Multi-response optimization of machining factors in pocket milling of AISI304 using grey relational analysis

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Abstract. Pocket milling finds applications in ship building and aerospace industries. To cut the required profile of the pocket on the material various tool trajectories may be used. Surface roughness is one of the quality parameters to accept products at the same time production time must be reduced to reduce the production cost. This shows the need of selecting the best parameters machining parameters to get good surface finish with less production time. Tool trajectories also play a vital role in pocket generation and production time. In the current study, first, optimum machining parameters are identified for AISI304 using Taguchi L9 Orthogonal Array and Grey Relational Analysis. Experiments are done with Speed (S), Feed (F) and Stepover (SO) as the influencing parameters. Secondly, suitable tool path is to be identified to improve the surface quality (SR) and Material Removal Rate (MRR). Two tool paths viz, follow periphery and zigzag are used to generate pockets. For each tool trajectory, from the obtained results, Grey Relational Grade is calculated. The combination of parameters with highest Grey Relational Grade is identified as the optimal parameters. Confirmation experiments indicate that predicted responses are closer to the optimal values.

Keywords: Multi-Response Optimization, Pocket Milling, AISI304, Taguchi, GRA,

1. Introduction
In the present scenario, quality of the object with less production cost and high production volume is forcing the manufacturing industry to use advanced technologies. Pocket milling is one of the basic machining processes in the manufacture of dies and molds. The quality of the pocket is directly assessed with its surface roughness Characteristic from the functional properties of the product.

AISI304 is the largely used austenitic stainless steel in various fields, where corrosion resistance and formability is given more importance. Some applications of AISI 304 include piping, heat exchangers, dish washers, fasteners etc., It is also one of the difficult to cut material. Hence its surface roughness plays important role in the quality of the end products. Productivity depends on production time and material removal rate. Surface roughness and material removal rate are affected by many factors like feed, Speed, Depth of cut, stepover, Number of passes, tool geometry etc., To obtain better surface finish the tool path can be modeled using various algorithms(1). In pocket milling, the path followed by tool to cut the given profile also important(2),(3). P.E. Romero et al.(4)studied the impact of pocket geometry and tool movement on surface roughness and cutting forces. From the study, they concluded that each tool path has its own influence on the responses based on pocket geometry selected. H. Perez, et al.(5)analyzed the effect of tool path on surface roughness and cutting force by developing a new mathematical model. A spiral tool path was produced using an algorithm in "POWERApox" package by Martin Held et al.(6) to generate pocket in high speed machining. They have identified good matching of the tool path data with real world data. A constrained based optimization technique is applied by Bouard et al.(7)for tool path computation in pocket milling, to study the effect on machining time. J Medina et al.(8) have tested different tool movements through simulation for calculating cutting time. In the study, they tried to check the influence of interpolation, distance between those points and toolpath curvature on cutting time. A. Ghani et al. (9) applied Taguchi
optimization to study the impact of cutting factors on surface roughness. The influence of cutting parameters on surface roughness in end milling is studied by Mohammed T. Hayajneh et al. (10). They used random experiments at all possible level combinations of the factors. Milon D. Selvam et al. (11) applied Taguchi and Genetic Algorithm to study the effect of process parameters on surface roughness in face milling of Mild Steel. B. Jabbaripour et al. (12) used four cutter directions and speed variations to study their influence on surface finish and cutting force.

