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Optimization of Machined Product Quality in the Milling Process of Inconel High-Tech Material

Yusuf Tansel İç, Zeki Anıl Adıgüzel, Ahmed Baran Azizoğlu, Alparslan Eren Keskin, Minesu Köksal, and Berat Subutay Özbek

Department of Industrial Engineering, Baskent University, Ankara, 06970, Turkey

ABSTRACT

Today, Inconel 601 materials are used in special areas and frequently processed in the aerospace industry. Due to the high specific expectation of sectors, the manufacturing quality of Inconel 601 material is crucial. There are some studies in the literature related to the optimization of milling process parameters such as cutting speed, feed rate, and depth of cut to reach high-quality characteristics depending on the quality expectations. We aimed to optimize the surface roughness, manufacturing lead time, and energy consumption that will occur during the milling process of the Inconel 601 work piece. Spindle speed, depth of cut, and feed rate of the cutting tool parameters and their levels are used as parameters (factors) in the design of the experimental study. Then the ANOVA tables are obtained. Furthermore, regression equations of the quality characteristics are determined. Finally, a multi-response optimization study is proposed to optimize parameter levels considering to achieve the maximum quality level of the machined part.

Keywords: Inconel 601, Multi-response optimization, Design of experiment

INTRODUCTION

Material processing methods are divided into two groups, conventional manufacturing methods, and unconventional manufacturing methods. Conventional methods are those that remove the material as a result of physical contact. As a result of this method, significant wear problems are inevitable.

One of the traditional manufacturing methods applied for the processing of the material in the relevant sectors is the milling process. During this process, using the relevant parameters, quality responses have been tried to be optimized.

Many studies were presented on this subject in the literature. During the literature search, it has been observed that in many studies on the subject, only one quality characteristic is concerned with optimization. The feed rate of the cutting tool, the spindle speed, and the depth of cut parameters tried to optimize the problems that arise during processing, such as surface quality (roughness), surface hardness, and energy consumption. This study is concerned with the multiple quality characteristics, unlike many studies in the literature.

Inconel 601 is a commonly used high-technology material (superalloy) and is one of the most widely used nickel alloy materials. Inconel 601 contains a high amount of nickel element. Generally, the nickel content is around 60 percent. In addition, this material has a chromium element of approximately 24 percent and is mainly composed of nickel and chromium elements (Special Metals, 2023).

Inconel 601 material is used in industrial heaters, heat treatment furnaces, furnace parts where the temperature is very high; exhaust tips, resistance heater parts, and many places where the temperature is very high. Another area where Inconel 601 material is used most frequently is jet engines and airline vehicle parts (Defence metal, 2020).

It is aimed to minimize the surface problems that will occur during the milling process, which is one of the traditional manufacturing methods of the material named Inconel 601, and the energy to be used while processing. During the milling of the part mentioned in the study, surface problems and excessive energy use may occur as a result of the inefficient use of parameters such as the spindle speed, feed rate of the cutting tool, and depth of the cut. This issue reduces processing efficiency and negatively affects the performance expected from the product.

Within the scope of this study, consider the spindle speed, cutting depth, and feed rate parameters by determining the most suitable machining parameters in the milling process of Inconel 601 material; we optimized the responses, such as surface quality (roughness), surface hardness, and energy consumption. In the study, efforts are made to respond directly to industry needs. We processed the part on the DOOSAN Mynx 7500/50 model CNC machine tool located in PI Machinery Co.

LITERATURE SURVEY

The summary table of the literature review is given in Table 1. Table 1 summarizes the parameters and responses used in the studies. Our study is different from the published works in the literature. We investigated four original responses that tried to be optimized. In this respect, the study will contribute to the literature.

EXPERIMENTAL DESIGN

There are many experimental design methods in the literature. The fractional factorial design methodology is used in this paper, which includes the effects of measurable factors with the least margin of error and the most effective. The main factor effects and their interaction effects are estimated using the fractional factorial design. The fractional factorial designs are quite frequently used to simultaneously investigate the main effects and interaction effects of two or more factors on the quality characteristics.

Three parameters (factors) are used in this paper:

A: Spindle speed (rpm)- 1115(low) and 1750 (high),

Table 1. Literature summary.

