POLİTEKNİK DERGİSİ

JOURNAL of POLYTECHNIC

ISSN: 1302-0900 (PRINT), ISSN: 2147-9429 (ONLINE)
URL: http://dergipark.org.tr/politeknik

Investigation of the effect of u drills with different properties on thrust force, torque and spindle load

Farklı özelliklere sahip u matkapların itme kuvveti, tork ve iş mili yüküne etkisinin incelenmesi

***Yazar(lar) (Author(s))**: Aslan AKDULUM[1*], Yunus KAYIR[2]*

ORCID[1]: 0000-0003-2030-3167

ORCID[2]: 0000-0001-6793-7103

__To cite to this article__: Akdulum A., Kayır Y., “Investigation of the Effect of U Drills with Different Properties on Thrust Force, Torque and Spindle Load”, ***Journal of Polytechnic***, 26(1): 387-400, (2023).

__Bu makaleye şu şekilde atıfta bulunabilirsiniz__: Akdulum A., Kayır Y., “Investigation of the Effect of U Drills with Different Properties on Thrust Force, Torque and Spindle Load”, ***Politeknik Dergisi***, 26(1): 387-400, (2023).

__**Erişim linki (To link to this article):**__ http://dergipark.org.tr/politeknik/archive

__**DOI:**__ **10.2339/politeknik.1113301**

Investigation of the Effect of U Drills with Different Properties on Thrust Force, Torque and Spindle Load

Highlights

- *Effect of Udrill length/diameter ratio on thrust force, torque and spindle load.*
- *Effect of extra coolant hole in Udrills on thrust force, torque and spindle load.*
- *Comparison of Udrills with different features.*
- *Optimization of drilling parameters.*
- *Mathematical models of output parameters according to Udrills.*

Graphical Abstract

In this experimental study, U drills with different characteristics were compared considering thrust force, torque and spindle load in drilling of AA 2024-T351.

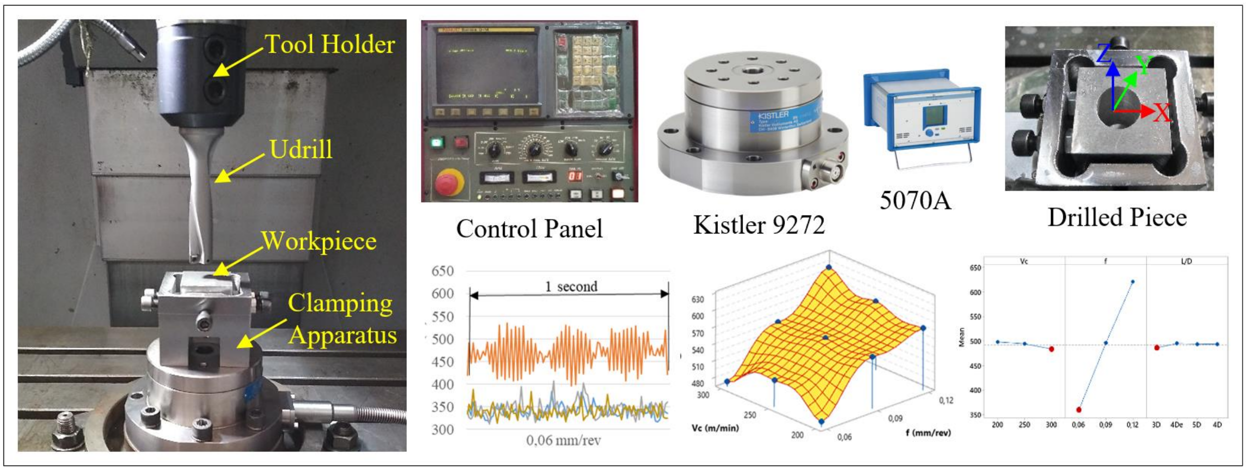


Figure. Experimental setup

Aim

It is aimed to compare the thrust force, torque and spindle load when drilling AA 2024-T351 using Udrills with different properties.

Design & Methodology

Three different cutting speeds, feed rates and length/diameter ratio have been chosen for performing the drilling process. A full factorial experimental design was used. The relationship between input and output parameters was explained through anova analysis, main effects plot, 3D graphics and mathematical models. Anova was used to determine the most important parameters of thrust, torque and spindle load.

Originality

The originality of the study is the comparison of U drills with different length/diameter ratio and extra coolant hole in terms of thrust force, torque and spindle load.

Findings

It was concluded that while the length/diameter ratio of Udrills had an effect of 56.97% on thrust force and 21.46% on spindle load, it was not effective for torque. The 4De Udrill with extra coolant hole gave 34.2% higher thrust force, 0.3% higher torque value and 26.53% lower spindle load compared to the 4D Udrill without extra coolant hole.

Conclusion

The length/diameter ratio of the U drill and the presence of the extra coolant hole have an impact on thrust force and spindle load.

Declaration of Ethical Standards

The authors of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

Investigation of the Effect of U Drills with Different Properties on Thrust Force, Torque and Spindle Load

Araştırma Makalesi / Research Article

Aslan AKDULUM[1*], Yunus KAYIR[2]
[1] Machine Technologies Area, Abidinpaşa Vocational and Technical High School, Ankara, Turkey
[2] Faculty of Technology, Department of Manufacturing Engineering, Gazi University, Ankara, Turkey

(Geliş/Received : 06.05.2022 ; Kabul/Accepted : 13.06.2022 ; Erken Görünüm/Early View : 24.08.2022)

ABSTRACT

Udrills are indexable insert drill commonly used in drilling operations. It is estimated that the market share among drilling tools is around 53%. They are produced in the same nominal diameter but in different lengths. There are usually two cooling holes, one behind the central insert and the other behind the peripheral insert. However, in some Udrills, an extra third cooling hole is drilled by the manufacturer. In this study, the effects of different length/diameter ratios, extra coolant hole and drilling parameters on thrust force, torque and spindle load were investigated in order to determine the effect of differences in U drills on hole drilling. AA 2024-T351 was drilled to a depth of 40mm using Udrills with a body diameter of 20mm. A total of 4 Udrills (3D, 4D, 4De, 5D) were used. Three feed rates (0.06, 0.09, 0.12mm/rev) and three cutting speeds (200, 250, 300m/min) were used in the experiments.

According to the Anova analysis, it was concluded that while the length/diameter ratio of Udrills had an effect of 56.97% on thrust force and 21.46% on spindle load, it was not effective for torque. The 4De Udrill with extra coolant hole gave 34.2% higher thrust force, 0.3% higher torque value and 26.53% lower spindle load compared to the 4D Udrill without extra coolant hole.

Anahtar Kelimeler: AA 2024-T351, Udrill, spindle load, thrust force, torque.

Farklı Özelliklere Sahip U Matkapların İtme Kuvveti, Tork ve İş Mili Yüküne Etkisinin İncelenmesi

ÖZ

U matkaplar delik delme operasyonlarında yaygın olarak kullanılan değiştirilebilir uçlu kesici takımlardır. Delme takımları içerisinde pazar payının %53 civarında olduğu tahmin edilmektedir. Aynı nominal çapta ancak farklı uzunluklarda üretilmektedirler. Genellikle biri merkezi ucun diğeri ise çevresel ucun arkasında olmak üzere iki tane soğutucu delik bulunmaktadır. Ancak bazı U matkaplarda üretici tarafından ekstra üçüncü bir soğutucu delik açılmaktadır. U matkaplarda bulunan bu farklılıkların delik delmeye etkisini tespit etmek amacıyla, bu çalışmada farklı uzunluk/çap oranlarının, ekstra açılmış soğutucu deliğin ve delme parametrelerinin itme kuvveti, tork ve iş mili yüküne etkisi araştırılmıştır. 2024-T351 alüminyum alaşımı, gövde çapı 20 mm olan U matkaplar kullanılarak 40 mm derinliğinde delinmiştir. Farklı uzunluk/çap oranlarının etkisini incelemek için 3 adet (3D, 4D ve 5D), ekstra soğutucu deliğin etkisini incelemek için ise 1 adet (4De) olmak üzere toplam 4 adet U matkap kullanılmıştır. Deneylerde, üç adet ilerleme miktarı (0.06, 0.09, 0.12 mm/rev) ve üç adet kesme hızı (200, 250, 300 m/min) kullanılmıştır.

Anova analizine göre U matkapların uzunluk/çap oranı itme kuvvetinde %56.97, iş mili yükünde %21.46 etkiye sahipken tork için etkili olmadığı sonucuna varılmıştır. Ekstra soğutucu deliği bulunan 4De U matkap, bulunmayan 4D U matkaba göre itme kuvvetinde %34.2, tork değerinde % 0.3 oranında yüksek, iş mili yükünde %26.53 düşük bir değer vermiştir.

Keywords: AA 2024-T351, U matkap, iş mili yükü, itme kuvveti, tork.

