Multi-Independent Optimization while Turning of Inconel-600 alloy using Grey Interactive Exploration

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1. Introduction

The challenges before manufacturing industries are to lessen the setup times, gain grander quality product, ease the costs of machining, and achieve a superb surface finish. Manufacturing is also known as a value addition process where the low utility and low-value raw materials are converted into high quality and valued products with actual dimensions, forms and finish imparting some function ability. With an escalation in advanced engineering businesses such as aerospace, motorized and bio-engineering presentation of challenging-to-cut resources having admirable mechanical and chemical features, it is very demanding to attain dimensional accuracy and surface finish required by a treated product and they cause a premature catastrophe of the tool, resulting in the decline of productivity (You et al., 2019).

Nickel established super alloy Inconel-600 holds broad applications in chemical industries, including heaters, stills, bubble towers, condensers, evaporator tubes, tube sheets etc. Owing to its power and oxidation resistance at high temperature, mark it worthwhile for various solicitations in the heat-treatment industries. It is cast-off for retorts, muffles, roller hearths and heat-treating baskets and treys. IN-600 is applied for a diversity of appliance and airframe elements in the aeronautical arena, which must bear great temperatures. It finds applications in the electronic turf for such parts as cathode ray duct spiders, webs, conduit backing supporters and springs. It also spots applications in nuclear reactors.

Down to low thermal conductivity and diffusivity of IN-600 alloy cause, precipitous temperature ascent at the tool edge and the shift of the scene of utmost temperature headed for the tool tip. It also contains hard carbide particles. As a consequence, extreme tool wear, impulsive cracking and built-up edge creation are noted. IN-600 is thus ordered as difficult-to-cut material (Ezugwu et al., 1999).

2. Literature review

In this section state-of-the-art analysis related to influence of turning process factors on surface roughness, material removal rate (MRR), tool vibrations and tool wear is presented. Chandrasekaran et al. (2013) carried out CNC turning on AISI 316 steel. They used single-layered (TiAlN) and multi-layered coated with Ti (C, N, B) cutting tools to study the phenomenon of surface finish and tool wear. Camposeco-Negrete et al. (2016) performed experiments by applying Taguchi’s L9 array through turning of AISI 1018 steel. They optimized the electrical energy required during machining against speed, feed and depth of cut. Eskandari et al. (2018) performed the multi-

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- Taguchi method
- Grey Interactive Rating
- ANOVA
- Wear sensation
unbiased optimization by applying Taguchi established grey relational study while turning of N-155 superalloy. They optimized tool wear, MRR and surface roughness. Deshpande et al. (2018) practiced cryogenically treated and untreated tungsten carbide inserts for machining of Inconel 718. They applied artificial neural network (ANN) to establish vibrations, surface roughness and cutting force. Parida and Maity (2019) studied the influence of warming temperature on strengths and chip morphology using finite element method (FEM) while turning of Inconel 625. Khanna et al. (2020) established tool wear, surface unevenness and energy consumption through machining of Inconel 718 under various cutting environments. Mou and Zhu (2020) performed dry machining and liquid nitrogen machining (LN2) on Inconel 718. They found improvement in performance features during the LN2 machining. Gunay et al. (2020) used coated carbide tool while machining Nimonic 80A alloy to examine the outcome of feed, speed and depth of cut on superficial integrity and tool life. They conducted experiments under various cutting environments and found that the best cutting performance was achieved at 60 m/min and in an oil spraying environment. Kacal (2020) conducted tests on Inconel-X750 under a dry environment. The cutting tool practiced was PVD coated carbide inserts. He investigated instrument wear, cutting force and exterior coarseness for feed rate and cutting speed. Abidi (2020) studied chip morphology and surface roughness while hard turning of AISI 1045 steel. He also developed correlation between surface roughness and chip morphology. Abidi (2021) performed turning operation on C45 hardened steel using ceramic tool. He optimized cutting parameters for MRR, tool life and tool wear.

This research work aims to examine the impact of governing factors, for example machining speed, feed and depth of cut on surface unevenness, tool vibrations and tool wear. The checks are accomplished by implementing Taguchi’s L9 orthogonal matrix. Tool wear analysis is studied using the SEM analysis. At last, multi-attribute optimization is performed using grey relational analysis.

3. Experimental Details

This section describes workpiece material, tool material, tool holder, experimental plan, performance measures and experimental setup, and grey relational analysis method for multi-feature optimization.