A. Noorul Haq, et al. (13) applied Taguchi OA with grey relational analysis to analyze multi response optimization in drilling Al/SiC metal matrix composite. M. Maiyar, et al. (14) analyzed multi-responses in milling of Inconel 718Super Alloy using Taguchi and grey relational analysis. Through experimentation they showed that through this approach, they are able to improve machining performance. Nayak et al. (15) analyzed multi response criteria in turning of AISI304 using Grey relational analysis based on Taguchi method. They observed 88% improvement in the responses, surface finish, MRR and cutting force through test experiments. Taguchi method coupled grey relational analysis is applied by Santha kumar et al. (16) to optimize one direction tool movement in pocketing of Ti-6Al-4V. By doing confirmation experiments, they observed that MRR, radial tool deflection and surface roughness are optimized by this method. Rajyalakshmi and Babu (17) optimized surface roughness in pocket milling of SAE304 using Taguchi analysis. In the experimental study, they have applied two different tool paths and compared the surface roughness in both criteria. M. Ay (18) applied Grey Taguchi method to optimize cutting factors in turning of AISI304L steel on surface roughness, cutting forces and surface hardness. They observed with confirmation experiments, the optimal cutting parameters are obtained with this method. Kedar Mallik, et al. (19) fabricated Co-Cr-Mo alloy samples using laser sintering and applied grey Taguchi method to study the effect of heat treatment on electro chemical properties, microstructure. M. Ayand A. Etyemez (20) used Grey Taguchi method to study the effect of cutting parameter and tool path on milling of Al7075. Emel Kuram and Babur Ozcelik (21) conducted experimental analysis to optimize cutting parameters using grey based taguchi method for micro milling of Al7075. Surface roughness, cutting forces and Tool wear are analyzed to get optimum response values. M. Nurhaniza et al. (22) analyzed the effect of process on surface integrity using Taguchi orthogonal array for milling of Al-CFRP composites. From the results, they observed good surface integrity at high speed, low feed and low DOC within the selected limits. Biswajit Das et al. (23) experimented on milling of Al–4.5%Cu–TiC metal matrix composites using Grey based fuzzy logic to optimize the response parameters.

From the above discussion it was observed that most of the researchers focused on single objective optimization. Very few researchers addressed pocket milling. Influence of step over in combination with speed and feed is not reported in pocket generation. Selection of tool trajectory for multi response optimization in pocket milling can also be studied. Grey Taguchi method gives better combination for multi response optimization. Hence in the current study, Multi-response optimization using Taguchi based Grey relational analysis is applied to find the better combination of parameters for generating pockets using two types of tool paths.

2. Material and methodology:

2.1 Material: For the present study, austenitic stainless steel-AISI304 grade workpieces of size 80mmX70mmX10mm are selected. The chemical composition of the material by weight percentage is shown in table 1.

| Element | C | Cr | Ni | Mo | Mn | Si | N | Others | Iron |
|---------|---|----|----|----|----|----|---|--------|------|
|         |   |    |    |    |    |    |   |        |      |

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Composition (Wt. %)  0.057  18.07  8.07  -  1.72  0.29  0.08  0.075  Balance

2.2 Methodology: Taguchi orthogonal arrays (OA) give effective and efficient results with minimum number of experiments and reduce cost. Based on the number of factors and number of levels for each factor suitable OA is selected. “Lower the better”, Signal to Noise ratio is used for surface roughness and “higher the better” for MRR.

In the present study, the machining parameters chosen are Speed, Feed, and stepover. The levels of the parameters are fixed based on literature review, machine specifications and material properties. Various levels of the machining parameters and responses are shown in table 2.

Table 2: Machining parameters and their Levels selected for experimentation

| Symbol | Parameters  | Units   | Level 1 | Level 2 | Level 3 | Responses                      |
|--------|-------------|---------|---------|---------|---------|--------------------------------|
| S      | Speed       | RPM     | 2000    | 3000    | 4000    | Surface Roughness (SR) (μm)   |
| F      | Feed        | mm/min  | 500     | 1000    | 1500    | Material Removal Rate (MRR) (gm/sec) |
| SO     | Step Over   | %       | 20      | 30      | 40      |                                |

The combinations of experimental runs using L9 orthogonal array for the specified parameters and level combinations are shown in table 3.