1. INTRODUCTION

The material AA2024-T351 is an aluminum alloy that has undergone an aging process. It is used in various industries, especially in aviation [1]. As is known, aluminum alloys have high adhesion/smearing rates. Therefore, thermal softening occurs with higher frictions between the tool and the workpiece [2]. The tendency of the chip to adhesion to the cutter increases with thermal softening. Due to the fact that the drilling process is in a closed area, there are difficulties in evacuating the chip to the outside [3]. Chips adhering to the helical chip evacuation channels of the drill increase the drilling forces [4]. This situation has various negative aspects from deterioration of surface quality to premature wear of cutters [5, 6]. Various experimental and mathematical modeling tools are used to detect these disadvantages and make inferences about the effect of cutting parameters [7-10]. One of the experimental tools with proven reliability is force-measuring dynamometers. However, dynamometers are expensive and suitable for use in experimental environments [11]. The use of dynamometers in a real production environment is somewhat difficult due to the constraints and sensitivity of clamping workpieces. As an alternative to the dynamometer, in various studies [3, 12-14], sound,

*Sorumlu Yazar (Corresponding Author)
e-posta : a.akdulum@gmail.com

vibration, consumed energy, wear, etc. studies were carried out. However, all of these mentioned systems mean an extra device. In addition, the analysis of the data measured with these devices in the real production environment is a time-consuming process. Data is analyzed after processing by researchers or engineers who are not in the production environment, slowing productivity [15]. However, every minute lost in production has a financial burden. Therefore, studies are carried out to understand or model the real-time cutting process [15-18]. The aim of the studies carried out is to understand the cutting process with the most cost-effective use without the use of additional devices or with the least device [19]. One of these devices is the spindle load information that shows the status of the cutting process in real time on the control panels integrated into the CNC machine tools [20]. Thus, no additional device is needed [21]. This issue has been investigated in various studies [4, 15, 16, 22-24], but the number of studies is very limited. Among these studies, no study has been found on the effect of Udrills, which have been increasingly used in recent years, on the spindle load. Udrill diameter is a cutter that starts from 12 and performs drilling up to 63 diameters. It is estimated that the market share of Udrill among drilling tools is around 53% [25]. It is a cutter that is used by attaching two inserts, one in the center and the other in the periphery, that can enter the solid material without drilling a pilot hole [26]. In general, it creates lower thrust force and moment values by prolonging tool life and reducing power consumption due to the asymmetric insert placement [27, 28] compared to a normal helical drill [29]. Due to these features, Udrill is used extensively by practitioners who want to remove a lot of chips in a short time in the production environment [30]. The use of dynamometer in drilling with Udrills has been studied before in the literature [31-34]. However, no study has been encountered on the effect of length/diameter ratio on drilling and spindle load in drilling operations using Udrill.

In order to fill this gap in the literature, AA2024-T351 aluminum alloy was drilled with a drill in this study. The effects of input parameters on thrust force (Fz), torque (Mz) and spindle load (SL) were investigated. The effect of the drilling parameters determined on the hole drilling was examined with the data obtained from the dynamometer and the control panel of the machine tool. For this purpose, 4 Udrill bodies (3D, 4D, 4De, 5D) were selected. As the ratio of the length to diameter of these Udrill bodies, 3 different lengths, 3D, 4D and 5D, were preferred. In order to control the effect of the extra coolant hole, 2 different Udrill bodies 4D and 4De, which belong to the same brand and can be fitted with the same feature, were selected. Of these, 4De has an extra coolant hole in the center, while 4D does not have an extra coolant hole in the center. In order to control the effect of drilling parameters, 3 different cutting speeds (Vc) and 3 different feed rates (f) were determined. Normality test, Anova test, main effect graph, regression equations and three-dimensional graphs were used to examine the experimental results.

2. MATERIAL AND METHOD

2.1. Experimental Material

AA 2024-T351 material for experimental studies was obtained from the domestic market. The material has been delivered as ready-made in the dimensions of 40x40x40mm with a certificate. After receiving the material, the hardness measurements and spectrum analysis were measured with at least three replications and the averages were taken. The average hardness of the AA 2024-T351 material was measured as 138 Brinell. The chemical composition of the material obtained from the spectrum analysis is given in table 1.

2.2. Machine Tool Used in Experiments

Johnford VMC-850 brand CNC vertical machining center was used for drilling using a Udrill. The spindle motor of the machine is 7.5 KW, the maximum spindle speed is 8000 rpm, the measurement accuracy is 0.001 and the operating system is Fanuc. For the cooling process, 5% semi-synthetic cutting and cooling fluid was mixed with water. If the hole length is less than three times the hole diameter, that hole is expressed as a short hole according to the literature and cutting tool catalogs. It is recommended to use an internal coolant at hole depths greater than three times. Since this ratio is two in this study, as in the experimental setup shown in figure 1, the coolant was adjusted to be sprayed from the outside and from one direction. Drilling was carried out

Table 1. Chemical composition of aluminum alloy AA 2024-T351, % by weight.

Fe	Si	Mn	Cr	Ti	Cu	Mg	Zn	Al
0.329	0.121	0.498	0.023	0.028	4.928	1.414	0.317	92.342

The effects of using different types of coolant on the output parameters in the hole drilling process are investigated [29]. However, when the literature is reviewed, it has not been examined before what kind of change the Udrill bodies with and without a cooling hole will cause in the output parameters. Considering the dynamism of the cutting process, not knowing the effect of the coolant hole on the output parameters is a big gap in the literature. Because the coolant holes mean an extra hole on the body. It is thought that this hole may cause instability in the mechanics and dynamics of the drilling process, compression / clogging of chips or an imbalance in the cutting process, causing differences in forces and other output parameters.

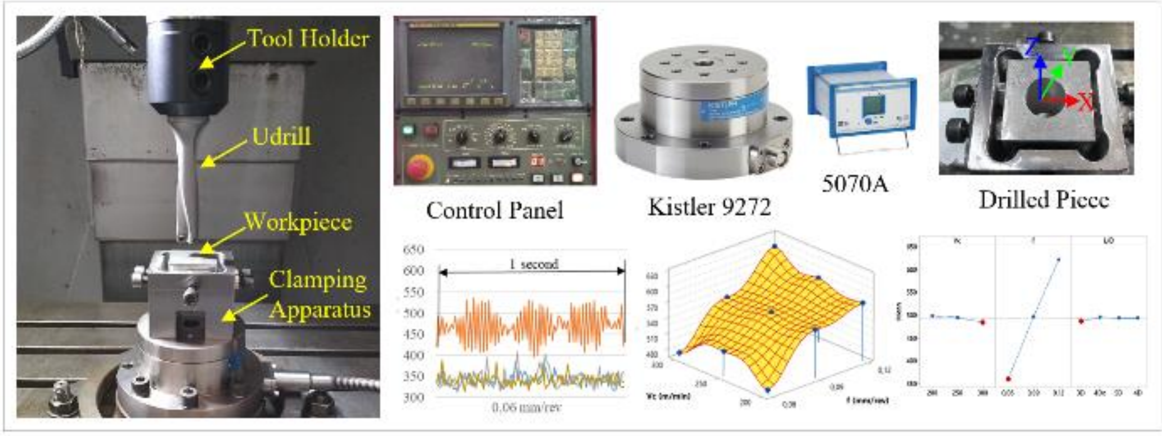


Figure 1. Experimental setup

according to the through-hole and normal hole drilling principle.

2.3. Cutting Tool and Cutting Parameters

Udrills with different length/diameter ratios were used in the experiments. A total of 4 Udrills were used, with three different length/diameter ratios (3D, 4D, 5D) (figure 2). While one of the 4D bodies has an extra coolant hole in the center (4De), the other does not have an extra coolant hole (4D). In table 2, the size information of the Udrills used in the experiments are given.

Table 2. Udrill dimensions used.

Udrill	Diameter (Dc: mm)	Length (L: mm)
3D	20	60
4D, 4De		80
5D		100

In figure 3, the size information of the used inserts are available. Usually no two inserts used are the same, both coating and edge geometry may vary as they operate at different Vc and under different load conditions [35].

In this study, the central and peripheral inserts of the Udrill have different geometric properties, but both are uncoated carbide inserts suitable for aluminum machining. XOET-ND 07T205 was used as the central insert, SPET-ND 07T208 and H01 quality inserts were used for the peripheral insert. Body of the same diameter and inserts with the same characteristics were used. BT 40 VT 25 90 Veldon type tool holder is used to connect the Udrill to the spindle.

Figure 1. Udrills used in experiments

A total of 36 experiments were conducted using the full factorial experimental design method. While determining the drilling parameters, the cutting tool catalog recommendations and literature information were taken into account. Drilling parameters are given in table 3.

Kistler 9272 dynamometer was used to measure thrust force and torque values. The measured force and torque values were obtained with the DynoWare program, which is the dynamometer's own software. The maximum value was recorded by following the "load" indicator on the control panel of the machine tool during drilling. The recorded value was determined as the

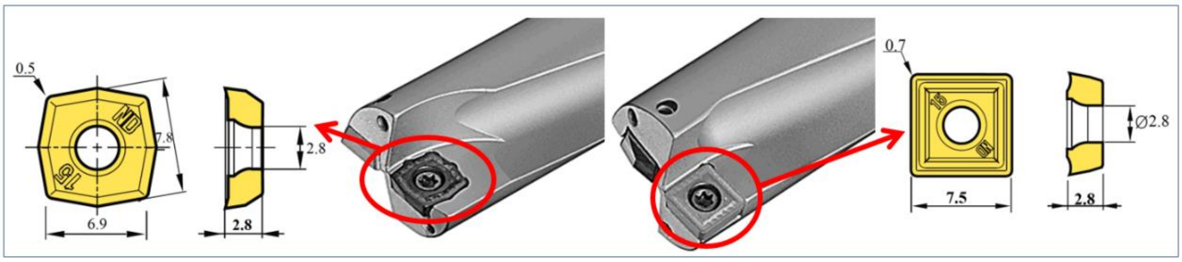


Figure 3. (Left) Central insert, (Right) Peripheral insert

spindle load value. Minitab 19 software was used for normality test, Anova test, mean effect graphs, regression equations and 3D graphs.

