Grey Relational Analyses for Multi-Objective Optimization of Turning S45C Carbon Steel

A.H.A. Shah1, A.I. Azmi1,2 and A.N.M. Khalil1
1School of Manufacturing Engineering, Universiti Malaysia Perlis (UniMAP), Pauh Putra Campus, 02600 Arau, Perlis, Malaysia
2Faculty of Engineering Technology, Universiti Malaysia Perlis (UniMAP), Pauh Putra Campus, 02600 Arau, Perlis, Malaysia

Abstract. The optimization of performance characteristics in turning process can be achieved through selection of proper machining parameters. It is well known that many researchers have successfully reported the optimization of single performance characteristic. Nevertheless, the multi-objective optimization can be difficult and challenging to be studied due to its complexity in analysis. This is because an improvement of one performance characteristic may lead to degradation of other performance characteristic. As a result, the study of multi-objective optimization in CNC turning of S45C carbon steel has been attempted in this paper through Taguchi and Grey Relational Analysis (GRA) method. Through this methodology, the multiple performance characteristics, namely; surface roughness, material removal rate (MRR), tool wear, and power consumption; can be optimized simultaneously. It appears from the experimental results that the multiple performance characteristics in CNC turning was achieved and improved through the methodology employed.

1. Introduction

Turning operation is defined as the removal of metal chips from workpiece in order to obtain a finished product with desired output characteristic. Many types of geometries can be produced through turning process, which includes flat surfaces and complex-curved surfaces. However, the challenge of turning process is to determine the global optimal machining parameters that can solve several performance characteristics such as surface roughness, Material Removal Rates (MRR), tool wear and power consumption simultaneously [1]. It is well known that all of these four outputs are the critical response in turning process, which is often used as indication of machining performance. Based on the existing literature, most of the current methods employed are only capable of single performance characteristic optimization. For instance, Taguchi Method has been widely accepted as an effective design of experiment approach that aims to investigate the effect of machining parameters and optimize their conditions at relatively less number of experiment [2-3]. Nevertheless, the need for the solution of multiple response optimization simultaneously, such as tool wear, surface roughness, MRR and power consumption, is inevitable.

It is reported that the original design of Taguchi method is to optimize a single output characteristic [4-5]. Each of the performance factors has its own characteristic, for instance, MRR employs the “higher-the-better” performance characteristic, while surface roughness and tool wear use the “lower-
the-better”. Very often, as one performance characteristic is improved, the other performance characteristic may deteriorate. In order to solve this, Grey Relational Analysis can be used to convert the multi-performance characteristic value into a single Grey Relational Grade value. As a result, the complicated multi-performance characteristic can be simplified into a single value so that the optimization process becomes easier.

For example, Azmi [8] proposed an application of Taguchi-Grey methodologies to optimize the performance characteristics of glass fiber reinforced polymer (GFRP) composites in end milling. In this reported study, Grey Relational Analysis was employed to solve multiple machinability characteristics of tool life, machining forces and surface roughness. The results showed that feed rate has the most significant influence on the multiple machinability characteristics. Through confirmation test, the author also reported that the Taguchi-Grey analysis can be effectively used to determine the multiple machinability characteristics and consequently improved the end milling of GFRP composites [8]. Apart from this study, other researchers successfully reported the systematic approach that combines Taguchi Method and GRA in optimizing the multiple performance characteristics of their experimental work [9-14].

In this paper, we aim to propose a near optimum turning parameters that can improve all four-performance characteristics simultaneously by combining the Taguchi and GRA methodologies. The four-performance characteristics are surface roughness, Material Removal Rates (MRR), tool wear and power consumption when turning SC45 carbon steel. In order to attain this objective, the main machining parameters that have been selected in this research are spindle speed and feed rate. Additionally, experimental plan was carried out through Taguchi Design of Experiment methodology.

