TheEurasiaProceedings of Science, Technology, Engineering&Mathematics (EPSTEM)
ISSN: 2602-3199

The Eurasia Proceedings of Science, Technology, Engineering & Mathematics (EPSTEM), 2023

Volume 26, Pages 366-374

IConTES 2023: International Conference on Technology, Engineering and Science

Multi-Objective Optimization of the Inconel 718 Turning Parameters Using MARCOS–Based Taguchi S/N ratio

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Abstract: Nickel-based alloys, such as Inconel 718, are widely used in space technology, rocket engines, nuclear reactors, petrochemicals, submarines, power plants, and other applications. It is classified as a challenging material to process due to its strong mechanical properties, low thermal conductivity, and other characteristics. The main objective of this work is to determine the optimal cutting parameters for turning Inconel 718 using a coated carbide tool, with the aim of reducing cutting tool vibration, minimizing surface roughness, and maximizing material removal rate. This is achieved by employing the Measurement of Alternatives and Ranking according to Compromise Solution technique (MARCOS) coupled with Taguchi's signal-to-noise ratio. The results have demonstrated that the configuration of the cutting parameters for achieving the aforementioned objectives is as follows: r = 0.8 mm, Vc = 70 mm/min, f = 0.08 mm/rev, and ap = 0.3 mm.

Keywords: MARCOS, Multi-objective optimization, Inconel 718, Taguchi

Introduction

In the machining process, optimization is considered a crucial activity that enables the selection of appropriate cutting conditions to enhance productivity, ensure product quality, and reduce production costs. Among the various optimization methods, multi-criteria decision-making (MCDM) methods are widely utilized due to their simplicity (Vats et al., 2022). These methods have been employed by numerous researchers in various machining processes, such as optimizing milling conditions (Arun Ramnath et al., 2019; Arun Ramnath & Thyla, 2022), drilling Ti-6Al-4V using the TOPSIS method (Samsedeensadham,2021), hard turning of medium carbon steel (Sristi, 2022), and grinding 9CrSi steel using CBN wheels (Thinh, & Trung,2022). Thirumalai et al. (2021) used the method (TOPSIS) to optimize the cutting parameters of Inconel 718 during turning. Sivalingam et al.(2021). used two MCDM approaches, ARAS and CODAS, to optimize the operating parameters for turning Inconel 718 alloy in dry cutting settings (ASCF). Several approaches have been proposed, combining multi-criteria decision-making methods with the Taguchi signal-to-noise ratio. Pawade and Joshi (2011) employed a coupled approach based on Taguchi's method and grey relational analysis (TGRA) to determine the optimal

- Selection and peer-review under responsibility of the Organizing Committee of the Conference

process parameters for turning operations on Inconel 718 using a CNC lathe with cubic boron nitride (CBN) tools. B. Satyanarayana et al. (2013) also utilized TGRA to optimize cutting force, flank wear, and surface roughness during turning operations on Inconel 718 using a CNC lathe with CBN tools. Alsoruji et al. (2022) introduced the Taguchi analysis combined with the GRA approach for producing an ideal cutting regime that fulfills high (MRR), lower taper angle, and lowest roughness.The material used in this study is Inconel 718. This selection was based on the material's known challenges in machining, attributed to its high shear strength, tendency to work harden, and low thermal conductivity (Rajurkar & Chinchanikar, 2022;De Bartolomeis et al., 2021). Extensive research has been conducted to identify optimal machining conditions that ensure ease of machining, high surface quality, low energy consumption, and maximum productivity at a cost-effective level (Roy et al., 2018; Dudzinsk et al., 2004). Devillez et al. (2011) employed a coated carbide tool to conduct surface integrity tests on Inconel 718, both with and without lubrication. The results demonstrated that dry machining with a coated carbide tool produced an acceptable surface, exhibiting residual stresses and microhardness values equivalent to those achieved under the lubricated machining condition when using the optimized cutting speed value.