Table 3. Drilling parameters used.

Udrill Length/Diameter Ratio, L/D	Feed rate, f (mm/rev)	Cutting Speed, Vc (m/min)
3D	0.06	200
4D 4De	0.09	250
5D	0.12	300

3. EXPERIMENTAL RESULTS AND DISCUSSION

Experiments were carried out to examine the thrust force (Fz), torque (Mz) and spindle load (SL) values obtained according to the entered drilling parameters. The test results are listed in table 4.

3.1. Effects of Drilling Parameters on Average Thrust Force

Table 4. Experimental results.

Vc (m/min)	f (mm/rev)	*3D* Fz (N)	*3D* Mz (Ncm)	*3D* SL (%)	*4De* Fz (N)	*4De* Mz (Ncm)	*4De* SL (%)	*4D* Fz (N)	*4D* Mz (Ncm)	*4D* SL (%)	*5D* Fz (N)	*5D* Mz (Ncm)	*5D* SL (%)
200	0.06	342	351	45	472	374	40	338	363	55	340	363	60
200	0.09	406	497	90	556	502	45	427	503	80	413	507	90
200	0.12	466	628	70	574	628	60	504	624	85	489	640	90
250	0.06	343	346	50	511	377	50	337	359	65	330	365	55
250	0.09	409	498	80	553	497	60	396	492	75	399	495	80
250	0.12	472	623	85	586	612	65	466	619	95	499	648	80
300	0.06	350	340	50	473	369	70	324	355	70	314	346	75
300	0.09	374	503	80	545	487	65	385	490	90	380	479	80
300	0.12	409	591	100	611	609	85	460	637	120	397	601	90

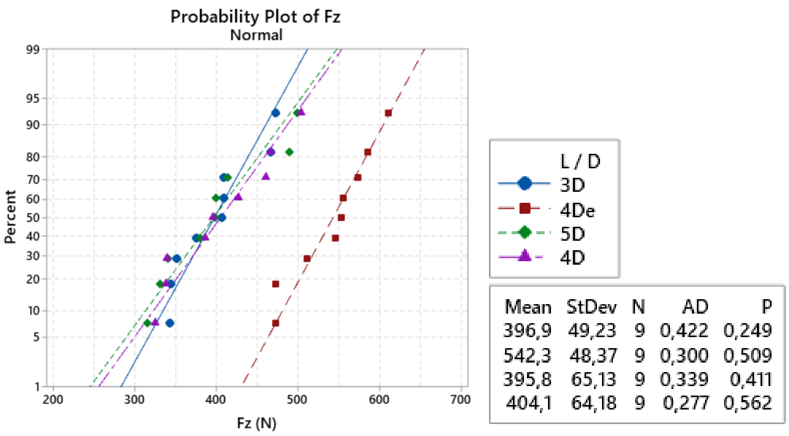


Figure 4. Normality test for Fz

According to the results of the experiments performed in the present study, the highest thrust force (Fz) value of 611N was obtained using the 4De body at the largest Vc and the largest f values. The smallest value, 314N, was obtained at the largest Vc and smallest f using the 5D body. The percentage difference between them was 94.59%.

Considering the Fz values in table 4, a normality test was performed for all Udrills used in the experiments. The normality test was grouped according to the length/diameter ratio (L/D) parameter. The graph and results obtained are shown in figure 4. Since the significance of the results for all Udrills was p>0.05, it was assumed that the data were obtained in accordance with the normal distribution.

When figure 4 is examined, the Fz values are close to each other. However, the Fz average of 542.3 N for 4De was quite high compared to other bodies, and it was clearly differentiated in the graph compared to other bodies. Anova test was applied to the results, as the normality test was suitable for normal distribution. Among the Udrills checked for the effect of the coolant hole, a higher value of 34.2% occurred in 4De compared to 4D. This result is thought to be caused by the extra cooling hole. The extra opened coolant hole disrupted the flow of the chip cut by the central insert, resulting in higher Fz values. In addition, the chips trying to enter the hole caused sudden increases and decreases as seen in the force graphs in figure 9.

Anova test for Fz was performed at 95% confidence interval. The R^2 value for the test was calculated as 98.09%. Calculation results are given in table 5. According to the p<0.05 significance values according to table 5, L/D (56.97%), f (36.29%) and Vc (1.94%) parameters, respectively, were effective on the Fz output response. The most effective cutting parameter for Fz was the L/D ratio. It was concluded that the combinations of other cutting parameters were not effective because p>0.05.

Table 5. Anova test results for Fz.

Source	DF	Seq SS	Contribution	Adj MS	F-Value	P-Value
Vc	2	4733	**1.94%**	2366.4	6.11	0.015
f	2	88542	**36.29%**	44270.9	114.26	0.000
L/D	3	138990	**56.97%**	46330.1	119.57	0.000
Vc*f	4	1259	0.52%	314.7	0.81	0.541
Vc* L/D	6	3702	1.52%	617.0	1.59	0.232
f* L/D	6	2116	0.87%	352.7	0.91	0.519
Error	12	4650	1.91%	387.5		
Total	35	243992	100.00%			

The main effects plot for Fz is given in figure 5. According to figure 5, the most effective cutting parameters were 300 m/min for Vc, 0.06 mm/rev for f value, and L/D value gave almost the same values for bodies other than 4De. It is clear that the 4De Udrill differs significantly from other bodies. The negative effect of the coolant hole on Fz is clearly shown here.

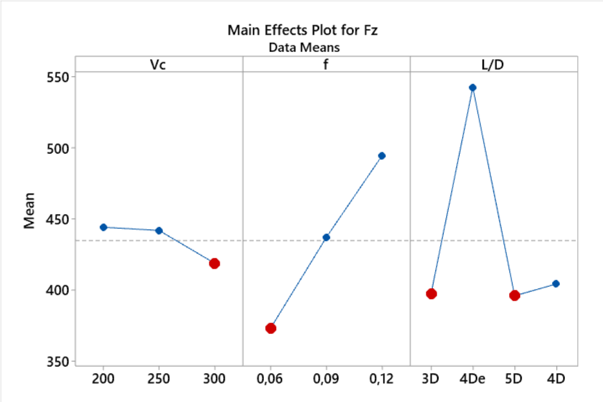


Figure 5. Main effects plot for Fz

In figure 6, the effect of drilling parameters on Fz for all bodies is shown as a three dimensional graphic. Considering the graphs obtained, the Fz values increased with the increase in the f for all bodies. This result was also obtained in various studies in the literature [12, 35]. In the literature, it has been stated that the increase in the f increases the chip thickness, so more thrust force is required to overcome the greater plastic strain, therefore the Fz value is high [29].

