Multi-response optimization of process parameters in Turn-milling processes- An experimental approach

K. Arun Vikrama,\*, Ch. Ratnamb, V.V.K.Lakshmia, R.D.V. Prasadc

*aDepartment of Industrial Engineering, GITAM Institute of Technology, Visakhapatnam-530045, Andhra Pradesh, India*

*bDepartment of Mechanical Engineering, Andhra University College of Engineering, Visakhapatnam-530003, Andhra Pradesh, India*

*cDepartment of Mechanical Engineering, ANITS Engineering College, Visakhapatnam-531162, Andhra Pradesh, India*

\*Corresponding author Email: arunvikram@gmail.com

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The present study focuses on multi-response optimality of machining parameter using Grey Relational Analysis combined with Principal Component Analysis coupled with Taguchi SN ratios. The responses like Surface Roughness (Ra) and Surface Hardness (H) are considered for study while machining in tangential and orthogonal turn-milling processes. Subsequently, study of individual optimality and empirical regression modeling of machining parameters like end mill cutter (tool) speed, feed rate and depth of cut on responses are also carried on. A-axis CNC Vertical Milling centre is considered for the process of single cut plain turning operations using high sped steel end mill cutters. Cylindrical extruded brass material is taken as workpiece material under dry condition. Experimentation results show that tangential turn-milling is more efficient than orthogonal turn-milling in generating the responses for same machining parameter combinations.

***Keywords*:** Grey Relational Analysis; Principal Component Analysis; Optimization; turn-milling

1. **Introduction**

Turn-milling operations are based on concept of Active Driven Rotary Tool mechanism with rotating workpiece. The rotary tool and workpiece are rotated with an external agency. It has wider advantages over conventional lathe and milling mechanisms in generating desired objectives. Turn-milling processes emerged from the foreseen advantages of James Napier in 1868 but due to complex kinematics between the rotary tool and rotating workpiece, the work was suppressed and came into light after the work of M.C. Shaw and his co-workers in 1950`s1. Turn-milling processes are one such technologies which can bridge the gap of high quality, high quantity, less cutting forces and temperatures, when compared to ordinary turning and milling processes due to relative rotational motion between the tool and workpiece2,3.

The microscopic level interaction between the rotary tool with multiple edges and rotary workpiece in turn-milling processes describes the burnishing activity between them, which results in surface hardness variations. Researchers reported that burnishing processes are used in manufacturing to improve the surface finish, surface hardness, dimensional consistency, tensile strength, etc by inducing residual compressive stress in the surface of the work piece4.

In turn-milling processes, the tool gives pressure contact on the workpiece surface due to depth of cut, while advancement of the rotary tool generates crest and trough irregularities, which are filled and pressed by the preceding tooth of the rotary tool. Hence, the end mill cutter acts as a burnishing tool making burnishing process on the workpiece surface and thereby varies surface hardness. In orthogonal turn-milling process, the edge tips of the end mill cutter behave like a ball burnishing tool make cold flow of work material from the peaks of the surface roughness to valleys of the workpiece. The cold working increases the surface finish and surface hardness. Whereas, in case of tangential turn-milling process, the sides/helix of the end mill cutter behave like a roller burnishing tool to increase surface finish and surface hardness.

In this work, the tool speed, feed rate and depth of cut with four levels each are considered for optimal study on generating the responses like surface roughness (Ra) and surface hardness (H) in turn-milling processes. The design of experiments (DOE) based on Taguchi philosophy which has wide publicity for efficiently optimizing the experiments in manufacturing process has been adopted and L16 combination of experimental runs based orthogonal arrays (OA) are derived for experimentation. The Signal-to-Noise ratios (SN ratio) of the responses are considered for optimality study.

Optimization is very much essential in every sector like layout design, health care, logistics, scheduling, manufacturing etc due to competitive increase in demand of products and services. The optimization techniques are developed based on mining of the data5,6. In case of manufacturing process/product optimization, Taguchi’s philosophy stands as the starting point but however, this philosophy is being worldwide criticized due to its inability to solve multi-response optimization problems7. To overcome this drawback, application of Grey relational analysis (GRA), utility theory, TOPSIS, fuzzy inference system, principal component analysis (PCA), entropy method etc are individually integrated with Taguchi method by converting multiple responses into an equivalent single response function, which can finally be optimized by Taguchi method. However, these approaches rely on some assumptions. Hence in this paper, multi-response optimization technique like GRA developed by Deng8 and PCA developed by Hoteling9,10 is adopted.