Deshpande et al. (2017) developed prediction models for surface roughness by considering cutting parameters, cutting force, sound emitted during machining, and vibrations during the turning of Inconel 718, using both cryogenically treated and untreated cutting tools. These models serve as a real-time control method for the turning process of Inconel 718. Tan et al. (2022) investigated the surface integrity of machined Inconel 718 using carbide and ceramic inserts. Surface roughness, residual stresses, and microhardness were studied in relation to the cutting parameters. Xu et al. (2022) conducted an experimental and numerical study on the machining of Inconel 718 using worn-out tools, examining chip formation, variations in cutting force, tool wear, heat distribution, and microstructure.

Numerous researchers have demonstrated the effectiveness of the signal-to-noise (SN) ratio when used in MCDM methods. Thus, this study distinguishes itself by applying the SN ratio-MARCOS, to optimize three objective functions: surface roughness, tangential vibrations of the cutting tool, and material removal rate during the turning of Inconel 718.

Theoretical Frameworks

Multi-Objective Optimization by MARCOS-Taguchi

Stevic et al.(2020) use equations the ideal solution "AI" and " the anti-ideal solution "AAI" to normalize the data set. In this work, the signal-to-noise ratio will be used.

Step 1: Data Normalization: using the following formulas:

Smaller-the-better $$\eta_i(j) = -10log_{10}\left[\frac{1}{n}x_i^2(j)\right] \tag{1}$$

Larger-the-better $$\eta_i(j) = -10log_{10}\left[\frac{1}{n.x_i^2(j)}\right] \tag{2}$$

Step 2: construct the Weighted Matrix

Generation of the weighted V matrix employing the criteria's weights:

$$V = \left[v_{ij}\right]_{m\times n} \tag{3}$$

Where $v_{ij} = \frac{\eta_{ij}}{Max(\eta_j)} \times w_j$ and $Max(\eta_j)$ is the maximum of column j.

Step 4: Perform the utility degrees for each alternative:

$$S_i = \sum v_{ij} \tag{4}$$

$$K_i^- = \frac{S_i}{\sum_{j=1}^{m} Max(\eta_j)} \quad (5)$$

$$K_i^+ = \frac{S_i}{\sum_{j=1}^{m} Min(\eta_j)} \quad (6)$$

Step 5: Construct the utility function

$$f(K_i^-) = \frac{K_i^+}{K_i^+ + K_i^-} \quad (7)$$

$$f(K_i^+) = \frac{K_i^-}{K_i^+ + K_i^-} \quad (8)$$

$$f(K_i) = \frac{K_i^- + K_i^+}{i + \frac{1-f(K_i^+)}{f(K_i^+)} + \frac{1-f(K_i^-)}{f(K_i^-)}} \quad (9)$$

Step 6: Ranking

Experimental Procedure

A cylindrical Inconel 718 bar with a diameter of 70 mm and a length of 350 mm was selected as the specimen. The turning tests were carried out on a conventional lathe (TOS TRENCIN) type SN40C (Pm=6.6 kW). The lathe is outfitted with an ABB series ACS355 variable speed drive with a speed sensor that allows the spindle speed to be controlled. SANDVIK metal carbide cutting inserts with a PVD coating of grade (GC1105) were used. The PVD coating is made up of a thin layer of TiAlN, which provides high tenacity, good adhesion, and even draft wear (Coromant & Catalogue, 2017). Fig. 1 shows the inserts mounted on a SANDVIK tool holder with the ISO designation PSBNR2525K12.

$$MRR = Vc.f.ap[cm^3/min] \quad (10)$$

Figure 1. Experimental equipments.

Figure 1 show the equipment used to measure the various output parameters. A roughness meter (2D) of the MITUTOYO type SJ-210 was used to measure roughness (Ra). It is made up of a 5 m diamond tip (feeler) that operates axially over a 4 mm distance on the machined surface. The measurements were obtained three times by flipping the workpiece across a 120° angle and using the average of the three measurements. A vibrometer type VM-6360 and an accelerometer were used to measure the tool's vibrations in the tangential direction (atng). The measurements were collected using the software (data collection system). As a measure of productivity, the material removal rate (MRR) was chosen, and Eq. (10) was used to calculate it.