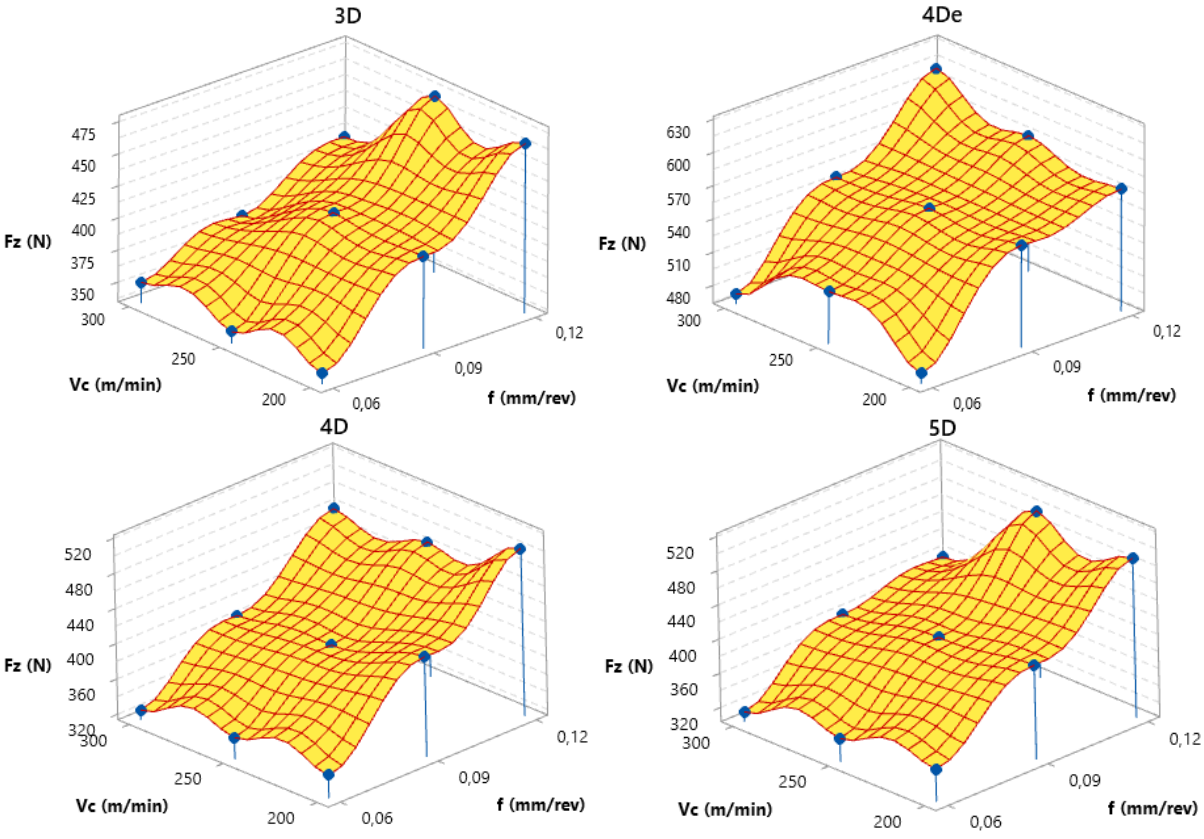


Figure 6. Variation of Fz according to drilling parameters

The variation of Fz according to the Vc was investigated. Fz values also increased with increasing Vc for low f when using a 3D Udrill. While Fz increased with increasing Vc for medium and high f, Fz values decreased considerably at high Vc.

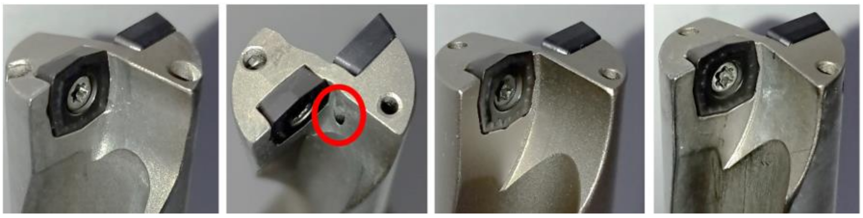
When examined according to the 4De Udrill Vc, Fz increased with the increase in Vc in the low f, while the Fz value decreased again at the highest Vc. Considering the medium f, the Fz values decreased with the increase in Vc. Considering the high f, the Fz values tended to increase with the increase in Vc. Considering the 4D Udrill Vc, the Fz values decreased with the increase of the Vc for all f values. Seeing the 5D Udrill Vc, the Fz values decreased with the increase in Vc for low and medium f. Considering the high f, the Fz value increased at medium Vc, while the Fz value decreased significantly at high Vc.

When all Udrills are examined in terms of Fz, the other Udrills except 4De produced close Fz values, while the 4De Udrill produced higher values. 9 holes were drilled with each U drill. When averaged for 9 holes, the Fz values were calculated as 396.9N for 3D, 404.1N for 4D, 395.8N for 5D, and finally 542.3N for 4De, respectively. In particular, the reason why such a difference occurs despite the 4D body and 4De being the same diameter and the same L/D ratio has been investigated in detail. While other Udrills have a coolant hole behind the central insert and the peripheral insert, an extra coolant hole is placed in the chip evacuation channel where the central insert of the 4De Udrill is located. It is thought that the extra opened coolant hole shown in figure 7 may cause an increase in Fz forces.

increase the forces in that area, the forces fall again with the recovery of the chips and this process continues with the continuous repetition. Thus, the cutting forces increase gradually and decrease abruptly with the breakage of the built-up edge (BUE) [36]. This fluctuation in Fz forces can be clearly seen, especially when the graphs of 4D and other Udrill bodies in figure 9 are examined. The graphs in figure 9 show the variation of the Fz values for the 1-second portion of each Udrill body during the drilling process.

When figure 9 is examined, the amplitude of the graph formed by the Fz values increase in parallel with the increase in the f. It is thought that this fluctuation occurs as a result of the cooling hole on the movement surface of the chips disrupting the chip flow, the accumulation of chips by jamming and the removal of the chips. On the other hand, it can be said that the cooling hole creates a gap along the body and mechanically weakens the rigidity of the body. Thus, it can be said that there is a fluctuation in the Fz force with the effect of torsional-axial and/or chatter vibrations. Because, with the increase in the f, the removed chip cross-section and therefore the amount of chip also increases [37]. With the increase in Vc and f, the drilling times decreased, while the chip removal rates increased [9, 38, 39].

Mathematical models related to Udrill are given in equations 1-4 for Fz as categorical variables, respectively. Second-order regression analysis for Fz was performed using experimental data. While determining these models, Vc and f were chosen as continuous factors



3D 4De 4D 5D

Figure 7. Coolant holes of Udrills

L/D				
3D	Fz	=	$-87 + 2.28\,Vc + 3662\,f - 0.00417\,Vc^2 - 3542\,f^2 - 5.18\,Vc*f$	(1)
4De	Fz	=	$-36 + 2.64\,Vc + 3685\,f - 0.00417\,Vc^2 - 3542\,f^2 - 5.18\,Vc*f$	(2)
5D	Fz	=	$-75 + 2.05\,Vc + 4159\,f - 0.00417\,Vc^2 - 3542\,f^2 - 5.18\,Vc*f$	(3)
4D	Fz	=	$-125 + 2.22\,Vc + 4320\,f - 0.00417\,Vc^2 - 3542\,f^2 - 5.18\,Vc*f$	(4)

In figure 8, there is an example of the chip sticking to the cutting edge and the coolant hole in the chip evacuation channel even after the drilling test. This sample image was obtained for the 4De Udrill after the drilling test at Vc 300 m/min, f 0.09 mm/rev.

The effect of the coolant holes on the Fz is also seen in the real-time force measurements obtained from the dynamometer (figure 9). It is also understood from the graphs obtained by the dynamometer that the chips removed by the central insert try to enter the coolant hole, therefore causing the chips to clog/accumulate and

and L/D as categorical factors. The R^2 obtained as a result of the calculations gives information about the accuracy of the obtained mathematical model.

Figure 8. The chips clogged/smeared into the 4De Udrill after drilling

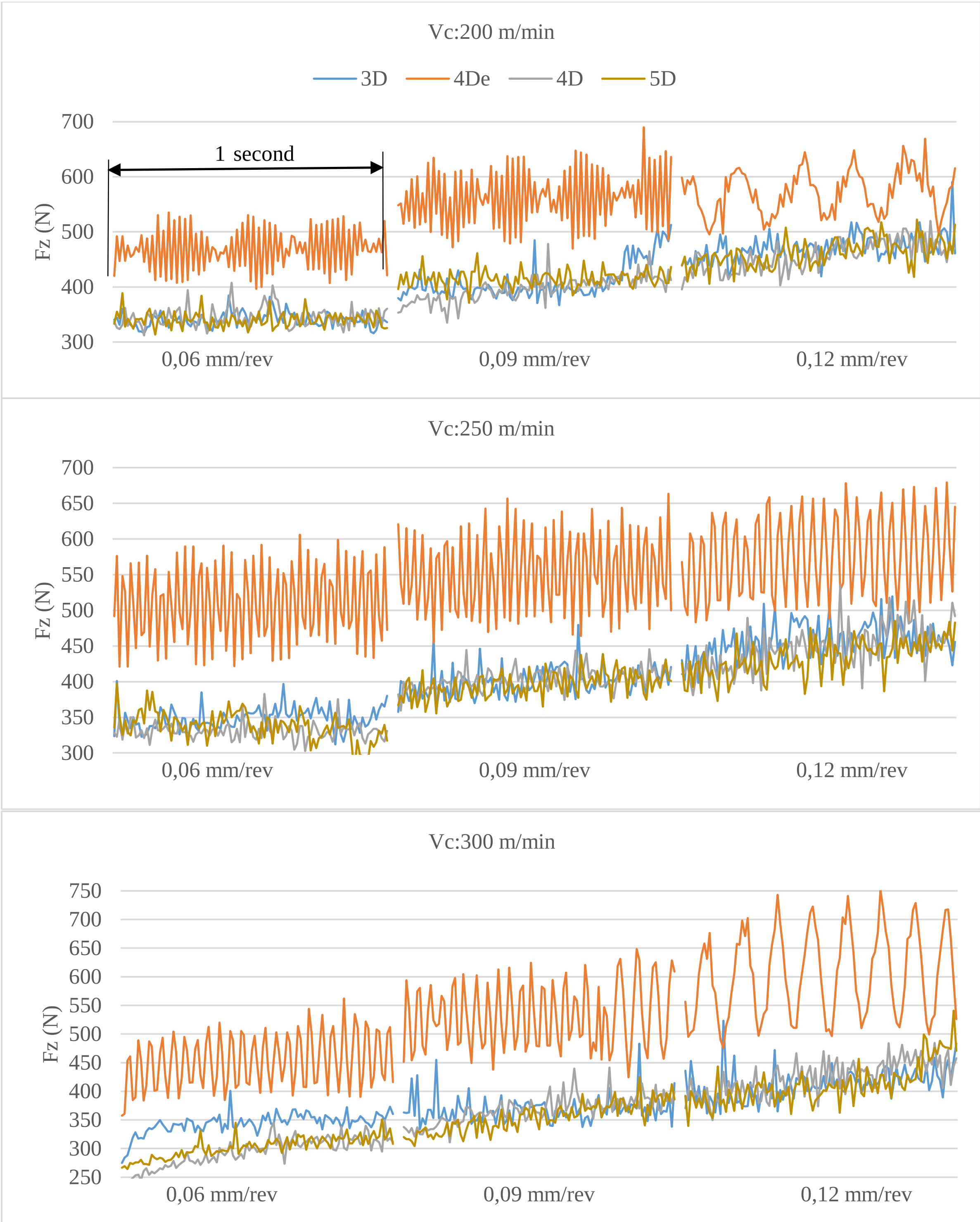


Figure 9. Fz dynamometer data (sampling time: 1 second)

In the present study, the R^2 value for Fz was calculated as 97.5%. This value shows the accuracy of the mathematical model and a powerful relationship between control factors and output parameters.