Table 3: Experimental runs in L9 orthogonal array

| Run No. | Speed (RPM) | Feed (mm/min) | Step Over (%) |
|---------|-------------|---------------|---------------|
| 1       | 2000        | 500           | 20            |
| 2       | 2000        | 1000          | 30            |
| 3       | 2000        | 1500          | 40            |
| 4       | 3000        | 500           | 30            |
| 5       | 3000        | 1000          | 40            |
| 6       | 3000        | 1500          | 20            |
| 7       | 4000        | 500           | 40            |
| 8       | 4000        | 1000          | 20            |
| 9       | 4000        | 1500          | 30            |

Number of researchers applied Grey Relational Analysis (GRA) [24–27] to get better combination of machining parameters in various fields of manufacturing to optimize the responses. In the present study, the experimental results are further processed with following steps to find the parameter levels for surface roughness and MRR using Grey relational Analysis (GRA).

1. Results obtained from the experiments are normalized using ‘lower the better’ for surface roughness using equations (1)

\[
\eta(\lambda) = \frac{\omega_1(R_1) - \min(\omega_1(R_1))}{\max(\omega(R_1)) - \min(\omega_1(R_1))}
\]

and ‘higher the better for MRR using equation (2).
\[ N_j(k) = \frac{\max(\omega_j(R_2)) - \omega_j(R_1)}{\max(\omega(R_2)) - \min(\omega(R_2))} \]  

Where, \( N_j(R_1) \) and \( N_j(R_2) \) are the normalized responses, for surface roughness and MRR respectively. \( \omega_j(R) \) is the experimental value of the corresponding response, \( \max(\omega(R)) \) and \( \min(\omega(R)) \) are maximum and minimum values of the corresponding response.

2. Grey relational Coefficient (GRC) is calculated with the normalized data

\[ GRC = \frac{\Delta_{\min} + 0.5\Delta_{\max}}{\Delta_{\omega(R)} + 0.5\Delta_{\max}} \]  

Where \( \Delta_{\omega(R)} = 1 - N_j(R) \), for the corresponding response, \( \Delta_{\max} \) and \( \Delta_{\min} \) are maximum and minimum values of the \( \Delta_{\omega(R)} \).

3. The Grey relational Grade (GRG) is the mean of the grey relational coefficients obtained in the previous step.

\[ GRG = \frac{1}{j} \sum_{i=1}^{j} P(R) \]  

Where, ‘\( j \)’ is the number of responses.

4. Combination of parameters having the highest GRG is considered as the optimal combination of parameters.

3. Simulation and Experimental set up:

3.1 Simulation: The Geometry of the pocket that is to be generated on the workpiece is modelled using Siemens NX 11.0 software. The tool trajectories, viz, follow periphery and zigzag are simulated on the pocket geometry separately as shown in fig. 1. Zigzag tool trajectory require finish cut also to generate the geometry accurately. NC part program for each tool path was also generated after simulation.

3.2 Experimental setup: Vertical Machining center of with Fanuc O controller is used to generate pockets with 10mm Carbide coated four flutes cutter. Experiments were conducted as per the run order generated by Minitab 11.0 software as shown in table 3. Each experiment was repeated for five times. A new cutter is used after 10 experiments for each tool path.

Weight of the Work pieces are noted before and after machining using a precision balance with 0.01gm least count. Machining time for each experiment was noted during experimentation. Surface roughness (SR) is measured using Mitutoyo SJ201P surftest. MRR is calculated with equation (5).
\[ MRR = \frac{1 - \frac{W_2}{W_1}}{t_m} \text{ gm/sec} \]  

Where, \( W_1 \), \( W_2 \) are weights of the workpiece before and after machining respectively and \( t_m \) is machining time in seconds

4. Results and discussion:
Experiments were conducted as per the order discussed in previous section and the surface roughness for each workpiece was measured. Material removal rate (MRR) was also calculated by weighing the workpiece before and after machining and dividing their absolute difference by machining time. Signal to noise ratios were also calculated for each response in both tool trajectories as shown in table 4.