To the best of knowledge of the author, experimentations on surface roughness were investigated in turn-milling processes. But none of the research focused on multi-response optimization of surface roughness (Ra) and surface hardness (H) of the workpiece material using GRA-PCA and findings related to them. In addition, relative comparisons between the two types of turn-milling processes like tangential and orthogonal turn-milling were also not attempted so far. Hence, this paper focuses on considerations of the above said based on Taguchi fractional factorial study in turn-milling processes.

1. **Experimental design and conditions**

This paper focus on plain single cut turning operation in turn-milling processes like tangential and orthogonal turn-milling methods, conducted on A-axis CNC Vertical Milling centre (VMC-1050) under dry conditions with High speed steel (HSS) tools. The machining parameters like tool speed (r/min), feed rate (mm/min) and depth of cut (mm) with 20r/min constant rotation of workpiece based on Taguchi (L16) fractional factorial study in turn-mill processes were taken for study on surface roughness and surface hardness.

SN ratio are useful in finding the optimal parametric setting values that directly influence the response for determining the minimum at the optimal policy and mentioned the formulae for SN ratios as given in the equations: (1) - (2)11,12.

 (1)

 (2)

Where ‘n’ is observation number, ‘yi’is observation value.

Extruded Brass (leaded) as per IS:319-2007-Grade:1 (Half Hard) which has wide range of customer and industrial applications and was taken for lathe turning study12 was considered as work piece material for extended study on plain turning operation in turn-milling processes. Commercially available 10mm diameter-300 helix long parallel shank HSS end mill cutters of ADDISON company as per BS: 122 (part-1)-1953 are used as cutting tools.

As recommended by the tool manufacturer, the tool speed was considered as 2400r/min with an increment of 250r/min thereon. The workpiece rotation does not have any influence on tool speed but relates to the movement (i.e. axial feed) of the cutting tool only, hence constant rotation of 20r/min for the workpiece was selected in combination of feed rates (3.27mm/min, 5.05mm/min, 8.76mm/min and 10.0mm/min). The depth of cut (d) varied from 0.25mm to 1.0mm in an increment of 0.25mm.

The determined SN ratios of the responses are used for determining the individual optimality and multi-response optimality. The formulae for determining optimum responses based on SN ratios is given in the equations: 3-413 was considered.

 (3)

 (4)

Where ‘n’ is observation number, ‘ηopt’ is optimum SN ratio, ‘ηavg’ is average SN ratio, ‘ηideal’is ideal level of each SN ratio parameter.

**2. 1. Experimentation setup**

Cylindrical work piece of Ф40mm and length 225mm was divided into 5 parts (i.e. 4 x 40mm+65mm extra length for avoiding tool holder hitting the A-axis chuck Vertical milling centre). Average Surface roughness ‘Ra’ and Average surface hardness ‘H’ was measured on the three diametrical end points as the response values.

Surface Roughness Tester of MITUTOYO Surface Test SJ-301 is used to measure the Ra, while Universal hardness testing machine of REICHERTER STIEFELMAYER is used for measuring Vickers surface hardness (H) values as per ASTM E92. For every tool speed, a new HSS tool was used for machining. Combination of machining parameters like tool speed (r/min), feed rate (mm/min) and depth of cut (mm) with constant rotational speed of 20 r/min of workpiece based on Taguchi DOE were adopted. The SN ratio for Ra is required to be minimum and so Smaller-the-Better formula for SN ratio was adopted; whereas for “H”H” it is required to have maximum and so Larger–the-Better formula for SN ratio was adopted, as shown in Table 1.