When experimental and prediction comparisons for Fz are made according to L/D ratios of mathematical models for medium Vc and medium f, 3D (experimental 409N, prediction result 406N), 4De (experimental 553N, prediction result 551N), 5D (experimental 399N, prediction result 405N), 4D (experimental 396N, estimation result 413N). It has been determined that the experimental results and the results predicted by the mathematical model are quite compatible.

3.2 Effects of Cutting Parameters on Average Moment

According to the results of the experiments performed in the present study, the highest mean moment (Mz) value of 648Ncm was obtained at medium Vc and the largest f values by using a 5D Udrill. The smallest value, 340 Ncm, was obtained using the 3D Udrill at the largest Vc and the smallest f. The percentage difference between the highest and lowest Mz value resulted as 90.59%.

Taking into account the Mz values in table 4, a normality test was performed for all Udrills used in the experiments. The normality test performed was grouped according to the L/D ratio parameter. Obtained graphics and results are in figure 10. Since the significance of the results found for all bodies was $p>0.05$, it was assumed that the data were obtained in accordance with normal distribution.

When figure 10 is examined, the Mz values of almost all Udrills gave values close to each other. While the highest

The most effective cutting parameter for Mz has been the f input parameter. It was concluded that the combinations of other cutting parameters were not effective because $p>0.05$.

The effect of f value, which is one of the input parameters for the Anova test, on the Mz output response was quite high. Although it has been stated that Vc input parameter is effective on Mz in various studies in the literature [29], it can be said that it is not effective for the current study. It is clear that the L/D ratio, which is quite effective on Fz, is not effective on Mz. So different Udrill sizes have no effect on Mz for drilling aluminum material.

When the main effects plot for Mz in figure 11 is examined, the most optimum results were obtained by using 300 m/min for Vc, 0.06 mm/rev for f and 3D Udrill

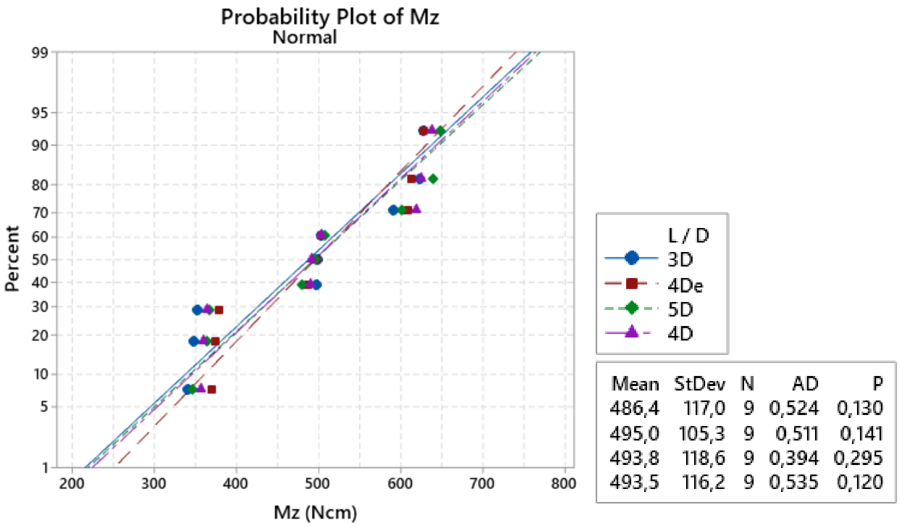


Figure 10. Normality test for Mz

Mz average was obtained with the 4De Udrill, the lowest Mz average was obtained for the 3D Udrill. However, the difference (1.77%) was not so large. Among the 4D Udrills checked for the effect of the coolant hole, a relatively negligible 0.3% higher value occurred in 4De compared to 4D.

Anova test for Mz was performed at 95% confidence interval. The R^2 value for the test was calculated as 99.75%. Calculation results are given in table 6. According to the $p<0.05$ significance values in table 6, f (98.77%) and Vc (0.32%) parameters were found to be effective on the Mz output response, respectively.

Table 6. Anova results for Mz.

Source	DF	Seq SS	Contribution	Adj MS	F-Value	P-Value
Vc	2	1322	**0.32%**	661	7.58	0.007
f	2	413944	**98.77%**	206972	2373.24	0.000
L/D	3	408	0.10%	136	1.56	0.250
Vc*f	4	178	0.04%	45	0.51	0.729
Vc* L/D	6	859	0.20%	143	1.64	0.219
f* L/D	6	1336	0.32%	223	2.55	0.079
Error	12	1047	0.25%	87		
Total	35	419094	100.00%			

for L/D ratio. The effect of the f input parameter on the Mz output response is clearly seen in this graph.

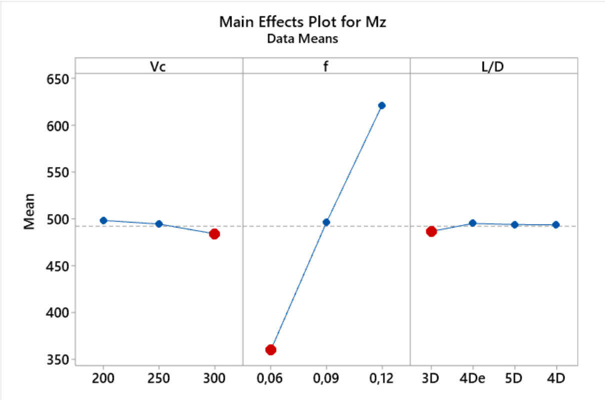


Figure 11. Main effects plot for Mz

In figure 12, the effect of drilling parameters on Mz for all bodies is shown as a three-dimensional graphic. In view of the graphs obtained, Mz values increased with the increase in the f for all bodies. This result was also obtained in various studies in the literature [40]. The graphics for all Udrill bodies resulted in almost the same characteristics.

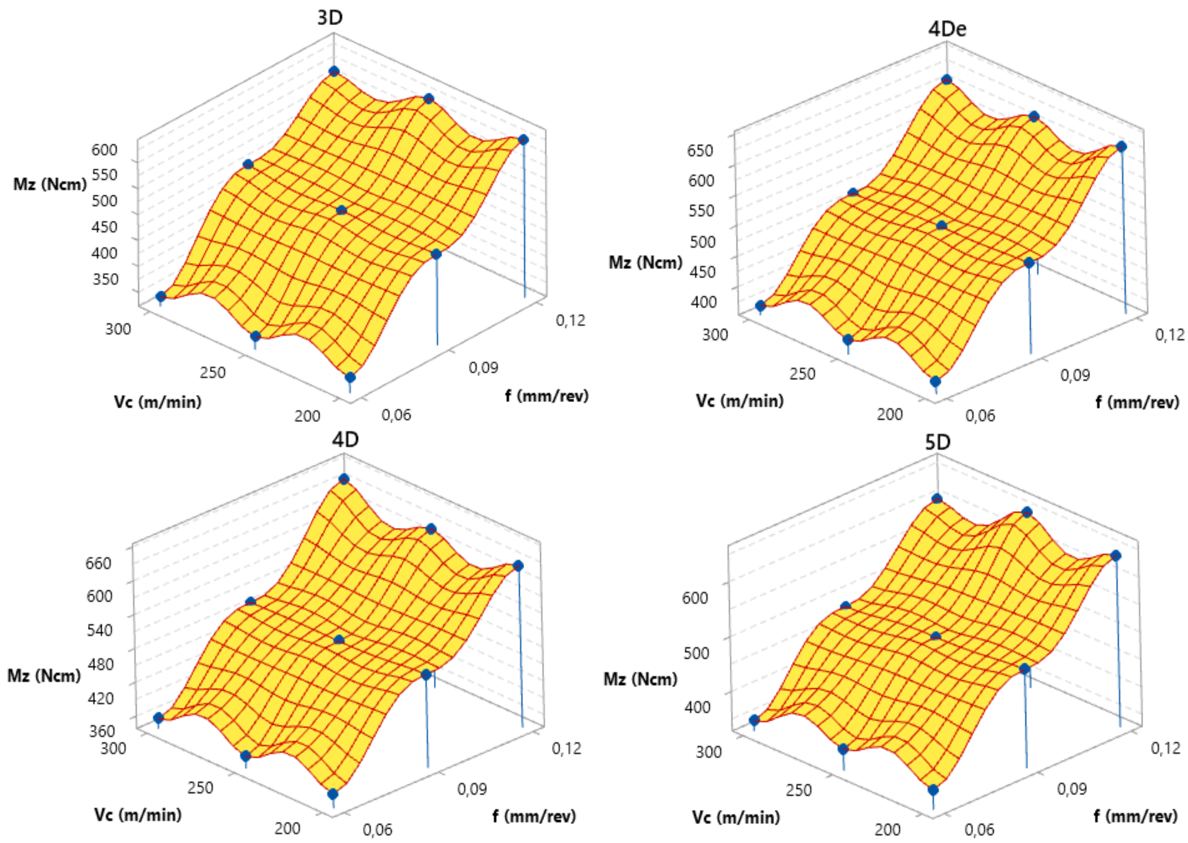


Figure 12. Variation of Mz with respect to drilling parameters

If the graphics are examined in terms of Vc, the Mz value decreased, albeit small, with the increase in Vc at low f for the 3D Udrill. With the increase in Vc at medium f, the Mz value increased, albeit small. The Mz value decreased with the increase of Vc at high f.