2. Experimental Setup

2.1 Design of Experiment

The turning experiment or process was carried out using Chevalier FCL-608 machine. This machine has a maximum spindle speed of 6000 RPM. It is also capable of machining a maximum cutting diameter of 260 mm and maximum cutting length of 290 mm. The S45C carbon steel bar with dimension of 50 mm in diameter and 100 cm in length was selected as the workpiece. The coated tungsten carbide insert was used to machine this carbon steel bar. The condition of the experiment was dry and the cutting process was in the form of straight turning. For the experimentation, two turning parameters were selected, namely; spindle speed and feed rate. These two parameters were set at three levels of acceptable operating range according to literature and machining handbook. The depth of cut was fixed at 0.1 mm. Table 1 shows the values of input parameters and their levels. Based on this selection; an L9 orthogonal array, which consists of nine experiments with different three-level input parameter, was laid-out.

| Input Parameters       | Levels |
|------------------------|--------|
|                        | 1      | 2  | 3  |
| Spindle speed (RPM)    | 1000   | 2000 | 3000 |
| Feed rate (mm/rev)     | 0.1    | 0.15 | 0.2 |

2.2 Experimental measurement

In this study, the tool wear was measured every time a single experiment is finished. This was done to ensure an accurate reading can be obtained. Leica microscope and scanning electron microscope were used to capture the image of worn tool. Later on, the measurement of wear was carried out based on the
length of flank wear on the tool flank surface. In determining the power consumption of the CNC machine during cutting process, the electrical current of the machine while it is in operating mode must be obtained. A Pico Log data logger was used to measure the electrical current of the machine during the cutting process. The value of electric current obtained from the data logger was then used to calculate power consumption of the CNC machine. Meanwhile, the surface roughness was measured at three equal divided spaces, with angle of separation of 120° using the Mitutoyo F-3000. Measurement also was repeated at least three times for each spot area to minimize the variation in the results obtained. The centerline average roughness, $R_a$ was selected to measure the roughness of surface on every machined part or workpiece with different machining parameter. Finally, MRR was calculated through Equation 2.1,

$$ MRR = \pi D df N $$

where $D$ is the average diameter of workpiece or the sum of diameter before and after divided by two, $d$ is depth of cut, $f$ is feed rate and $N$ is the spindle speed of the turning machine.

Figure 1: (a) PicoLog data logger and (b) Mitutoyo F-3000 surface measurer used to determine the power consumption and surface roughness, $R_a$.

3. Results and Discussion

3.1 Taguchi Method

There are a total four types of performance characteristics that have been considered in this study, namely; MRR, surfaces roughness, tool wear and power consumption of the CNC machine.

3.1.1 Material Removal Rate (MRR)

Figure 2 shows the plots of the relationship between machining parameters at the three different levels and the mean $S/N$ ratios of the MRR. It can be seen clearly that both spindle speed and feed rate are directly proportional to the MRR. In other words, there is a direct effect of changing spindle speed or feed rate or both, on the MRR. Table 2 shows the response table for the MRR based on the changing spindle speed and feed rate. It is evident that the desired setting of spindle speed for maximising the MRR is at the highest level, which is level 3 or at spindle speed of 3000 RPM. Likewise, the feed rate should be set at the rate of 0.2 mm/rev, which is at the highest level (level 3) as to maximise the MRR. On the other hand, the ranking shown in the response table describes the significant of the parameter towards the output response, MRR. From this rank, spindle speed is given rank 1. This implies that spindle speed influences the MRR the most as compared to that of the feed rate.

Table 2: Response table of the $S/N$ ratio for the MRR

| Factor       | MRR ($S/N$ ratio) | Delta | Rank |
|--------------|-------------------|-------|------|
|              | Level 1 | Level 2 | Level 3 |       |
| Spindle Speed| 28.19   | 34.21   | 37.73   | 9.54  | 1     |
| Feed Rate    | 30.20   | 33.72   | 36.22   | 6.02  | 2     |
3.1.2 Surface Roughness

Figure 3 shows the main effects of machining parameters on the surface roughness, $R_a$, based on the $S/N$ ratio values. From the pattern or trend of this plot, it can be seen that the surface roughness is improved, as the spindle speed increases. On the other hand, as the value of feed rate changes from lower level to the higher level, the surface roughness value increases. This implies that the surface roughness deteriorated with the increase of feed rate, which is in-line with literature and theoretical reports. Similar to that of MRR, the response table of machining parameters for the surface roughness values was also constructed. The maximum value at level 1 parameter setting is belonging to the feed rate with a value of -3.29. At level 2 is the spindle speed with a value of -2.84 and at level 3 is also the spindle speed with a value of -0.36. From Table 3, it is also implied that the best setting for minimizing the surface roughness is at the spindle speed of 3000 RPM (level 3) and the feed rate of 0.1 mm/rev (level 1). Based on the rank given, the spindle speed is ranked 1 and the feed rate is ranked 2. This shows that the main machining parameter that contributes to the changes of the surface roughness is the spindle speed and followed by the feed rate.