| Expt. | Follow periphery | Zigzag |
|-------|------------------|--------|
|       | SR (µm) | S/N Ratio | MRR (gm/sec) | S/N Ratio | SR (µm) | S/N Ratio | MRR (gm/sec) | S/N Ratio |
| 1     | 1.5846   | -3.998     | 0.1706       | 1.3779     | 1.9392   | -5.753     | 0.10282      | -19.759   |
| 2     | 1.5352   | -3.723     | 0.272        | 2.6717     | 1.070    | -5.607     | 0.15807      | -16.024   |
| 3     | 2.175    | -6.752     | 0.3367       | 4.5252     | 2.2328   | -6.977     | 0.17397      | -15.191   |
| 4     | 1.4478   | -3.214     | 0.2565       | 2.163      | 1.793    | -5.072     | 0.16298      | -15.758   |
| 5     | 1.7142   | -4.708     | 0.2135       | 5.667      | 1.8226   | -5.215     | 0.17812      | -14.986   |
| 6     | 1.8656   | -5.417     | 0.2909       | 3.2566     | 1.8226   | -5.215     | 0.18119      | -14.837   |
| 7     | 1.8484   | -5.338     | 0.238        | 1.5154     | 1.8226   | -5.176     | 0.14096      | -17.019   |
| 8     | 1.7361   | -4.792     | 0.2353       | 1.4138     | 1.6374   | -4.284     | 0.15701      | -16.082   |
| 9     | 1.9344   | -5.731     | 0.3642       | 5.2074     | 1.8872   | -5.516     | 0.21511      | -13.347   |

The means plots from ANOVA for follow periphery and Zigzag trajectories are shown in figure 2. From the plot it is observed that medium speed, low feed and medium step over gives minimum surface roughness value, whereas the means plot for zigzag trajectory indicates medium speed, medium feed and lower stepover gives minimum surface roughness value.

The means plots also indicate that feed has more influence on surface roughness, next comes the speed in follow periphery and speed is the most significant factor in zigzag trajectory, next comes the feed. The means plots for signal to Noise ratio from ANOVA for Material Removal Rate for both the trajectories is also shown in figure 4.
Figure 3: Means plot for Material Removal rate.

From figure 4(a), it was observed that at higher speed, higher feed and medium stepover gives maximum material removal rate and Feed is the most influencing in the parameters selected. Figure 4(b) indicates that for zigzag trajectory also higher speed, higher feed and medium stepover gives maximum material removal rate, but speed is the most influencing parameter, then comes the feed.

Grey relational Grade for the experimental results are calculated for the two tool trajectories using the equations (1) to (4) and tabulated. Table 5 shows the GRG value and the ranks allotted for Follow periphery tool trajectory.

Table 5: Grey Relational values for Follow periphery.

| Expt. No | SR   | MRR  | Normalized SR | Delta SR | MRR | Delta MRR | Grey coefficient | GRG  | Rank |
|----------|------|------|---------------|----------|-----|-----------|------------------|------|------|
| 1        | 1.5846 | 0.1706 | 0.8119 | 0 | 0.1881 | 1 | 0.7266 | 0.3333 | 0.53 | 5    |
| 2        | 1.5352 | 0.272 | 0.8798 | 0.5238 | 0.1202 | 0.4762 | 0.8062 | 0.5122 | 0.6592 | 3    |
| 3        | 2.175 | 0.3367 | 0 | 0.858 | 1 | 0.1420 | 0.3333 | 0.7788 | 0.5561 | 4    |
| 4        | 1.4478 | 0.2565 | 1 | 0.4437 | 0 | 0.5563 | 1 | 0.7373 | 0.7376 | 1    |
| 5        | 1.7142 | 0.2135 | 0.6337 | 0.2216 | 0.3663 | 0.7784 | 0.5771 | 0.3911 | 0.4841 | 8    |
| 6        | 1.8656 | 0.2909 | 0.4255 | 0.6214 | 0.5745 | 0.3786 | 0.4653 | 0.5691 | 0.5172 | 6    |
| 7        | 1.8484 | 0.238 | 0.4492 | 0.3481 | 0.5509 | 0.6519 | 0.4758 | 0.4341 | 0.455 | 9    |
| 8        | 1.73614 | 0.2353 | 0.6035 | 0.3342 | 0.3965 | 0.6658 | 0.5577 | 0.4289 | 0.4933 | 7    |
| 9        | 1.9344 | 0.3642 | 0.3309 | 1 | 0.6691 | 0 | 0.4277 | 1 | 0.7139 | 2    |

