PRODUCTION ENGINEERING ARCHIVES 2021, 27(4), 277-282

PRODUCTION ENGINEERING ARCHIVES

ISSN 2353-5156 (print)
ISSN 2353-7779 (online)

Exist since 4th quarter 2013
Available online at https://pea-journal.eu

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

Sachin Sonawane[1,*], Sandeep Wangikar[1], Kuldip Pukale[1]

[1] SVERI's College of Engineering, Pandharpur-4133304, Maharashtra, India
*Correspondence: sonawanesachin09@gmail.com

Article history
Received 13.06.2021
Accepted 22.09.2021
Available online 15.11.2021

Keywords
Taguchi method
Grey Interactive Rating
ANOVA
Wear sensation

Abstract

This investigation effort offers multi-quality attributes optimization while turning of Inconel-600 superalloy. Taguchi's L9 orthogonal planning is implemented to review the upshot of governing aspects such as machining speed, feed rate, and depth of cut on vibrations and surface roughness (SR). To heighten all the three leading variables, the grey interactive exploration (GIE) is implemented. The grey interactive rating (GIR) is practiced as a multi-quality exclusive key (MQEK). The finest formation of central variables acquired from the investigational grades is cutting speed 500 m/min, feed rate 0.22 mm/rev and depth of cut 0.5 mm. ANOVA scrutiny signposts that feed rate is a crucial variable relating to the superiority yields. Products of endorsement pilots display that the ideal foremost variables developed the grey interactive rating from 0.6932 to 0.8138 for the numerous retorts. Scanning Electron Microscopic (SEM) scrutiny of cutting tool spectacles that fracture, chipping, abrasion and adhesion are the primary wear phenomena.

DOI: 10.30657/pea.2021.27.37 JEL: L69, M11

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 tooltip. 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 turining 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 multiunbiased 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.

Fig. 1. Carbide insert tool holder

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

Table 1. Taguchi's L9 orthogonal group

Sr. No.	Factor	Rank		
		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

Fig. 2. Trial system

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

3.4.2. Tool Vibrations

Tool vibrations were assessed by using an FFT analyzer with an accelerometer. Vibrations were judged in m/s^2. Fig. 4 indicates mounting of an accelerometer.

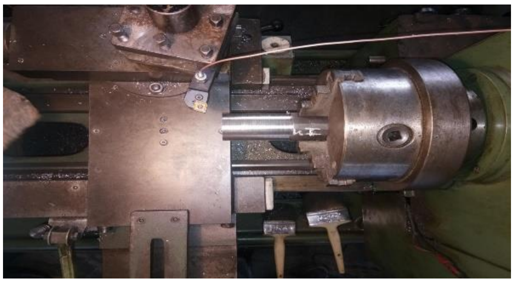

Fig. 4. Mounting of Accelerometer

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).

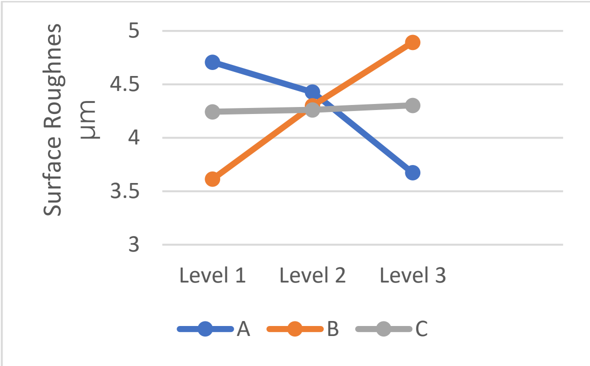

Fig. 5. Perturbation plot for surface unevenness (µm)

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).