When 4De Udrill was used, the Mz value first increased and then decreased with the increase in Vc at low f. Mz value decreased with increasing Vc at medium f. Mz value decreased with increasing Vc at high f.

When 4D Udrill was used, Mz value decreased with increasing Vc at low f. Mz value decreased with increasing Vc at medium f. With the increase in Vc at high f, the Mz value first decreased and then increased.

When a 5D Udrill was used, the Mz value first increased and then decreased with the increase in Vc at low f. Mz value decreased with increasing Vc at medium f. With the increase in Vc at high f, the Mz value first increased and then decreased.

9 holes were drilled with each U drill. When averaged for 9 holes, the Mz values were calculated as 486.4Ncm for 3D, 493.5Ncm for 4D, 493.8Ncm for 5D, and finally 495Ncm for 4De, respectively. While the effect of the extra cooling hole on Fz is high, it has little effect on Mz. It is considered that this situation is caused by the increase in the Vc towards the periphery while the Vc is zero in the center of the drill. Because the central insert of the Udrill has a greater effect on the Fz values, while the peripheral insert has a greater effect on the Mz values.

L/D

3D $\quad Mz = -45.5 + 0.667\, Vc + 6020\, f - 0.00130\, Vc^2 - 6228\, f^2 - 1.72\, Vc*f$ (5)

4De $\quad Mz = -0.9 + 0.675\, Vc + 5597\, f - 0.00130\, Vc^2 - 6228\, f^2 - 1.72\, Vc*f$ (6)

5D $\quad Mz = -8.7 + 0.528\, Vc + 6079\, f - 0.00130\, Vc^2 - 6228\, f^2 - 1.72\, Vc*f$ (7)

4D $\quad Mz = -67.1 + 0.782\, Vc + 6019\, f - 0.00130\, Vc^2 - 6228\, f^2 - 1.72\, Vc*f$ (8)

While the extra coolant hole in the center of the 4De Udrill disrupts the flow of chips, it is considered that it does not reflect negatively on the Mz values since there is no such effect on the peripheral insert.

Mathematical models related to Udrill are given in equations 5-8 for Mz as categorical variables, respectively. Regression analysis was performed for Mz. The R^2 value was calculated as 99.52%.

When experimental and predictive comparisons of mathematical models for Mz are made according to L/D ratios for medium Vc and medium f, 3D (experimental 498Ncm, predicted result 492Ncm), 4De (experimental

497Ncm, predicted result 501Ncm), 5D (experimental 495Ncm, predicted result 500Ncm), 4D (experimental 492Ncm, estimated result 499Ncm). It has been determined that the experimental results and the results predicted by the mathematical model are quite compatible.

3.3 Effects of Cutting Parameters on Spindle Load

The spindle load information (SL) in CNC machines shows that the machine has real-time difficulties in cutting during the process. Therefore, the spindle load information gives the opportunity to determine the appropriate cutting parameters at the beginning of the work or to intervene in the cutting parameters used during the operation of the machine. According to the results of the experiments performed in the present study, the highest SL value of 120% was obtained using the 4D body at the largest Vc and the largest f values. The smallest value, 40%, was obtained at the smallest Vc and smallest f by using the 4De body.

Taking into account the SL values in table 4, a normality test was performed for all bodies used in the experiments. The normality test performed was grouped according to the L/D ratio parameter. Obtained graphics and results are given in figure 13. Since the significance of the results for all bodies was p>0.05, it was assumed that the data were obtained in accordance with normal distribution.

When figure 13 is examined, the highest SL average was obtained with the 4D Udrill, while the lowest SL value was obtained with the 4De Udrill. Among the 4D Udrills checked for the effect of the coolant hole, a lower value of 26.53% occurred in 4De compared to 4D.

Anova test for SL was performed at 95% confidence interval. The R^2 value for the test was calculated as 95.64%. Calculation results are given in table 7. According to the p<0.05 significance values in table 7, the f (44.72%), L/D (21.46%), Vc (11.48%) and f*L/D combination on the SL output response, respectively (8.86%) was effective. The most effective drilling parameter for SL was the f value. It was concluded that the combinations of other cutting parameters were not effective because p>0.05.

Table 7. Anova results for SL

Source	DF	Seq SS	Contribution	Adj MS	F-Value	P-Value
Vc	2	1287.5	**11.48%**	643.75	15.80	0.000
f	2	5016.7	**44.72%**	2508.33	61.57	0.000
L/D	3	2407.6	**21.46%**	802.55	19.70	0.000
Vc*f	4	433.3	3.86%	108.33	2.66	0.085
Vc* L/D	6	590.3	5.26%	98.38	2.41	0.091
f* L/D	6	994.4	**8.86%**	165.74	4.07	0.019
Error	12	488.9	4.36%	40.74		
Total	35	11218.8	100.00%			

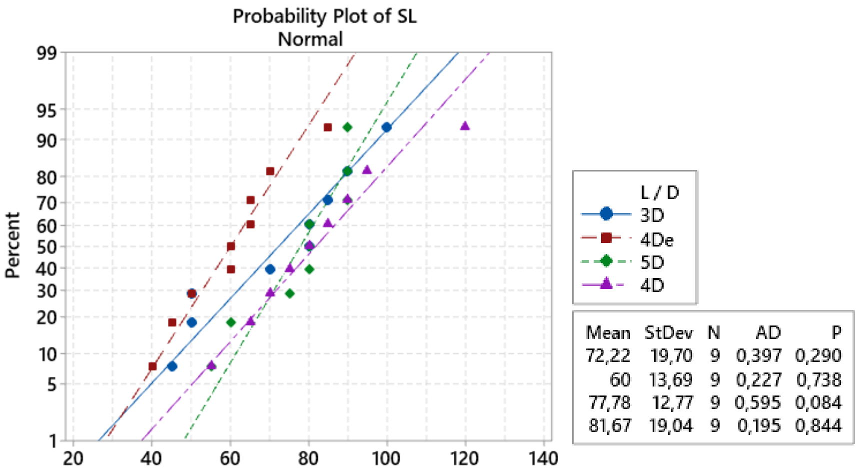


Figure 13. Normality test for SL

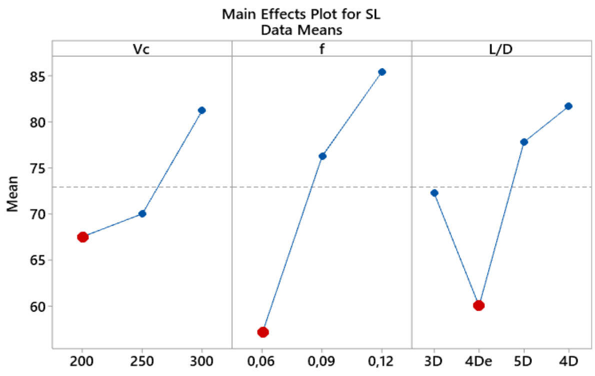


Figure 14. Main effects plot for SL

When the main effects plot for SL in figure 14 is examined, the most optimum results were obtained by using 200 m/min for Vc, 0.06 mm/rev for f and 4De Udrill for L/D ratio. According to the mean effects plot for Fz, while 4De produced the highest values, it produced the lowest values for SL.