Autor(s)	Prameter	Response
Choudhury and El-Baradie (1998)	Spindle speed, feed rate, cutting depth	Tool life
Coelho et al. (2004)	Spindle speed, feed rate, cutting depth	Surface roughness
Öktem et al. (2005)	Spindle speed, feed rate, cutting depth	Surface roughness
Altın et al. (2006)	Spindle speed, feed rate, cutting depth	Cutting force, surface roughness
Pawade et al. (2007)	Spindle speed, feed rate, cutting depth	Cutting force, surface roughness
Nalbant et al. (2007)	Spindle speed, feed rate, cutting depth	Surface roughness
Taşlıyan et al. (2007)	Spindle speed, feed rate, cutting depth	Cutting force, power requirement
Thakur et al.(2009)	Spindle speed, feed rate, cutting depth	Tool life
Che Haron et al. (2011)	Spindle speed, feed rate, cutting depth	Surface roughness
Kasım et al. (2013)	Spindle speed, feed rate, cutting depth	Surface roughness
Lohithaksha et al (2013)	Cutting depth, feed rate, spindle speed	Surface roughness
Altın (2014)	Spindle speed, feed rate, cutting depth	Cutting force, surface roughness
Amini et al. (2014)	Spindle speed, feed rate, cutting depth	Cutting force, surface roughness
Vinod et al. (2016)	Spindle speed, feed rate	Tool life, surface roughness
Kaynak (2017)	Spindle speed, feed rate, cutting depth	Cutting force, power requirement
Zhou et al. (2017)	Spindle speed, feed rate, cutting depth	hardness
Tamang et al. (2018)	Spindle speed, feed rate, cutting depth	Cutting force, tool life
Aytaç and Aztekin (2019)	Spindle speed, feed rate, cutting depth	Surface roughness
Thrinadh et al. (2019)	Spindle speed, feed rate, cutting depth	Cutting force, flank wear of the tool
Waghmode, and Dabade (2019)	Spindle speed, feed rate, cutting depth	Surface roughness
Kasım et al. (2019)	Spindle speed, feed rate, cutting depth	Surface roughness
Pereira and Delijaicov (2019)	Spindle speed, feed rate, cutting depth	Cutting force, surface roughness
Thirumalai et al. (2020)	Spindle speed, feed rate, cutting depth, cutting tool costing type	Tool life, surface roughness
Ji et al. (2021)	Spindle speed, feed rate, cutting depth	Surface roughness

Table 1. Continued.

Danish et al. (2022)	Spindle speed, feed rate, cutting depth, cutting tool costing type	surface roughness, burr type
Proposed study	Spindle speed, feed rate, cutting depth	surface roughness, energy cunsumption, manufacturing lead time

Table 2. Experimental design and results.

Design of Exp.	Parameter levels			Responses			
No	Spindle Speed (rpm)	Feed rate (mm/min)	Cutting Depth (mm)	Lead time (Y1)	Surface roughness (Ra-μm) (Y2)	Surface Hardness (Brinel) (Y3)	Energy Consumption (kWh) (Y4)
1	1115	50	1	3.13.36	0.28	103.6	2.7342
2	1750	24	1	5.26.91	1.1	104.8	4.6183
3	1115	24	3	5.20.72	0.83	106.9	4.5333
4	1750	24	1	5.33.73	0.64	104.9	4.7175
5	1115	50	3	2.59.08	0.42	100.9	2.55
6	1750	50	1	3.13.36	0.31	104.7	2.7342
7	1115	50	3	2.39.12	0.27	104.4	2.2525
8	1750	24	3	5.53.03	0.44	102	5.0008

B: Feed rate (mm/rev)- 24 and 50,
C: Depth of cut (mm)- 1 and 3.

On the other hand, four different responses are optimized in the study (Table 2). In this study, the experimental design is created as 2ˆ(3-1) = 4 x (2 repetitions) = 8 experiments using the fractional factorial design.

The Inconel 601 workpiece is processed on the CNC machine tool according to the experimental plan created by MINITAB software. Then, the surface roughness and machined surface hardness values are measured, and the results are obtained for each experiment (Table 2). The energy consumption response is calculated using the experimental results. As a result of the ANOVA analysis with the help of the MINITAB, effective parameters-related regression equations are obtained:

$$Y1 = -5.59055E-04A-0.0969231B-0.142500\,C+8.74200(R-Sq(adj)=\%98.98) \tag{1}$$

$$Y2 = 0.000224409A-0.0166346B-0.0462500\,C+0.922764(R-Sq(adj)=\%45.84) \tag{2}$$