3.1. Workpiece Material

The workpiece material put on in this research study was Inconel 600 alloy (UNS N06600), which is usually studied in chemical, heat treatment, aircraft and nuclear industry. The workpiece was in the bar shape with a diameter of 50 mm and 200 mm in length. The chemical composition of IN-600 alloy is Ni & Co-72%, Cr-14-17%, Fe-6-10%, C-1.5% max, Mn-1% max, S-0.015% max, Si-0.5% max Cu-0.5% max.

3.2. Cutting tools and Tool Holder

A 4-cutting edge uncoated cemented carbide tool insert Sandvik make CN1204 was used as a cutting tool having the cutting edge effective length as 12.09 mm, back rake angle -23°, approach angle 80° and corner radius 0.8 mm. The dimension of the tool holder applied was 25 mm x 25 mm x 145 mm with ISO specification of PCLNR2525M12. The tool holder, along with the cutting tool, is shown in Fig. 1.

3.3. Idea of Checks

In the current analysis, three governing variables, machining speed, feed and depth of cut were chosen. The limits and their associated ranks selected based on the preliminary investigation are indicated in Table 1. Taguchi’s L9 orthogonal matrix was employed to perform the tests. This matrix has 8 grades of autonomy and it can lever three-equal design factors. Each test was conducted three times. Thus, inclusive 27 checks are conducted. The L9 orthogonal group for the three cutting factors is indicated in Table 1. The trials were carried out on the conventional center lathe. In Figure 2 indicates the arrangement of experimental set up showing the workpiece, measurement system of FFT analyser and tool holder.

![Fig. 1. Carbide insert tool holder](image1)

![Fig. 2. Trial system](image2)

| Sr. No. | Factor                         | 1  | 2  | 3  |
|--------|--------------------------------|----|----|----|
| 1      | Cutting Speed (A) m/min        | 140| 320| 500|
| 2      | Feed (B) mm/rev                | 0.2| 0.45| 0.7 |
| 3      | Depth of Cut (C) mm             | 0.5| 1.0| 1.5 |

Table 1. Taguchi’s L9 orthogonal group
3.4. Assessment of Performance features

3.4.1. Surface Unevenness (Ra Value)

The surface unevenness (Ra value) of the machined surface was gauged via a Mitutoyo make digital surface tester SJ-210 in μm once taking every cut. The surface finish was quantified three times on each cut surface at three different locations around the circumference of the cut surface and then the standard value was obtained by averaging. The sampling length is considered as 0.8 mm during an assessment. Fig. 3 displays the quantification of the surface unevenness of a machined surface.

![Fig. 3. Quantification of surface roughness](image)

3.4.2. Tool Vibrations

Tool vibrations were assessed by using an FFT analyzer with an accelerometer. Vibrations were judged in m/s². Fig. 4 indicates mounting of an accelerometer.

![Fig. 4. Mounting of Accelerometer](image)

3.4.3. Tool Wear

Tool wear was weighed by a scanning electron microscope (SEM) (JEOL 6300F, Japan).

4. Results and discussion

From Figure 5, it is seen that the surface unevenness decreased with progressive values cutting speed. This is credited to an upsurge in cutting zone hotness with a cumulative cutting speed that lessens the yield bound of the workpiece material, and material reduction is violent. This marks in the tempering of the workpiece material, which expands the cutting process. Roughness raises repetitively with feed rate but in sufficient larger slope. This fact is related to the furrows left along the surface of the cut model as the cutting tool travels, whereby with an upsurge in the feed rate, a bigger departure between consecutive the loci occurs. The depth of a cut positively predisposed the surface coarseness. Roughness is augmented with intensification in the depth of cut. This style is because developed values of depth of a cut yield extra thrust forces, which upturn roughness due to a larger distortion of flaw that is more violently pressed alongside the machined exterior, resulting in an inferior surface gloss (Yousefi and Zohoor, 2019).

![Fig. 5. Perturbation plot for surface unevenness (μm)](image)

Figure 6 depicts the influence of machining aspects on vibrations. As cutting speed surges, cutting force declines that diminish the vibrations. All the features of the cutting force rise with prominent feed rate standards that promote escalation in the chip section and thus vibration level rises. As the depth of a cut raises, more cutting volume is removed, leading to large values of cutting forces, thus subsequently upturn in vibrations (Yousefi and Zohoor, 2019).