Table 1. Experimental values recorded in turn-milling processes using HSS End mill cutters

|  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Exp  No. | Machining parameters | | | Tangential turn-milling process | | | | Orthogonal turn-milling process | | | |
| A | B | C | Ra | H | SN  ratio  Ra | SN  ratio  H | Ra | H | SN  ratio  Ra | SN  ratio  H |
| 1 | 2400 | 3.27 | 0.25 | 0.78 | 142.3 | 2.16 | 43.06 | 4.82 | 120.0 | -13.7 | 41.58 |
| 2 | 2400 | 5.05 | 0.50 | 1.11 | 145.9 | -0.91 | 43.28 | 5.65 | 134.0 | -15.0 | 42.54 |
| 3 | 2400 | 8.76 | 0.75 | 1.83 | 151.3 | -5.25 | 43.60 | 6.50 | 143.7 | -16.3 | 43.15 |
| 4 | 2400 | 10.0 | 1.00 | 2.30 | 151.5 | -7.23 | 43.61 | 7.30 | 148.0 | -17.3 | 43.41 |
| 5 | 2650 | 3.27 | 0.50 | 0.56 | 156.7 | 5.04 | 43.90 | 4.41 | 134.7 | -12.9 | 42.59 |
| 6 | 2650 | 5.05 | 0.25 | 0.73 | 153.3 | 2.73 | 43.71 | 5.35 | 127.3 | -14.6 | 42.10 |
| 7 | 2650 | 8.76 | 1.00 | 1.80 | 163.0 | -5.11 | 44.24 | 5.93 | 154.0 | -15.5 | 43.75 |
| 8 | 2650 | 10.0 | 0.75 | 1.88 | 158.4 | -5.48 | 44.00 | 7.12 | 145.0 | -17.1 | 43.23 |
| 9 | 2900 | 3.27 | 0.75 | 0.50 | 170.0 | 6.02 | 44.61 | 2.95 | 148.7 | -9.40 | 43.45 |
| 10 | 2900 | 5.05 | 1.00 | 0.77 | 172.3 | 2.27 | 44.73 | 4.10 | 156.7 | -12.3 | 43.90 |
| 11 | 2900 | 8.76 | 0.25 | 1.08 | 161.0 | -0.67 | 44.14 | 5.50 | 125.0 | -14.8 | 41.94 |
| 12 | 2900 | 10.0 | 0.50 | 1.50 | 162.3 | -3.52 | 44.21 | 6.18 | 136.0 | -15.8 | 42.67 |
| 13 | 3150 | 3.27 | 1.00 | 0.34 | 177.3 | 9.37 | 44.97 | 1.89 | 163.0 | -5.53 | 44.24 |
| 14 | 3150 | 5.05 | 0.75 | 0.42 | 175.4 | 7.54 | 44.88 | 2.74 | 151.3 | -8.76 | 43.60 |
| 15 | 3150 | 8.76 | 0.50 | 0.84 | 167.7 | 1.51 | 44.49 | 4.65 | 141.7 | -13.4 | 43.03 |
| 16 | 3150 | 10.0 | 0.25 | 1.01 | 162.3 | -0.09 | 44.21 | 5.70 | 128.3 | -15.1 | 42.16 |
| A: Tool Speed (r/min) B: Feed Rate (mm/min) C: Depth of Cut (mm)  Ra: Microns (μm) H: Vickers hardness (VHN) | | | | | | | | | | | |

1. **Analysis of individual optimality and Regression modelling**

Based on Eqs:1-2, the SN ratios are computed for Ra and H, considering Smaller-is-better for roughness and larger-is-better for hardness and is tabulated as shown in Table 1. Considering these determined SN ratios, the average ideal SN ratio of tool speed, feed rate and depth of cut are taken for calculating individual optimal value of responses using Eq:3 and 4.

**3.1 Discussions on individual optimality**

The individual optimal levels of cutting parameters depends on individual ideal mean effect of SN ratios and were found as A4-B1-C1 and A4-B1-C4 for tangential and orthogonal turn-mill processes for generating Ra and evaluated as 0.31 µm and 2.1 µm respectively. Similarly the optimal levels of cutting parameters were found as A4-B2-C4andA4-B2-C4 for tangential and orthogonal turn-mill processes for generating H and evaluated as 177.01HV and 162.18 HV respectively. The validations of experiments of the optimal combinations were performed and the errors of percentage from theoretical and experimental were between 0.12% to 11%.