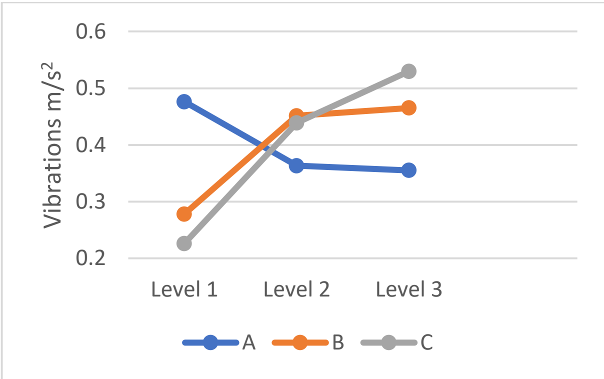

Fig. 6. Perturbation plot for vibrations (m/s^2)

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

$$\mathrm{Zi}*(\mathrm{k}) = \frac{\max \mathrm{Zi}(\mathrm{k}) - \mathrm{Zi}(\mathrm{k})}{\max \mathrm{Zi}(\mathrm{k}) - \min \mathrm{Zi}(\mathrm{k})} \quad (1)$$

where $\mathrm{Zi}*(\mathrm{k})$ is the value of a grey interactive group, min $\mathrm{Zi}(\mathrm{k})$ is the tiniest charge of $\mathrm{Zi}(\mathrm{k})$ the k^{th} reply, and the max $\mathrm{Zi}(\mathrm{k})$ is the maximum rate of $\mathrm{Zi}(\mathrm{k})$ the k^{th} reaction. The ideal order is Zi*(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

$$\gamma\mathrm{i}(\mathrm{k}) = \frac{\Delta\min + \zeta.\Delta\max}{\Delta\min + \zeta.\Delta\max} \quad (2)$$

where $\Delta0\mathrm{i}(\mathrm{k}) = |\, \mathrm{Z0}*(\mathrm{k}) - \mathrm{Zi}*(\mathrm{k})|$ = variance of the total value among $\mathrm{Z0}*(\mathrm{k})$ and $\mathrm{Zi}*(\mathrm{k})$, $\Delta_{\min}$ and $\Delta_{\max}$ are correspondingly the minima and maxima values of the complete alterations of all the comparing arrangements; ζ is the unique coefficient, ζ ϵ (0,1), the drive of which is to deteriorate the Δmax when it goes too large and thus broadens the change significance of the interactive constant.

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

$$\gamma(\mathrm{Z0},\mathrm{Zi}) = \frac{\sum_{i=1}^{m} \gamma\,\{\mathrm{Z0}(\mathrm{k}),\mathrm{Zi}(\mathrm{k})\}}{m} \quad (3)$$

where $\gamma\{\mathrm{Z0}(\mathrm{k}),\ \mathrm{Zi}(\mathrm{k})\}$ 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 GRR 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.

Table 2. Results of the tests and Grey Relational Exploration

Sr, No.	Cutting Speed (A), m/min	Feed Rate (B), mm/rev	Depth of Cut (C), mm	Vibrations m/s^2	Ra, µm	Normalized Decision Matrix		Grey Interactive Number		Grey Interactive Rating	
						Vibrations, m/s^2	Ra, µm	Vibrations m/s^2	Ra, µm	Value	Rank
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	0.26	4.85	0.8542	0.2227	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