![Fig. 6. Perturbation plot for vibrations (m/s²)](image)

5. Multi-Feature Optimization with Grey Interactive Exploration (GIE)

The Grey theory is founded on the chance ambiguity of minor examples, which settled into an appraisal practice to unravel sure problems of structure that are composite and are having partial evidence. A scheme for which the pertinent material is fully identified is a white arrangement, while a structure for which application data is fully strange is a “black” scheme. Some scheme between these boundaries is a grey
method having miserable and inadequate statistics (Sonawane et al. 2019). Grey interactive exploration is a normalized appraisal technique that effectively solves the complicated multi-performance characteristic optimization. The various steps involved in the GIE are as follows.

5.1. Data Preprocessing

In this, training a direct regulation of the tentative effects for vibrations and surface lumpiness were executed in the series between zero and one, which is also called grey interactive group.

The normalized data processing for vibrations and surface coarseness conforming to the lower-the-better norm can be stated as indicated by

\[
Z_i*(k) = \frac{\max Z_i(k) - Z_i(k)}{\max Z_i(k) - \min Z_i(k)}
\]

where \(Z_i*(k)\) is the value of a grey interactive group, \(\min Z_i(k)\) is the tiniest charge of \(Z_i(k)\) the \(k^{th}\) reply, and the \(\max Z_i(k)\) is the maximum rate of \(Z_i(k)\) the \(k^{th}\) reaction. The ideal order is \(Z_i^{\prime}(k)\) (\(K = 1, 2, 3\) for vibrations and surface coarseness, respectively). The grey interactive group is shown in Table [2].

The larger normalized results match to the enhanced performance and the best normalized result should be equivalent to one. Next, the grey interactive number is evaluated to direct the affiliation between the ideal (best) and real normalized investigational results. The grey interactive number can be computed as shown by

\[
y_i(k) = \frac{\Delta \min + \zeta \Delta \max}{\Delta \min + \zeta \Delta \max}
\]

where \(\Delta \theta_i(k) = |Z_0*(k) - Z_i*(k)|\) = variance of the total value among \(Z_0*(k)\) and \(Z_i*(k)\), \(\Delta \max\) and \(\Delta \max\) are correspondingly the minima and maxima values of the complete alterations of all the comparing arrangements; \(\zeta\) is the unique coefficient, \(\zeta \in (0,1)\), the drive of which is to deteriorate the \(\Delta \max\) when it goes too large and thus broadens the change significance of the interactive constant.

In the current situation, \(\zeta = 0.5\) is used. Once averaging the grey interactive numbers, the grey relational rating (GRR) can be calculated by

\[
\gamma(Z_0, Z_i) = \frac{\sum_{i=1}^{m} y(Z_0(k), Z_i(k))}{m}
\]

where \(\gamma(Z_0(k), Z_i(k))\) is the grey interactive mark for the \(jth\) trial, and \(m\) is the quantity of eminence features. The GIR signifies the amount of intimacy between the reference runs and comparability progressions. A greater value of the GIR indicates a stronger unification between the orientation runs and comparability sets. The values of GRR are represented in Table 2. Thus, the GRE is a measurement of the total amount of variation between results of sequences, and it can be employed to quantity adjacent linking between the progressions.

The upper grey relational rating embodies that the corresponding investigational end result (Table 2, Experimental No. 8) is closer to the ideally normalized value. In other words, optimization of the complex manifold performance physiognomies can be transformed into optimization of a distinct grey interactive rating. Meanwhile the investigational strategy is orthogonal, it is likely to discrete out the result of each cutting constraint on grey interactive rating at different levels. Basically, the larger the grey interactive rating the healthier is the manifold recital physiognomies. However, the absolute ranking between the machining limits for the numerous performance appearances still necessities to be identified to facilitate the prime groupings of the machining constraint levels. Table 3 and Fig. 7 show that the third level of speed, the first rank of feed rate, and the first equal of depth of cut are the finest grouping of process limits for several presentation features.