The experimental design was based on the conventional Taguchi L27 (3^4) orthogonal array. The first input component was allocated to the tool nose radius (r), the second to the cutting speed (Vc), the third to the feed rate per revolution (f), and the fourth to the depth of cut (ap). The range of variation for each factor is for r (0.8,1.2,1.6) mm, Vc (30,50,70) mm/min, f (0.08,0.12,0.16) mm/rev, and ap (0.1,0.2,0.3) mm. The cutting conditions are chosen in accordance with the manufacturer's instructions (SANDVIK). The Design of Experiments matrix, based on the Taguchi L27 design, provides various combinations of input factors, as illustrated in Table 1.

Table 1. Taguchi L27 experimental design

N° of test	Input parameters r (mm)	Vc (m/min)	f (mm/rev)	ap (mm)
1	1	1	1	1
2	1	1	2	2
3	1	1	3	3
4	1	2	1	2
5	1	2	2	3
6	1	2	3	1
7	1	3	1	3
8	1	3	2	1
9	1	3	3	2
10	2	1	1	1
11	2	1	2	2
12	2	1	3	3
13	2	2	1	2
14	2	2	2	3
15	2	2	3	1
16	2	3	1	3
17	2	3	2	1
18	2	3	3	2
19	3	1	1	1
20	3	1	2	2
21	3	1	3	3
22	3	2	1	2
23	3	2	2	3
24	3	2	3	1
25	2	3	1	3
26	3	3	2	1
27	3	3	3	2

Results and Discussions

ANOVA Signal to Noise Analysis

After machining operation, the performance characteristics of Ra, and atng were measured and they are summarized in Table 2. The responses were analyzed using lower is the better for Ra and atng using Taguchi's signal-to-noise ratio. The resulting response mean tables are shown in Tables 3, and 4. ANOVA is utilized to determine the significance and contribution of each process parameter to performance characteristics. Table 3 presents the ANOVA results for Ra.

The most influential factor affecting Ra is the feed rate (f), contributing 26.27% cont%. This is attributed to the fact that an increase in feed rate (f) leads to an expansion of grooves formed by the nose radius of the tool on the surfaces of Inconel 718, consequently resulting in surface quality deterioration. The results confirm previous findings in the literature (Amigo et al., 2023; Yin et al., 2020).

The interaction between radius (r) and feed rate (f) ranks as the second most significant contributor after f, accounting for 23.79%. This is supported by the interaction graph depicted in Figure 2 (c), where a clear interaction is observed. Specifically, for a tool radius of r = 1.6 mm, which generally yields good surface roughness, the feed rate has no substantial impact on Ra. However, for a radius of r = 0.8 mm, increasing the feed rate leads to a significant decrease in the Ra signal-to-noise ratio, indicating surface deterioration (Venkatesan et al.,2019).

The second factor that significantly contributes to surface roughness is cutting speed, with a contribution of 23.51%. This can be explained by the phenomenon of vibrations occurring in the cutting tool at high cutting speeds, primarily due to the increased hardness and resistance of Inconel 718. Consequently, the surface roughness of the machined part deteriorates (Fang et al., 2011; Thakur & Gangopadhyay, 2016). An effective approach to enhancing surface roughness involves increasing the tool radius. This approach is substantiated by the interaction graph depicted in Figure 2 (a), demonstrating a contribution percentage of 4.39% for the (r*Vc) interaction. Lastly, we observe the (r*ap) interaction, as well as the two factors (r and ap), contributing 3.20%, 1.94%, and 5.18%, respectively.