**3.2 Regression modelling**

Regression models based on experimental tests (empirical) are widely in exercise for predicting the behaviour and effects of machining parameters on generated responses to aid the selection of working parameters for a given required response. Empirical regression models with second order linear equations were developed for predicting and analyzing the “Ra” and “H” as a function of tool speed, feed rate and depth of cut. The model depicts a significance more than 95% confidence level. The regression analysis based on statiscal analysis using Analysis of Variance (ANOVA) on response values and their SN ratios are carried to indicate the significance of process parameters on the models. The regression models indicates all the parameters are significant excluding depth of cut in generating Ra in tangential process, while all parameters are significant in generating H except feed. Similarly, in orthogonal process, all the parameters are significant in generating Ra, while all parameters are significant in generating H except feed.

1. **Multi-response optimization**

The methodology of combining Grey Relational Analysis (GRA) with Principal Component Analysis (PCA) for finding the optimal combination of experiment for the correlated response for multi objective optimization (Lu, H.S. et al. (2009)) is shown in figure 1.

The multi-response optimal values determined using GRA-PCA coupled with Taguchi gives A4-B1-C4 combination for Ra of 0.34 µm and 1.89 µm, while H of 177.3 HV and 163.0 HV in tangential and orthogonal turn-mill process respectively.

1. **Results and Discussions**

Result plots between first two predominant machining factors on the generated responses interprets the Ra to be increasing with the feed rate but is decreasing with tool speed, whereas H to be increasing with the depth of cut and tool speed, in both the turn-milling processes. The results of optimal design reveal that the proposed approach of combining GRA with PCA can effectively acquire the optimal combination of cutting parameters and can be a useful tool to improve the cutting performance of turn-milling processes. From ANOVA of regression and GRA-PCA, it is clear that the tool speed is highly effective in generating the combined and individual responses in tangential turn-mill process, while feed and depth of cut are effective for individual response. Similarly, in orthogonal turn-mill the depth of cut is undoubtedly effective in generating the combined and individual responses and feed is less effective.

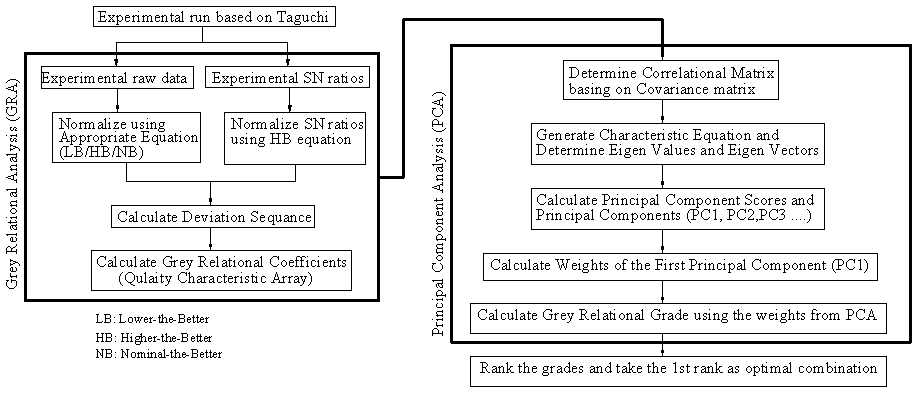


Figure 1: Procedural methodology of GRA-PCA

1. **Conclusions**

The investigation of this study is on individual and multi-response optimal machining parameters like tool speed, feed rate and depth of cut on Ra and H in turn-milling processes.

* The improved surface finish increases surface hardness in both the turn-milling processes. But when compared tangential turn-milling over orthogonal turn-milling, the tangential turn-milling seems to generate good surface finish and higher surface hardness. More research is required for predicting the stresses, micro-structural changes and surface integrity generation in the surface layers, which are responsible for development of cracks, corrosion and cavitations.
* Individual optimization of a single response depends on its own ideal mean effect of SN ratios of the parameters, but if we require optimizing multi-responses, then combined effect of all the responses with highest SN ratio can be treated as optimal combination. In this context, one has to choose multi-response optimization, if he has a weight-age or priority of responses to be generated and on the other hand for single optimization, weight-age can be given 100%.

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