| Factor   | Surface Roughness, $R_a$ ($S/N$ ratio) | Delta | Rank |
|----------|--------------------------------------|-------|------|
| Level 1  | Level 2                              | Level 3|      |
| Spindle Speed | -13.00                               | -2.84 | -0.36 | 12.64 | 1   |
| Feed Rate | -3.29                                | -5.04 | -7.86 | 4.57  | 2    |
In term of the main effect of machining parameters on the tool wear, Figure 4 depicts that as the spindle speed increases, the tool wear deteriorated. On the contrary, for the feed rate, the pattern initially shows a decrease from level 1 to level 2, but then, increases from level 2 to level 3. Table 4 shows the response table of the spindle speed and the feed rate towards the tool wear. For level 1 parameter setting, the feed rate shows a higher value of 17.14, compared to the spindle speed, which is 15.38. Meanwhile at level 2, the spindle speed is higher with value of 17.69, whilst the feed rate has a value 16.34 and at level 3 the spindle speeds still leading with 18.05 compare to 17.63 for the feed rate. Based on the rank given, the spindle speed is ranked 1, as it influences the tool wear generated the most, as compared to the feed rate, which ranked at number 2. Figure 5 shows the tool wear images captured using scanning electron microscopy for different levels of spindle speed (a) 1000 RPM, (b) 2000 RPM, (c) 3000 RPM. The value of the feed rate at these three levels of spindle speed is constant, at 0.15 mm/rev. The images clearly indicate that the wear mechanism was abrasion on the flank face of the cutting tool.

| Factor       | Tool Wear (S/N ratio) | Delta | Rank |
|--------------|-----------------------|-------|------|
|              | Level 1               | Level 2 | Level 3 |
| Spindle Speed| 15.38                 | 17.69  | 18.05 |
| Feed Rate    | 17.14                 | 16.34  | 17.63 |

3.1.3 Tool Wear

Table 4: Response table for S/N ratio of the tool wear
3.1.4 Power consumption

The plot of main effect of the spindle speed and the feed rate on the power consumption based on the \( S/N \) ratio values is given in Figure 6. The graph shows that the value of \( S/N \) ratio for the power consumption decreases with the changes in the spindle speed. This directly implies that the higher spindle speed leads to more consumption of the power during machining. This is may be due to the fact that at elevated cutting speed, the rate of tool wear is higher. Hence, due to the increase in friction during machining, more force is needed to machine the workpiece. As this happens, the power used for machining increases at the higher cutting speed. Meanwhile, the \( S/N \) ratio of power consumption has little affect by the increase in the feed rate. This is quite surprising and requires further explanation or experimental validation. Table 5 shows the response table of the machining parameter towards the power consumption \( S/N \) ratios. At level 1 and level 2 setting parameter, the spindle speed is dominant with value of -14.16 and -14.67. However, the highest value of level 3 is the feed rate with -15.44 compared to -15.44 of the spindle speed. The rank from the response table indicates that the spindle speed is ranked 1 with 1.29 delta value and the feed rate is ranked 2 with 0.15 delta values. This shows that the spindle speed is more influence towards the power consumption compared to that of the feed rate. As far as the desired setting is concerned, the spindle speed should be set at level 1, which is at 1000 RPM, and the feed rate at 0.20 mm/rev, in order to minimize the consumption of the power during machining process.
Figure 5: SEM images of the tool wear at different spindle speed
(a) Spindle speed 1000 RPM (b) Spindle speed 2000 RPM (c) Spindle speed 3000 RPM

Table 5: Response table for S/N ratio of the power consumption

| Factor     | Power Consumption (S/N ratio) | Delta | Rank |
|------------|-------------------------------|-------|------|
|            | Level 1                       | Level 2 | Level 3 |     |
| Spindle Speed | -14.16                       | -14.67 | -15.44 | 1.29 | 1   |
| Feed Rate  | -14.80                       | -14.81 | -14.66 | 0.15 | 2   |
3.2 Grey Relational Analyses