From Table 5, it is observed that medium speed, low feed and medium stepover gives highest GRG value. This combination gives minimum surface roughness and near to optimum material removal rate. The grey relational grade is 0.7367. From the level means plot shown in figure 5, it is identified that low speed, high feed and medium stepover is the combination that gives highest Grey relational Grade.
Similarly, grey relational calculations for zigzag trajectory are shown in table 6. It is identified that higher speed, higher feed and medium step over gives optimal combination of parameters to get surface roughness closer to minimum and maximum material removal rate.

Table 6: Grey Relational values for Zigzag.

| Expt. No | SR    | MRR  | Normalized SR  | MRR  | Delta Grey coefficient SR  | MRR  | GRG  | Rank |
|----------|-------|------|----------------|------|---------------------------|------|------|------|
| 1        | 1.9392| 0.1028| 0.4931         | 0    | 0.5069                    | 1    | 0.4966| 0.3333| 0.415| 9    |
| 2        | 1.907 | 0.1581| 0.5472         | 0.492| 0.4528                    | 0.508| 0.5248| 0.496 | 0.5105| 6    |
| 3        | 2.2328| 0.174 | 0.7387         | 0.5357| 0.2613                    | 0.4643| 0.6568| 0.5185| 0.5876| 5    |
| 4        | 1.793 | 0.163 | 0.6889         | 0.6706| 0.3111                    | 0.3294| 0.6164| 0.6028| 0.6097| 4    |
| 5        | 1.8226| 0.1781| 0.6889         | 0.698 | 0.3111                    | 0.302 | 0.6164| 0.6234| 0.6199| 3    |
| 6        | 1.8226| 0.1812| 0.5069         | 0.3397| 0.4931                    | 0.6603| 0.5035| 0.4309| 0.4672| 7    |
| 7        | 1.931 | 0.141 | 0.4826         | 1     | 0.5174                    | 1    | 0.4914| 0.7458| 2     |
| 8        | 1.6374| 0.1570| 0.5805         | 1     | 0.4195                    | 0.5438 | 1   | 0.7719| 1    |

The level means plot drawn for grey relational data of zigzag trajectory shown in figure 6. From the figure also it was indicated that higher speed, higher feed and medium stepover gives optimum response values.

Figure 5: GRG means plot for Zigzag

Confirmation experiments are conducted for follow periphery to test the optimal combination of parameters. The test results confirm that low speed, high feed and medium stepover gives surface roughness and material removal rates closer to the optimal value. The Grey relational Coefficient
obtained for the 2000RPM speed, 1500mm/min feed and 30% stepover is 0.8417. The surface roughness value obtained is 1.5832μm and the material Removal Rate is 0.3596gm/sec. There is 14.25% improvement in the GRG Value for the optimal combination of parameters.

**Conclusions**

Present study is concentrated on multi response optimization of machining parameters using Taguchi and Grey Relational Analysis. One linear and one nonlinear tool trajectories viz, zigzag and follow periphery are used to generate pockets. For each tool trajectory, Experimental results are further processed with Grey relational analysis. Following conclusions can be drawn from the study.

1. For follow periphery tool path, the combination of parameters from the mean plots is low speed, high feed and medium stepover. Confirmation test ensures the result with 14.25% increase in the GRG value.
2. For zigzag tool path, the optimal combination from the mean plot is higher speed, higher feed and medium stepover and experimental GRG value confirms the combination as the best combination for generating surface roughness closer to minimum and MRR closer to maximum values.
3. Taguchi method when combined with Grey relational analysis gives better results to find the optimal combination of parameters in multi-response optimization. Follow periphery gives better surface roughness and material removal rate when compared to zigzag within the limits of the parameters selected.
4. ANOVA results shows that for follow periphery feed is the influencing factor and for that of zigzag, speed is most influencing factor.

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