Table 2. Experimental result of performance parameters

N° of test	*Input parameters* r (mm)	Vc (m/min)	f (mm/rev)	ap (mm)	*Output parameters* Ra (µm)	a_{tng} (m/s^2)	MRR (cm^3/min)
1	0.8	30	0.08	0.1	0.401	2.077	0.240
2	0.8	30	0.12	0.2	0.571	2.247	0.720
3	0.8	30	0.16	0.3	0.672	2.691	1.440
4	0.8	50	0.08	0.2	0.328	1.334	0.800
5	0.8	50	0.12	0.3	0.349	2.142	1.800
6	0.8	50	0.16	0.1	0.787	1.603	0.800
7	0.8	70	0.08	0.3	0.280	1.828	1.680
8	0.8	70	0.12	0.1	0.338	1.484	0.840
9	0.8	70	0.16	0.2	0.435	2.106	2.240
10	1.2	30	0.08	0.1	0.457	2.870	0.240
11	1.2	30	0.12	0.2	0.431	3.537	0.720
12	1.2	30	0.16	0.3	0.582	3.728	1.440
13	1.2	50	0.08	0.2	0.386	2.865	0.800
14	1.2	50	0.12	0.3	0.433	2.673	1.800
15	1.2	50	0.16	0.1	0.649	2.037	0.800
16	1.2	70	0.08	0.3	0.428	2.428	1.680
17	1.2	70	0.12	0.1	0.282	2.012	0.840
18	1.2	70	0.16	0.2	0.476	2.440	2.240
19	1.6	30	0.08	0.1	0.394	3.393	0.240
20	1.6	30	0.12	0.2	0.390	3.683	0.720
21	1.6	30	0.16	0.3	0.464	3.535	1.440
22	1.6	50	0.08	0.2	0.434	2.157	0.800
23	1.6	50	0.12	0.3	0.445	2.839	1.800
24	1.6	50	0.16	0.1	0.457	2.400	0.800
25	1.6	70	0.08	0.3	0.433	2.579	1.680
26	1.6	70	0.12	0.1	0.357	2.383	0.840
27	1.6	70	0.16	0.2	0.284	2.588	2.240

Table 3. Analysis of variance for SN ratios (Ra).

Source	DF	Seq SS	Adj SS	Adj MS	F	P	Cont%
r	2	4.134	4.134	2.067	0.82	0.483	3.2082
Vc	2	30.304	30.304	15.152	6.04	0.036	23.5177
f	2	33.859	33.859	16.93	6.75	0.029	26.2766
ap	2	2.507	2.507	1.254	0.5	0.63	1.9456
*r*Vc*	4	5.664	5.664	1.416	0.56	0.698	4.3956
*r*f*	4	30.667	30.667	7.667	3.06	0.107	23.7994
*r*ap*	4	6.68	6.68	1.67	0.67	0.638	5.1841
ResidualError	6	15.042	15.042	2.507			11.6735
Total	26	128.856					100

Table 4 shows the ANOVA for the tangential vibrations (atng). The radius (r) has the most impact its contribution is 42.64%%, this can be explained by the fact that increasing the tool nose radius (r) leads to an increase in the contact length between the cutting edge and the workpiece, causing additional friction. Consequently, this causes an amplification of the tangential vibrations of the cutting tool. As for the cutting speed with a contribution of 35.35% , its increase when machining Inconel 718 is associated with excessive wear of the tool, poor surface quality, pressure of high cut and high vibration (Vats et al., 2022). Follow up factor. finally (ap) with a contribution of 9.42%.

Table 4. Analysis of variancefor SN ratios (a_{tng}).

Source	DF	Seq SS	Adj SS	Adj MS	F	P	Cont%
r	2	59.852	59.852	29.9259	30.02	0.001	42.6436
Vc	2	49.629	49.629	24.8145	24.89	0.001	35.3599
f	2	2.16	2.16	1.0799	1.08	0.397	1.5390
ap	2	13.228	13.228	6.614	6.63	0.03	9.4247
*r*Vc*	4	1.84	1.84	0.46	0.46	0.763	1.3110
*r*f*	4	3.221	3.221	0.8053	0.81	0.563	2.2949
*r*ap*	4	4.442	4.442	1.1106	1.11	0.431	3.1649
ResidualError	6	5.982	5.982	0.9969			4.2621
Total	26	140.354					100