In figure 15, the effect of drilling parameters on SL for all Udrills is shown as a three-dimensional graphic. When the literature is examined, it has been stated that

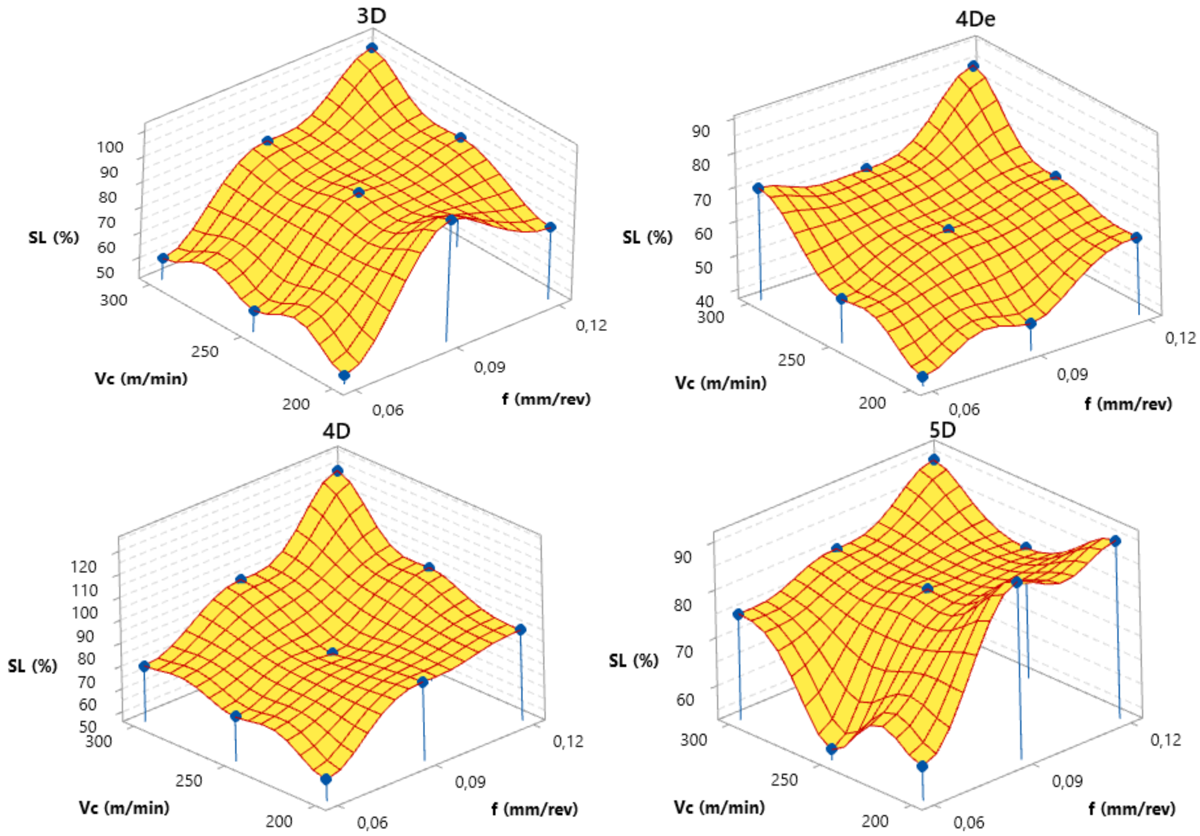


Figure 15. Variation of SL according to drilling parameters

SL values are similar to force values and increase with the increase of chip load [41].

It has been determined that the changes in chip load change the forces instantaneously [42, 43]. In addition to the adhesion between the cutting tool and the workpiece, it was stated that the SL increased as the feed rate increased [4]. Considering the obtained graphics, the SL value for the 3D Udrill at low Vc first increased with the increase of the f, and then decreased. However, SL values increased with the increase in f at medium and high Vc values. Considering the Vc according to the f, it first increased and then remained constant with the increase in Vc at low f. At medium f, the SL value first decreased and then remained constant with the increase in Vc. At high f, the SL value increased with the increase in Vc. The effect of Vc on SL was more pronounced at high f.

When the 4De Udrill graph is examined, the SL value increased with the increase in the f at low and medium Vc. However, with the increase in f at high Vc, the SL value first decreased and then increased. The SL values increased with increasing Vc for the whole f.

According to the 4D Udrill graph, SL values increased with the increase in the f for all Vc. Considering the f, the SL value increased with the increase in Vc at low and high f. With the increase in Vc at medium f, the SL value first decreased and then increased.

When the 5D Udrill graphs are examined, the SL value increased significantly with the increase in the f at low and medium Vc, but then remained constant. At high Vc, the SL value increased with the increase in the f. With the increase in Vc at low and high f, the SL value first decreased and then increased. At medium f, it first decreased and then remained constant with the increase in Vc.

The result of the Anova analysis resulted in an R^2 value of 95.4% for SL. This value was slightly lower when compared to Fz (98.09%) and Mz (99.75%) values. Some interpretations have been encountered in the literature regarding this relatively low result. In a study examined, it was stated that the dynamometer used for load measurement was rigidly fixed when attached to the bench table in a static position. Thus, it was stated that the spindle rotates and there is a loss of information while sensing and capturing the power (spindle load) due to the damping effect of the spindle rotor caused by inertia, and chip clogging in the drill flutes may cause a change in the power data [11]. In another study, it has been suggested that the spindle load information changes randomly because the low-frequency changes in drilling torque due to chips stuck in the hole cannot be captured by the spindle load signal [1]. Due to the aforementioned conditions, the spindle load R^2 value is considered to be relatively low compared to Fz and Mz. However, the R^2 values that resulted in the current study were quite significant.

Mathematical models related to Udrill are given in equations 9-12 for SL as categorical variables, respectively. Regression analysis was performed for SL. The R^2 value was calculated as 86.57%.

When experimental and predictive comparisons of mathematical models for SL are made according to L/D ratios for medium Vc and medium f, 3D (experimental 80%, prediction result 73%), 4De (experimental 60%, prediction result 60%), 5D (experimental 80%, estimation result 78%), 4D (experimental 75%, estimation result 82%). It has been determined that the experimental results and the results predicted by the mathematical model are quite compatible.

L/D		
3D	$SL = 84.6 - 0.885\,Vc + 1351\,f + 0.00175\,Vc^2 - 5556\,f^2 + 1.04\,Vc*f$	(9)
4De	$SL = 60.7 - 0.719\,Vc + 1017\,f + 0.00175\,Vc^2 - 5556\,f^2 + 1.04\,Vc*f$	(10)
5D	$SL = 126.8 - 0.952\,Vc + 1128\,f + 0.00175\,Vc^2 - 5556\,f^2 + 1.04\,Vc*f$	(11)
4D	$SL = 64.9 - 0.769\,Vc + 1351\,f + 0.00175\,Vc^2 - 5556\,f^2 + 1.04\,Vc*f$	(12)

4. CONCLUSION

The effect of the cutting parameters determined in this study, the thrust force (Fz) and torque (Mz) obtained from the dynamometer were compared with the maximum spindle load (SL) information obtained from the CNC machine tool. Dynamometer data and spindle load normality test were interpreted using Anova test, mean effects plot, regression equations and three-dimensional graphs. Similarities and differences between the data were tried to be determined. Obtained results were listed as follows:

1. According to the Anova analysis, it was concluded that while the length/diameter ratio of Udrills had an effect of 56.97% on Fz and 21.46% on SL, it was not effective for Mz.

2. The extra cooling hole in the center of the 4De Udrill caused a force increase of approximately 34.2% in Fz values. It produced a relatively negligible 0.3% increase in the Mz value, albeit slightly. When the SL value is taken into account, a decrease of 26.53% occurred.

3. The Fz values for all Udrills increased as the f increased. The highest Fz value was obtained with the 4De Udrill, while the lowest Fz value was obtained with the 5D Udrill.

4. According to the Anova test, L/D (56.97%), f (36.29%) and Vc (1.94%) parameters were found to be effective on the Fz output parameter, respectively. The R^2 value of the test was calculated as 98.09%.

5. The highest Mz value of 648 Ncm was obtained using a 5D Udrill at medium Vc and the largest f values. The smallest value, 340Ncm, was obtained using the 3D Udrill at the largest Vc and smallest f. The Mz values increased with the increase of the f.

6. The parameters f (98.77%) and Vc (0.32%) were found to be effective on the Mz output response, respectively. The R^2 value for the test was calculated as 99.75%. It was found that f value was effective with a very high value on Mz value, while L/D ratio was not effective. Accordingly, it can be said that the coolant hole is more effective than the L/D ratio in drilling aluminum material using a Udrill.

7. The highest SL value of 120% was obtained using the 4D body at the largest Vc and largest f values. The smallest value, 40%, was obtained at the smallest Vc and smallest f by using the 4De body. The R^2 value for the test was calculated as 95.64%. The order of effects on the SL output response resulted in f (44.72%), L/D (21.46%), Vc (11.48%), and the f*L/D combination (8.86%).

8. A second-order regression analysis was performed using experimental data. According to the analysis, R^2 values were calculated as 97.5% for Fz, 99.52% for Mz and 86.57% for SL.

ACKNOWLEDGMENTS

It was supported by Gazi University Scientific Research Projects Unit with the code 07/2019-08. The researchers thank the Gazi University BAP unit for their support.

DECLARATION OF ETHICAL STANDARDS

The authors of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

AUTHORS' CONTRIBUTIONS

Aslan AKDULUM: He conducted the drilling experiments, analyzed the results, and carried out the writing process of the article.

Yunus KAYIR: He conducted the drilling experiments, analyzed the results.

CONFLICT OF INTEREST

There is no conflict of interest in this study.

REFERENCES

[1] Yalçın N., Kayır Y. and Erkal S., "AA2024 alüminyum alaşımına uygulanan yaşlandırma yöntemlerinin işlenebilirliğe etkisinin taguchi ve anova ile araştırılması", ***Politeknik Dergisi***, 20:743-751, (2017).

