was observed that the depth of cut is the most significant cutting parameter affecting the cutting force. The cutting parameter affecting the cutting force is cutting speed followed by feed rate. The results of ANOVA analysis show that the depth of cut, cutting speed and feed rate are affecting cutting force approximately 76%, 12.7% and 4.5%, respectively. Similarly, it was observed that the depth of cut is the most significant cutting parameter affecting the tool temperature. The cutting parameter affecting the tool temperature is cutting speed followed by feed rate. The results of ANOVA analysis show that the depth of cut, cutting speed and feed rate are affecting tool temperature approximately 52%, 10.4% and 4.5%, respectively.

Table 3. Cutting force and corresponding signal to noise ratio.

| No | Cutting speed(m/min) | Feed rate(mm/rev) | The depth of cut(mm) | Cutting force(N) | S/N(db) |
|----|----------------------|-------------------|----------------------|-----------------|---------|
| 1  | 80                   | 0.05              | 0.1                  | 103.20          | -40.27  |
| 2  | 80                   | 0.1               | 0.2                  | 183.85          | -45.29  |
| 3  | 80                   | 0.15              | 0.3                  | 330.64          | -50.39  |
| 4  | 80                   | 0.2               | 0.4                  | 423.79          | -52.54  |
| 5  | 100                  | 0.05              | 0.2                  | 143.53          | -43.14  |
| 6  | 100                  | 0.1               | 0.3                  | 237.28          | -47.50  |
| 7  | 100                  | 0.15              | 0.4                  | 390.38          | -51.83  |
| 8  | 100                  | 0.2               | 0.1                  | 128.62          | -42.19  |
| 9  | 120                  | 0.05              | 0.3                  | 190.26          | -45.59  |
| 10 | 120                  | 0.1               | 0.4                  | 181.38          | -45.17  |
| 11 | 120                  | 0.15              | 0.1                  | 105.95          | -40.50  |
| 12 | 120                  | 0.2               | 0.2                  | 157.11          | -43.92  |
| 13 | 140                  | 0.05              | 0.4                  | 269.26          | -48.60  |
| 14 | 140                  | 0.1               | 0.1                  | 101.98          | -40.17  |
| 15 | 140                  | 0.15              | 0.2                  | 114.26          | -41.16  |
| 16 | 140                  | 0.2               | 0.3                  | 207.36          | -46.33  |
Table 4. Tool temperature and corresponding signal to noise ratio.

| No | Cutting speed (m/min) | Feed rate (mm/rev) | The depth of cut (mm) | Tool temperature (°C) | S/N (dB) |
|----|-----------------------|---------------------|-----------------------|-----------------------|----------|
| 1  | 80                    | 0.05                | 0.1                   | 505                   | -54.07   |
| 2  | 80                    | 0.1                 | 0.2                   | 609                   | -55.69   |
| 3  | 80                    | 0.15                | 0.3                   | 637                   | -56.08   |
| 4  | 80                    | 0.2                 | 0.4                   | 668                   | -56.50   |
| 5  | 100                   | 0.05                | 0.2                   | 688                   | -56.80   |
| 6  | 100                   | 0.1                 | 0.3                   | 640                   | -56.12   |
| 7  | 100                   | 0.15                | 0.4                   | 625                   | -55.92   |
| 8  | 100                   | 0.2                 | 0.1                   | 572                   | -55.15   |
| 9  | 120                   | 0.05                | 0.3                   | 589                   | -55.40   |
| 10 | 120                   | 0.1                 | 0.4                   | 650                   | -56.26   |
| 11 | 120                   | 0.15                | 0.1                   | 612                   | -55.74   |
| 12 | 120                   | 0.2                 | 0.2                   | 628                   | -55.96   |
| 13 | 140                   | 0.05                | 0.4                   | 660                   | -56.39   |
| 14 | 140                   | 0.1                 | 0.1                   | 601                   | -55.58   |
| 15 | 140                   | 0.15                | 0.2                   | 660                   | -56.39   |
| 16 | 140                   | 0.2                 | 0.3                   | 641                   | -56.14   |

Table 5. Ranging analysis for cutting force and tool temperature.