The multiple performance optimization was carried out using the grey relational analysis, in which the optimization processes are carried out in step by step stage until the grey relational grade (GRG) is obtained. It is to emphasize here that the GRG value reflects the single optimisation value of the multiple experimental output or performance. It is also to note here that the original concept of GRA states that, the higher value of GRG, the closer the parameter to its optimum value. Once the GRG value has been identified, the next step is to develop the response table. Table 6 shows the response table developed based on the GRG values. At the level 1 setting parameter, the feed rate shows a higher value with 0.5390 compared to the spindle speed with 0.4141. However, level 2 and level 3 show that the values of the mean GRG of the spindle speed are higher with 0.5611 and 0.6284 compared to the feed rate with 0.4738 and 0.5907, respectively. From the ranking of the parameters, it appears that the spindle speed has the most effect on the GRG value compared to that of the feed rate. This will be further confirmed through the statistical analysis of variance or ANOVA, which is explained in the next section. Meanwhile, based on the GRG plot shown in Figure 7, the optimal process parameter level can be identified according to the highest value of the GRG. Thus, the best parameter setting that has been determined in the current study is the $S_3f_3$, in which the spindle speed is at 3000 RPM and the feed rate of 0.2 mm/rev. This setting has considered all of the experimental outputs or performance simultaneously based on the GRG value.

Table 6: Response table based on the GRG values

| Factor       | Grey Relational Grade (GRG) | Delta  | Rank |
|--------------|----------------------------|--------|------|
|              | Level 1     | Level 2 | Level 3 |        |       |
| Spindle Speed| 0.4141      | 0.5611  | 0.6284  | 0.2144 | 1      |
| Feed Rate    | 0.5390      | 0.4738  | 0.5907  | 0.1169 | 2      |

Figure 6: Effects of the machining parameters on power consumption
3.3 Analysis of Variance (ANOVA)
ANOVA is performed to statistically determine which machining parameters affect the performance evaluation the most. Very often, ANOVA can be used to evaluate the contribution of each factor on the experimental outputs. Initially, the ANOVA is carried out through the calculation of the sum of squared deviations from the total mean of the grey relational grade. Following that, the effect of each experimental parameter can be separated according to the contributions and error of each machining parameters. Any machining parameter that poses the highest mean square value is considered as the most significant machining parameter that affects the multiple performance characteristics. The result of ANOVA is shown in the Table 7. It is evident that the spindle speed is considered as the most significant factor as it represents 68.60 % of the contribution to the combined outcomes of the experiment. On the other hand, the feed rate is less significant as it only represents 19.57 % of contribution towards the multiple experimental outputs. The error that may due to experiment determined from this ANOVA test was only 11.83 %, which is statistically acceptable.

Table 7: ANOVA results based on the Grey Relational Grade

| Factor      | Sum of square | Mean of square | F-test  | F-ratio | % Contribution |
|-------------|---------------|----------------|---------|---------|----------------|
| Spindle speed | 0.072         | 0.036          | 11.602  | 19      | 68.60          |
| Feed rate   | 0.021         | 0.010          | 3.311   | 19      | 19.57          |
| Error       | 0.012         | 0.003          |         |         | 11.83          |
| Total       | 0.105         |                |         |         |                |

Figure 7: The GRG response graph
3.4 Validation Test
Based on the results of the validation test obtained in Table 8, it can be seen that the predicted value of the tool wear is quite close to the value of actual experiment, which is 0.116 mm and 0.118 mm, respectively. Meanwhile, the value of the surface roughness was also improved to 1.55 µm in the prediction compared to 1.67 µm from the experiment. However, the value of the MRR has decreased from 106.8 mm³/s in the actual experiment to 97.9 mm³/s in the prediction. Lastly, the value of the power consumption is increased from 5.750 kW in the experiment to 5.854 kW in the prediction. The percentage error between the prediction and the actual experiment is 1.72%, 7.43%, 9.09% and 1.78% for the tool wear, the surface roughness, the MRR and the power consumption, respectively. This implies that the result is statistically acceptable in optimizing the turning parameters using the GRA.