$$Y3 = -0.00086614A-0.0480769B-0.475000\,C+107.995(R-Sq(adj)=\%0) \tag{3}$$

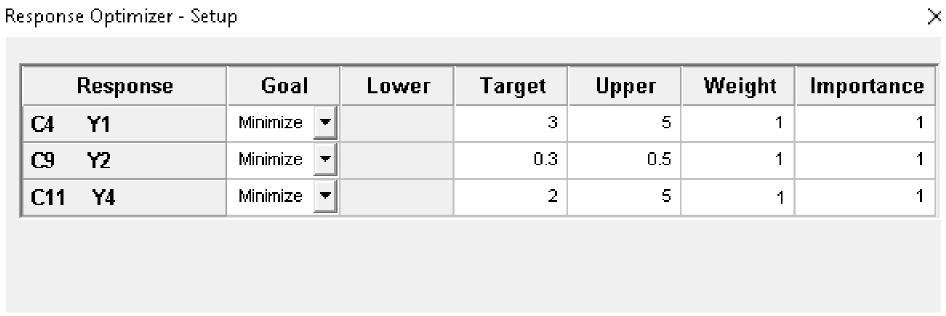
$$Y4 = -3.40236E-04A-0.0826827B-0.0584500\,C+7.30615(R-Sq(adj)=\%97.09) \tag{4}$$

OPTIMIZATION AND CONCLUSION

A multi-objective optimization study is carried out using the regression functions of Y1, Y2, and Y4 responses. The response weights are assigned in the Response Optimizer tool for the "All Objectives Are Equal Weighted Scenario" (Scenario 1), as in Figure 1.

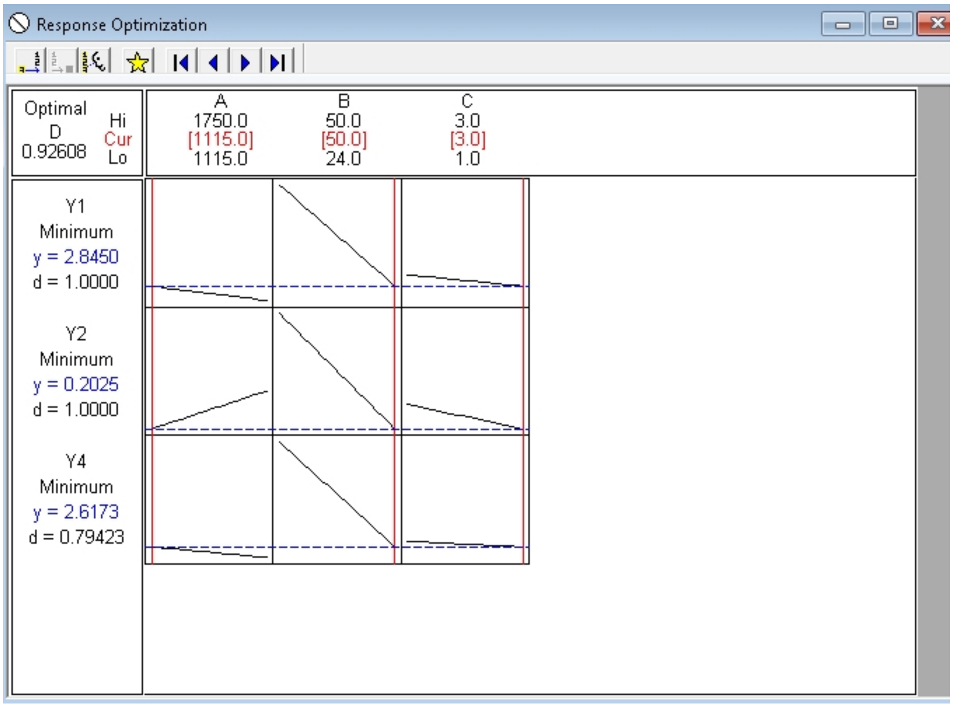
The optimization result is obtained (Figure 2). Accordingly, the best values are found as 1115rpm for A, 50mm/min for B, and 3mm for C. In addition, the results from the surface graphs are analysed. Therefore, the Y1 response is optimal at the upper levels of A, B, and C (Figure 3).

The results obtained in this study are analysed (Table 3) and reported in this section. The best parameter values according to the scenarios are given in Table 4. As we can see from Table 4, the feed rate (B) parameter is equal



Response	Goal	Lower	Target	Upper	Weight	Importance
C4 Y1	Minimize		3	5	1	1
C9 Y2	Minimize		0.3	0.5	1	1
C11 Y4	Minimize		2	5	1	1

Figure 1: Weight assignment for three responses in scenario 1.