| Sr. No. | Cutting Speed (A), m/min | Feed Rate (B), mm/rev | Depth of Cut (C), mm | Vibrations m/s² | Ra, μm | Normalized Decision Matrix | Grey Number | Interactive Rating |
|---------|--------------------------|------------------------|----------------------|-----------------|--------|--------------------------|--------------|-------------------|
|         |                          |                        |                      |                 |        |                          |              |                   |
| 1       | 135                      | 0.22                   | 0.5                  | 0.222           | 4.18   | 0.9408                   | 0.4844       | 0.8941            | 0.4923         | 0.6932            | 4                  |
| 2       | 135                      | 0.4                    | 1                    | 0.572           | 4.52   | 0.1435                   | 0.3516       | 0.3686            | 0.4354         | 0.4020            | 7                  |
| 3       | 135                      | 0.71                   | 1.5                  | 0.635           | 5.42   | 0.0000                   | 0.0000       | 0.3333            | 0.3333         | 0.3333            | 9                  |
| 4       | 215                      | 0.22                   | 1                    | 0.244           | 3.8    | 0.8907                   | 0.6328       | 0.8206            | 0.5766         | 0.6986            | 3                  |
| 5       | 215                      | 0.4                    | 1.5                  | 0.586           | 4.63   | 0.1116                   | 0.3086       | 0.3601            | 0.4197         | 0.3899            | 8                  |
| 6       | 215                      | 0.71                   | 0.5                  | 0.485           | 2.86   | 0.8542                   | 0.2274       | 0.7743            | 0.3914         | 0.5828            | 5                  |
| 7       | 500                      | 0.22                   | 1.5                  | 0.368           | 2.86   | 0.6082                   | 1.0000       | 0.5607            | 1.0000         | 0.7803            | 2                  |
| 8       | 500                      | 0.4                    | 0.5                  | 0.196           | 3.75   | 1.0000                   | 0.6523       | 1.0000            | 0.5899         | 0.7949            | 1                  |
| 9       | 500                      | 0.71                   | 1                    | 0.501           | 4.41   | 0.3052                   | 0.3945       | 0.4185            | 0.4523         | 0.4354            | 6                  |
Table 3. Reply Bench for Means

| Level | A    | B    | C    |
|-------|------|------|------|
| 1     | 0.4762 | 0.7240 | 0.6903 |
| 2     | 0.5571 | 0.5289 | 0.5120 |
| 3     | 0.6702 | 0.4505 | 0.5012 |
| Delta | 0.1940 | 0.2735 | 0.1891 |
| Rank  | 2     | 1     | 3     |

From Table 5, it may be recognized that there is a decent settlement among the assessed value (0.7949) and the tentative assessment (0.8138). The increase in grey interactive rating from original cutting conditions to optimal cutting conditions is 0.1206. Hence it may be resolved that several performance features of turning Inconel-600 superalloys such as surface coarseness and vibrations, are upgraded together by this style.

Table 5. Outcomes of the endorsement assessment

|             | Starting Cutting Conditions | Optimal cutting conditions |
|-------------|-----------------------------|-----------------------------|
| Starting Level | A1B1C1                      | A3B1C1                      |
| Vibrations, m/s²    | 0.222                       | 0.185                       |
| Surface roughness, μm | 4.18                       | 3.05                        |
| GRR          | 0.6932                      | 0.7949                      |
| Improvement in GRR | 0.8138-0.6932 =0.1206       |

6. Tool Wear Analysis

From Figure 8, it is observed that the major tool wear occurs due to fracture, chipping, abrasion and adhesion wear phenomena. Fracture and chipping occurrence is attributed to the characteristic behaviour of extraordinary strain frequency and work hardening, followed by the surprising heat concentration at the chip-tool edge.

Fig. 8. Tool wear phenomenon

As Nickel built alloys have a great chemical attraction with many cutting tool materials, built edge formation takes place, which breaks and particles come out of the cutter, which results from dissolution and diffusion wear.

Chipping can also be triggered owing to mechanical shakings from the instrument shaft, part fixtures, overworks, extraordinary feed rate and cutting speed. Flank wear or abrasion mechanism is down to the manifestation of stiff carbide and oxide elements existing in the workpiece material KACAL (2020).
7. Summary and conclusion

In this investigation work, turning of Inconel-600 super alloy is executed. Taguchi based grey interactive exploration is applied for multi-distinctive optimization. Grey relational examination directly assimilates compound quality characteristics (vibrations and surface roughness) into a solitary performance individual called the grey relational rating. The optimal cutting aspects situations achieved is cutting speed 500 m/min, feed rate 0.22 mm/rev and depth of cut 0.5 mm. The ANOVA breakdown point out that the feed amount is more substantial at a 95% confidence level than the other two factors. Endorsement research expresses an upturn in the grey relational rating from the opening cutting situations to the prime cutting settings and is 0.1206. Fracture, chipping, abrasive and adhesion wear phenomenon is perceived for the cutting tools.

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