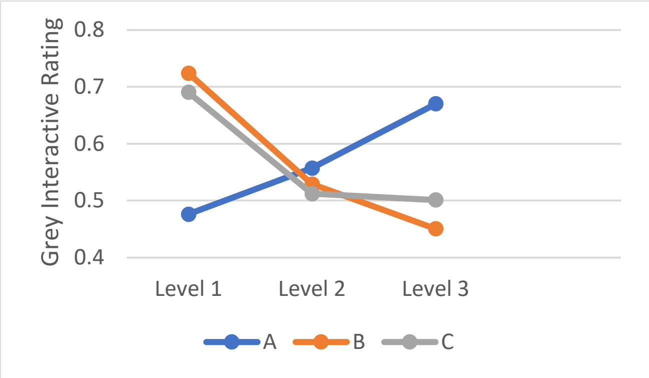

Fig. 7. Perturbation plot for Grey Relational Rating

5.2. Analysis of Variance (ANOVA)

The resolve of ANOVA is to inspect which of the process structures meaningfully upset the performance measures. This is realized by sorting out the entire unpredictability of the grey interactive rankings, which is quantified by the totality of squared aberrations from the whole mean of the grey interactive ranking, into involvement by every machining limit and the error. Table [4] illustrates ANOVA results for multiple performance characteristics, i.e. vibrations and surface roughness.

Table 4. Examination of Change for Means (ANOVA)

Source	DF	Seq SS	Adj SS	Adj MS	F
A	2	0.05700	0.05700	0.028499	3.21
B	2	0.11902	0.11902	0.059509	6.71
C	2	0.06769	0.06769	0.033847	3.81
Residual Error	2	0.01775	0.01775	0.008873	
Total	8	0.26146			

5.3. Authorization Test

After the ideal level of machining parameters has been recognized, a proof assessment needs to be performed to check the exactness of the breakdown. The projected grey interactive ranking γ* using the best equal of process limits can be calculated by

$$\gamma^* = \gamma m + \sum_{i=1}^{0}(\gamma i - \gamma m) \quad (4)$$

γm is the mean grey interactive ranking, γi is the mean grey interactive rating at the top level, and '0' is the chief design parameter. Table 5 compares the projected grey interactive rating and actual grey interactive ranking obtained in experiments using the optimal level of cutting parameters.

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	
		Prediction	Experiment
Starting Level	A1B1C1	A3B1C1	A3B1C1
Vibrations, m/s^2	0.222		0.185
Surface roughness, μm	4.18		3.05
GRR	0.6932	0.7949	0.8138
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.

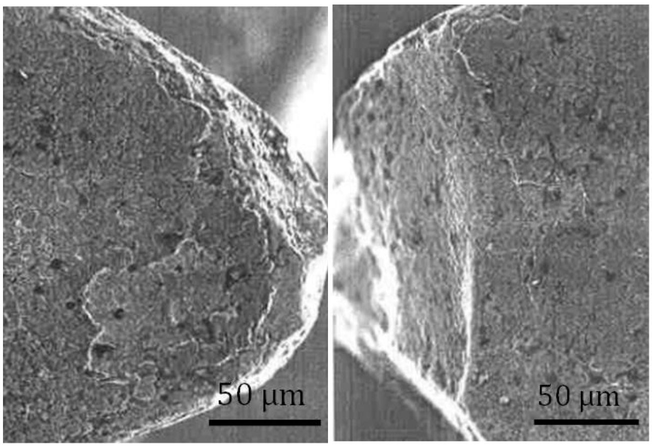

Fig. 8. Tool wear phenomenon

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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基于灰色交互探索的 Inconel-600 合金车削多独立优化

關鍵詞
田口法
灰色互动评级
方差分析
佩戴感

摘要
这项调查工作在车削 Inconel-600 超级合金时提供了多质量属性优化。 Taguchi 的 L9 正交规划用于审查控制方面的结果，例如加工速度、进给率以及振动和表面粗糙度 (SR) 的切削深度。为了提高所有三个主要变量，实施了灰色交互探索（GIE）。灰色交互评级 (GIR) 被实践为多质量独占密钥 (MQEK)。从研究级获得的最精细的中心变量形成是切削速度 500 m/min、进给速率 0.22 mm/rev 和切削深度 0.5 mm。 ANOVA 审查表明，进料速率是与优势产量相关的关键变量。代言飞行员的产品显示，理想的首要变量将灰色交互评级从 0.6932 发展到 0.8138，以应对众多反驳。对切削刀具眼镜进行扫描电子显微镜 (SEM) 检查，断裂、碎裂、磨损和粘附是主要的磨损现象。