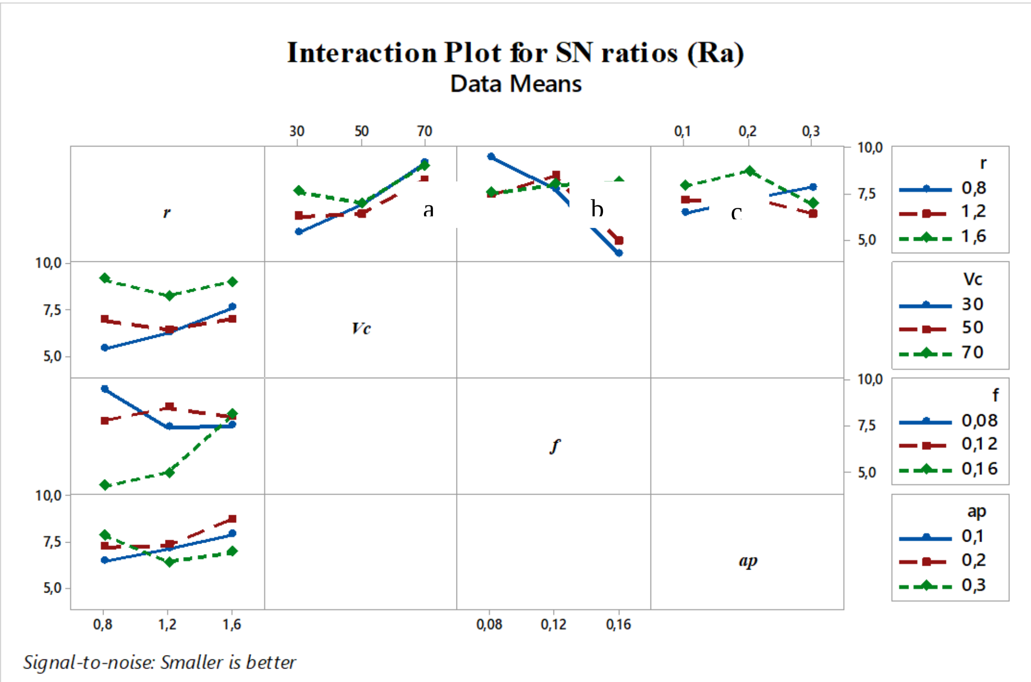

Figure 2. Interaction plot for SN (Ra)

Multi-Objective Optimization

The output parameters of table 2 are used for multi-objective optimization using The MARCOS-S/N ratio method. The normalization matrix for Ra, atng, and MRR is generated, considering Ra and atng as features to be minimized and MRR as a feature to be maximized. Table 5 the results of step 1 to 6 of the MARCOS-S/N ratio method.

Columns 2 to 4 contain the S/N ratio of step 1. Columns 5 to 7 form the element of weighting matrix. Here the weights are $\omega_1 = \omega_2 = \omega_3 = 0.33$ for all characteristics, but they can be modified by the maker according to the order of importance of each response. Columns 8 and 9 are the results of the calculation of the utility degree and the utility function.The utility function of the MARCOS using the Taguchi signal-to-noise ratio is ranked in descending order to determine the optimal solution. Finally, columns10 show the rank. The smallest values of the rank in table 6 correspond to optimum alternative. Table 6 highlights the optimization results provided by the strategies adopted.

Table 5. Results of the application of the MARCOS-S/N ratio.