| Cutting parameter       | Mean S/N ratio | Max-Min ranking |
|-------------------------|----------------|-----------------|
|                         | Level 1 | Level 2 | Level 3 | Level 4 |          |
| Cutting force           |         |         |         |         |          |
| Cutting speed           | -47.12  | -46.17  | -43.80  | -44.07  | 3.32  | 2       |
| Feed rate               | -44.40  | -44.53  | -45.97  | -46.25  | 1.85  | 3       |
| The depth of cut        | -40.78  | -43.38  | -47.45  | -49.54  | 8.76  | 1       |
| Tool temperature        |         |         |         |         |          |
| Cutting speed           | -55.59  | -56.00  | -55.84  | -56.13  | 0.54  | 2       |
| Feed rate               | -55.67  | -55.91  | -56.03  | -55.94  | 0.36  | 3       |
| The depth of cut        | -55.14  | -56.21  | -55.94  | -56.27  | 1.13  | 1       |

Table 6. Results of the AVOVA for cutting force and tool temperature.

| Cutting parameter       | Degrees of freedom | Sum of squares | Mean square | F ratio | Contribution(%) |
|-------------------------|--------------------|----------------|-------------|---------|-----------------|
| Cutting force           | 3                  | 31.33          | 10.44       | 3.76    | 12.7            |
| Cutting speed           | 3                  | 11.01          | 3.67        | 1.32    | 4.5             |
| Feed rate               | 3                  | 186.87         | 62.29       | 22.40   | 76              |
| The depth of cut        | 3                  | 16.69          | 2.78        | 6.8     | 6.8             |
| Error                   | 6                  | 245.90         |             |         |                 |
| Total                   | 15                 | 245.90         |             | 100     |                 |

Tool temperature

| Cutting parameter       | Degrees of freedom | Sum of squares | Mean square | F ratio | Contribution(%) |
|-------------------------|--------------------|----------------|-------------|---------|-----------------|
| Cutting speed           | 3                  | 0.65           | 0.22        | 0.64    | 10.4            |
| Feed rate               | 3                  | 0.28           | 0.09        | 0.14    | 4.5             |
| The depth of cut        | 3                  | 3.25           | 1.08        | 3.13    | 52              |
| Error                   | 6                  | 2.07           | 0.345       |         |                 |
| Total                   | 15                 | 6.25           |             | 100     |                 |
6. Conclusions

The analysis of finite element with the design of orthogonal test, analysis of signal to noise ratio and range analysis were used in finding out the optimal combination of cutting parameters for cutting force and tool temperature. The analysis of ANOVA was used in finding out the contribution of three cutting parameters to cutting force and tool temperature.

The analysis of signal to noise ratio and range indicate that a cutting speed of 120 m/min, a feed rate of 0.05 mm/rev and the depth of cut of 0.1 mm are found to give the lowest cutting force during the process of dry turning of Gcr15 hardened steel, a cutting speed of 80 m/min, a feed rate of 0.05 mm/rev and the depth of cut of 0.1 mm are found to give the lowest tool temperature during the process of dry turning of Gcr15 hardened steel.

The analysis of ANOVA indicate that the depth of cut, cutting speed and feed rate are affecting cutting force approximately 76%, 12.7% and 4.5%, respectively. The results of ANOVA analysis show that the depth of cut, cutting speed and feed rate are affecting tool temperature approximately 52%, 10.4% and 4.5%, respectively.

References

[1] Liu Y J, Li Z H, Wang Y and Wang X J 2018 Optimization of cutting 45 steel parameters based on Taguchi method Machinery Design & Manufacture (3) 2-3

[2] Du J and Wang L G 2018 Experimental study of cutting performance in machining of H13 hard steel with TiN coated tools MACHINE TOOL & HYDRAULICS 46(11) 2-3

[3] D Philip Selvaraj, P Chandramohan and M Mohanraj 2013 Optimization of surface roughness, cutting force and tool wear of nitrogen alloyed duplex stainless steel in a dry turning process using Taguchi method Measurement 1-2

[4] Jiang F and Li H W 2018 Finite element simulation software for metal cutting user manual Beijing: China Machine press 1-2

[5] Li M B, Zhou L P and Wu W D 2016 The high silicon aluminum alloy cutting research based on Advantedge Chengdu:mechanical engineering of Xihua university 32-49

[6] Xu X B and Shao H 2015 Multiple-object optimization of parameters for turning based on Taguchi Method and Grey Relational Analysis Tool Engineering 49(8) 4-5