Optimal
D
0.92608

Hi
Cur
Lo

A
1750.0
[1115.0]
1115.0

B
50.0
[50.0]
24.0

C
3.0
[3.0]
1.0

Y1
Minimum
y = 2.8450
d = 1.0000

Y2
Minimum
y = 0.2025
d = 1.0000

Y4
Minimum
y = 2.6173
d = 0.79423

Figure 2: Response optimizer result for scenario 1.

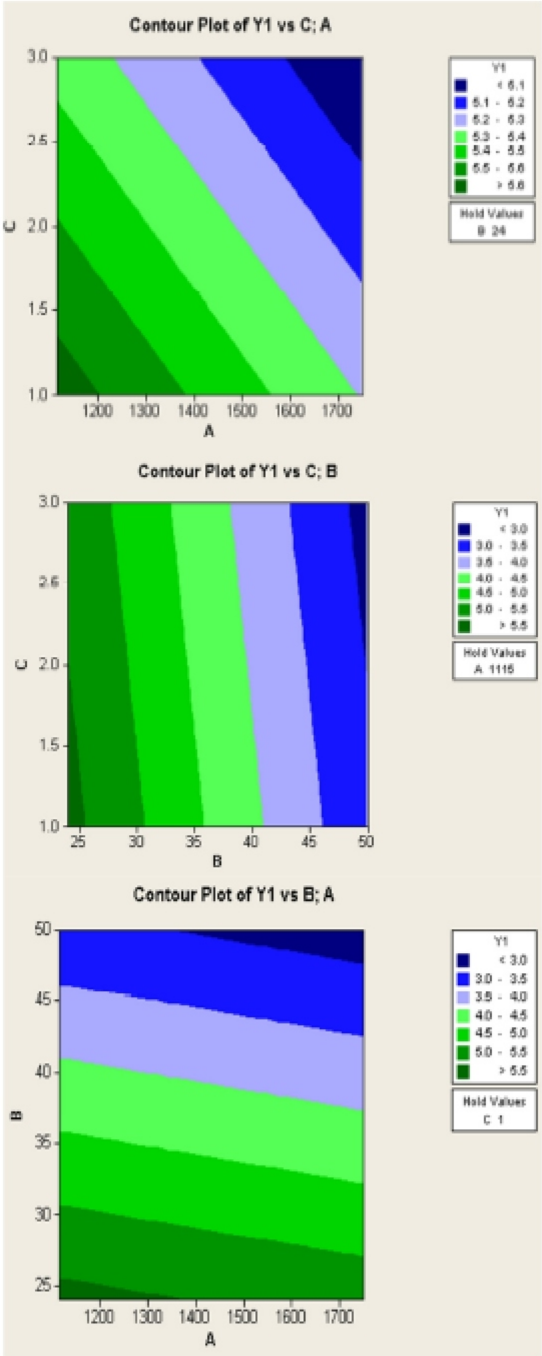


Figure 3: Response optimizer result: Contour plot example for scenario 1.

to 50 mm/min (high level) in all scenarios, and it does not influence the different weight preferences. So, in future studies, this value can be assigned as a low level, and a new high-level value could be determined. On the other hand, spindle speed and depth of cut parameters are sensitive to response weight changes, and they reflect different results in the response expectation

Table 3. Weight values for scenario analysis.

Responses	Weights for Scenario 1	Weights for Scenario 2	Weights for Scenario 3	Weights for Scenario 4
Y1	1	0.7	0.2	0.1
Y2	1	0.2	0.7	0.2
Y4	1	0.1	0.1	0.7

Table 4. Scenario analysis results.

Parameters	Scenario 1	Scenario 2	Scenario 3	Scenario 4
A (rpm)	1115	1549.4737	1150	1496.52
B (mm/min)	50	50	50	50
C (mm)	3	3	3	2.75

related to the weight values. If we expect different surface roughness, manufacturing lead time, and energy consumption expectations from the Inconel 601 material milling process, we can set some new target values and optimize parameter values according to the selected target values.

Based on the regression functions obtained, it is observed that the changes in the parameter values used did not affect the Y3 (surface hardness) response. So, the optimal parameter levels are determined for responses Y1, Y2, and Y4 using the response optimizer tool in the MINITAB program.

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