![Table 8: Results of the validation test](image)

| Setting Level          | Prediction | Experiment | % Error |
|------------------------|------------|------------|---------|
| TW (mm)                | S_3 f_1    | S_3 f_1    | 1.72    |
| Ra (µm)                | 1.55       | 1.67       | 7.43    |
| MRR (mm³/s)            | 97.90      | 106.80     | 9.09    |
| Power Consumption (kW) | 5.854      | 5.750      | 1.78    |
| Grey Relational Grade  | 0.685      | 0.731      | 6.72    |

4. Conclusion
As a conclusion, the application of the Taguchi and Grey Relational Analysis in the optimization of the turning process for the S45C carbon steel with multiple performance characteristics has been successfully reported in this paper. The experimental results indicated that the increase in spindle speed leads to improvement in the surface roughness and the MRR values. However, the higher spindle speed leads to the increased of the power consumption of the CNC machine. On the other hand, the tool sharpness is less affected by the increase of the spindle speed. This ambiguity calls for further investigation in the future work. Meanwhile, the results from GRA showed that the optimum parameter setting that has been found in the current study is the S_3f_3, in which at the spindle speed of 3000 RPM and the feed rate of 0.2 mm/rev respectively. It is also important to emphasize that the result of the confirmation test shows that the actual experimental value is close to the prediction value with the percentage error of less than 10%.

5. References
[1] C. Lin 2004 “Use of the Taguchi method and grey relational analysis to optimize turning operations with multiple performance characteristics”, Mater. Manuf. Process., vol. 19, no. 2, pp 209-220.
[2] D.C. Montgomery 1997 Design and analysis of experiments. 7th Edition, Wiley New York.
[3] A.R. Pedersen and N. Ringgade, Design and analysis of experiments. 1985.
[4] M. Nalbant, H. Gökkyaya, and G. Sur 2007 “Application of Taguchi method in the optimization of cutting parameters for surface roughness in turning”, Mater Design, vol. 28, no. 4, pp 1379-1385.

[5] C.-J. Tzeng, Y.H. Lin, Y.K. Yang, and M.C. Jeng 2009 “Optimization of turning operations with multiple performance characteristics using the Taguchi method and Grey relational analysis”, J. Mater. Process. Technol., vol. 209, no. 6, pp 2753-2759.

[6] Ross, P.J., Taguchi techniques for quality engineering: loss function, orthogonal experiments, parameter and tolerance design. 1988.

[7] W.Y. Fowlkes, C.M. Creveling, and J. Derimiggio 1995, Engineering methods for robust product design: using Taguchi methods in technology and product development. Addison-Wesley Reading, MA.

[8] A. I Azmi 2012 “Multi-objective Optimisation of Machining Fibre Reinforced Composites”, J. App. Sci., vol. 12, no. 23, pp. 2360-2367.

[9] J. Lin and C. Lin 2005 “The use of grey-fuzzy logic for the optimization of the manufacturing process”, J. Mater. Process. Technol., vol. 160, no. 1, pp 9-14.

[10] Y. Hsiao, Y. Tarng and W. Huang 2007 “Optimization of plasma arc welding parameters by using the Taguchi method with the grey relational analysis”, Mater. Manuf. Process. vol. 23, no. 1, pp 51-58.

[11] C. Ahilan, S. Kumanan, and N. Sivakumaran 2010 “Application of grey based taguchi method in multi-response optimization of turning process”, Adv. Produc. Eng. Manage., vol. 5, no. 3. pp 171-180.

[12] C. Ahilan, S. Kumanan, and N. Sivakumaran 2009 “Multi-objective optimisation of CNC turning process using grey based fuzzy logic”, Int. J. Mach. Machinability Mater, vol. 5, no.4, pp 434-451.

[13] K.-T, Chiang and F.-P. Chang 2006 “Application of grey-fuzzy logic on the optimal process design of an injection-molded part with a thin shell feature”, Int. Comm. Heat Mass Trans., vol. 33, no. 1, pp 94-101.

[14] J. Antony 2001 “Simultaneous optimisation of multiple quality characteristics in manufacturing processes using Taguchi’s quality loss function”, The Int. J. Adv. Manuf. Technol., vol. 17, no. 2, pp 134-138.