Altern -atives N°:	S/N ration			Steps of MARCOS-S/N ration					
	Ra	a_{tng}	MRR	v_1	v_2	v_3	Si	f(k)	Rank
1	22.2508	7.9649	1.9179	0.2894	0.2225	0.0297	0.5417	0.0084	25
2	19.1809	7.2816	11.4603	0.2495	0.2035	0.1774	0.6303	0.0098	20
3	17.7663	5.7154	17.4809	0.2311	0.1597	0.2706	0.6614	0.0103	16
4	23.9962	11.8105	12.3754	0.3121	0.3300	0.1916	0.8337	0.0130	2
5	23.4571	7.6972	19.4191	0.3051	0.2151	0.3006	0.8208	0.0128	5
6	16.3941	10.2150	12.3754	0.2132	0.2854	0.1916	0.6902	0.0108	13
7	**25.3705**	**9.0741**	**18.8198**	**0.3300**	**0.2535**	**0.2913**	**0.8749**	**0.0136**	**1**
8	23.7353	10.8850	12.7992	0.3087	0.3041	0.1981	0.8110	0.0126	6
9	21.5439	7.8445	21.3186	0.2802	0.2192	0.3300	0.8294	0.0129	3
10	21.1153	5.1560	1.9179	0.2747	0.1441	0.0297	0.4484	0.0070	26
11	21.6241	3.3409	11.4603	0.2813	0.0933	0.1774	0.5520	0.0086	24
12	19.0152	2.8841	17.4809	0.2473	0.0806	0.2706	0.5985	0.0093	22
13	22.5819	5.1711	12.3754	0.2937	0.1445	0.1916	0.6298	0.0098	21
14	21.5839	5.7737	19.4191	0.2807	0.1613	0.3006	0.7427	0.0116	10
15	18.0687	8.1338	12.3754	0.2350	0.2273	0.1916	0.6539	0.0102	17
16	21.6848	6.6087	18.8198	0.2821	0.1847	0.2913	0.7580	0.0118	8
17	25.3087	8.2411	12.7992	0.3292	0.2303	0.1981	0.7576	0.0118	9
18	20.7615	6.5658	21.3186	0.2700	0.1835	0.3300	0.7835	0.0122	7
19	22.4037	3.7020	1.9179	0.2914	0.1034	0.0297	0.4245	0.0066	27
20	22.4923	2.9896	11.4603	0.2926	0.0835	0.1774	0.5535	0.0086	23
21	20.9833	3.3458	17.4809	0.2729	0.0935	0.2706	0.6370	0.0099	19
22	21.5638	7.6366	12.3754	0.2805	0.2134	0.1916	0.6854	0.0107	15
23	21.3464	5.2503	19.4191	0.2777	0.1467	0.3006	0.7250	0.0113	12
24	21.1153	6.7094	12.3754	0.2747	0.1875	0.1916	0.6537	0.0102	18
25	21.5839	6.0846	18.8198	0.2807	0.1700	0.2913	0.7421	0.0116	11
26	23.2603	6.7712	12.7992	0.3026	0.1892	0.1981	0.6899	0.0108	14
27	25.2473	6.0544	21.3186	0.3284	0.1692	0.3300	0.8276	0.0129	4

Table 6. Optimal results

Method	Altern-atives N°:	r	Vc	f	ap	Ra	a_{tng}	MRR
MARCOS-Taguchi	7	0.8	70	0.08	0.3	0.280	1.828	1.680

Conclusions

The present research proposes and implements the MARCOS-S/N ratio approach to address the challenge of multi-objective optimization during Inconel 718 dry turning. The research and analysis led to the following conclusions:

1. ANOVA analysis of Ra reveal that the most important factors that affect surface roughness is the feed rate (f), contributing 26.27%. The interaction between radius (r) and feed rate (f) ranks as the second most significant contributor after (f), accounting for 23.79%. The third factor that significantly contributes to surface roughness is cutting speed, with a contribution of 23.51%..
2. The radius (r) of cutting tools has the most impact on atng its contribution is 42.64%%, followed by the cutting speed with a contribution of 35.35%.Finally (ap) with a contribution of 9.42%.
3. Optimal cutting parameters for maximizing MRR while minimizing tangential vibration components and surface roughness are: r = 0.8 mm, Vc = 70 mm/min, f = 0.08 mm/rev, and ap = 0.3 mm.

Scientific Ethics Declaration

The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Acknowledgements

This article was presented at the International Conference on Technology, Engineering and Science (www.icontes.net) held in Antalya/Turkey on November 16-19, 2023.

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To cite this article:

Boucherit, S., Yallese, M. A., Kouahla, I., Belhadi, S., & Haddad, A. (2023). Multi-objective optimization of the inconel 718 turning parameters using MARCOS –based Taguchi S/N ratio. *The Eurasia Proceedings of Science, Technology, Engineering & Mathematics (EPSTEM), 26,* 366-374.