[2] Fernández-Pérez J., Cantero J., Díaz-Álvarez J. and Miguélez M., "Hybrid composite-metal stack drilling with different minimum quantity lubrication levels", ***Materials***, 12:448, (2019).

[3] Zolgharni M., Jones B., Bulpett R., Anson A. and Franks J., "Energy efficiency improvements in dry drilling with optimised diamond-like carbon coatings", ***Diamond and Related Materials***, 17:1733-1737, (2008).

[4] Bourne K.A. and Kapoor S.G., "Process monitoring during micro-drilling via acoustic emission, ultrasonic sound, and spindle load sensors", ***ASME 2012 International Manufacturing Science and Engineering Conference***, 781-790, USA, (2012).

[5] Bhattacharya A., Das S., Majumder P. and Batish A., "Estimating the effect of cutting parameters on surface finish and power consumption during high speed machining of AISI 1045 steel using Taguchi design and ANOVA", ***Production Engineering***, 3:31-40, (2009).

[6] Muthukrishnan N., Murugan M. and Rao K.P., "Machinability issues in turning of Al-SiC (10p) metal matrix composites", ***The International Journal of Advanced Manufacturing Technology***, 39:211-218, (2008).

[7] Wang Q., Zhang D., Tang K. and Zhang Y., "A mechanics based prediction model for tool wear and power consumption in drilling operations and its applications", ***Journal of Cleaner Production***, 234:171-184, (2019).

[8] Larek R., Brinksmeier E., Meyer D., Pawletta T. and Hagendorf O., "A discrete-event simulation approach to predict power consumption in machining processes", ***Production Engineering***, 5:575, (2011).

[9] Yoon H.-S., Lee J.-Y., Kim M.-S. and Ahn S.-H., "Empirical power-consumption model for material removal in three-axis milling", ***Journal of Cleaner Production***, 78:54-62, (2014).

[10] Shokrani A., Dhokia V. and Newman S., "Modelling and verification of energy consumption in CNC milling", ***International Conference on Sustainable Design and Manufacturing***, Greece, 123-133, (2016).

[11] Kim H., Ahn J., Kim S. and Takata S., "Real-time drill wear estimation based on spindle motor power", ***Journal of Materials Processing Technology***, 124:267-273, (2002).

[12] Mendes O., Avila R., Abrao A., Reis P. and Davim J.P., "The performance of cutting fluids when machining aluminium alloys", ***Industrial Lubrication and Tribology***, (2006).

[13] Shah P. and Khanna N., "Comprehensive machining analysis to establish cryogenic LN_2 and LCO_2 as sustainable cooling and lubrication techniques", ***Tribology International***, 148:106314, (2020).

[14] Da Silva L., Del Claro V., Andrade C., Guesser W., Jackson M., and Machado A., "Tool wear monitoring in drilling of high-strength compacted graphite cast irons", ***Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture***, 235(1-2): 207–218, (2020).

[15] Corne R., Nath C., El Mansori M. and Kurfess T., "Enhancing spindle power data application with neural network for real-time tool wear/breakage prediction during inconel drilling", ***Procedia Manufacturing***, 5:1-14, (2016).

[16] Cho H.S., Han J.-h., Chi S.-y. and Yoo K.-H., "A tool breakage detection system using load signals of spindle motors in CNC machines", ***Eighth International Conference on Ubiquitous and Future Networks (ICUFN)***, Austria, 160-163, (2016).

[17] Bose T., Majumdar A. and Chattopadhyay T., "Machine load estimation via stacked autoencoder regression", ***2018 IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP)***, Canada, 2126-2130, (2018).

[18] Griffin R., Cao Y., Peng J. and Chen X., "Tool wear monitoring and replacement for tubesheet drilling", ***The International Journal of Advanced Manufacturing Technology***, 86:2011-2020, (2016).

[19] Kim S., "Integration of pre-simulation and sensorless monitoring for smart mould machining", ***International Journal of Simulation Modelling***, 15:623-636, (2016).

[20] Peña-Parás L., Maldonado-Cortés D., Rodríguez-Villalobos M., Romero-Cantú A.G. and Montemayor O.E., "Enhancing tool life, and reducing power consumption and surface roughness in milling processes by nanolubricants and laser surface texturing", ***Journal of Cleaner Production***, 253:119836, (2020).

[21] Prickett P., Amer W. and Grosvenor R., "Sweeping filters and tooth rotation energy estimation (TREE) techniques for machine tool condition monitoring", ***Int J Mach Tools Manu***, 45:1-8, (2005).

[22] Franco-Gasca L.A., Herrera-Ruiz G., Peniche-Vera R., de Jesús Romero-Troncoso R. and Leal-Tafolla W., "Sensorless tool failure monitoring system for drilling machines", ***International Journal of Machine Tools and Manufacture***, 46:381-386, (2006).

[23] Lee K.-J., Lee T.-M. and Yang M.-Y., "Tool wear monitoring system for CNC end milling using a hybrid approach to cutting force regulation", ***The International Journal of Advanced Manufacturing Technology***, 32:8-17, (2007).

[24] Peña-Parás L., Maldonado-Cortés D., Rodríguez-Villalobos M., Romero-Cantú A.G., Montemayor O.E., Herrera M., Trousselle G., González J., and Hugler W., "Optimization of milling parameters of 1018 steel and nanoparticle additive concentration in cutting fluids for enhancing multi-response characteristics", ***Wear***, 426:877-886, (2019).

[25] Parsian A., "Regenerative Chatter Vibration in Indexable Drills: Modeling and Simulation", ***PhD Thesis***, University West-Department of Engineering Science-Research Enviroment Production Technology West, (2018).

[26] Parsian A., Magnevall M., Eynian M. and Beno T., "Time domain simulation of chatter vibrations in indexable drills", ***The International Journal of Advanced Manufacturing Technology***, 89:1209-1221, (2017).

[27] Liu L.L., Zhou L.P. and Ying Z.J., "The FEM Dynamic Simulation in the Drilling process with Indexable Inserts", ***Advanced Materials Research***, 557-559: 1292-1297, (2012).

[28] Parsian A., Magnevall M., Beno T. and Eynian M., "Sound analysis in drilling, frequency and time domains", ***Procedia CIRP***, 58:411-415, (2017).

[29] Rahman M., Seah K. and Venkatesh V., "Performance evaluation of endrills", ***International Journal of Machine Tools and Manufacture***, 28:341-349, (1988).

[30] Kabakli E., Bayramoglu M. and Geren N., "Evaluation of the surface roughness and geometric accuracies in a

drilling process using the Taguchi analysis", ***Mater. Tehnol,*** 48:91-98, (2014).

[31] Tasdelen B., Wikblom T. and Ekered S., "Studies on minimum quantity lubrication (MQL) and air cooling at drilling", ***Journal of Materials Processing Technology***, 200:339-346, (2008).

[32] Kheireddine A., Ammouri A., Lu T., Jawahir I. and Hamade R., "An FEM analysis with experimental validation to study the hardness of in-process cryogenically cooled drilled holes in Mg AZ31b", ***Procedia Cirp***, 8:588-593, (2013).

[33] Parsian A., Magnevall M., Beno T. and Eynian M., "A mechanistic approach to model cutting forces in drilling with indexable inserts", ***Procedia Cirp***, 24:74-79, (2014).

[34] Okada M., Asakawa N., Sentoku E., M'Saoubi R. and Ueda T., "Cutting performance of an indexable insert drill for difficult-to-cut materials under supplied oil mist", ***The International Journal of Advanced Manufacturing Technology***, 72:475-485, (2014).

[35] Ahmed L.S. and Kumar M.P., "Cryogenic drilling of Ti–6Al–4V alloy under liquid nitrogen cooling", ***Materials and manufacturing processes***, 31:951-959, (2016).

[36] Venkatesh V. and Xue W., "A study of the built-up edge in drilling with indexable coated carbide inserts", ***Journal of Materials Processing Technology***, 58:379-384, (1996).

[37] Gökçe H., Çiftçi İ. and Gökçe H., "Frezeleme operasyonlarında kesme kuvvetlerinin deneysel ve sonlu elemanlar analizi ile incelenmesi: saf molibdenin işlenmesi üzerine bir çalışma", ***Politeknik Dergisi***, 22:947-954, (2019).

[38] Rajesh S., Pethuraj M., Kumaran S.T., Uthayakumar M. and Rajini N., "Some studies on drilling of red mud reinforced aluminum composite", ***Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications***, 231:382-393, (2017).

[39] Ma F., Zhang H., Cao H. and Hon K., "An energy consumption optimization strategy for CNC milling", ***The International Journal of Advanced Manufacturing Technology***, 90:1715-1726, (2017).

[40] Kaymakci M., Kilic Z. and Altintas Y., "Unified cutting force model for turning, boring, drilling and milling operations", ***International Journal of Machine Tools and Manufacture***, 54:34-45, (2012).

[41] Zhu J., Kim H.J. and Kapoor S.G., "Microscale drilling of bulk metallic glass", ***Journal of Micro and Nano-Manufacturing***, 1:1-9, (2013).

[42] Aydın M., "Parmak Frezeleme Sırasında Takım Salgısının Etkisi Dahil Edilerek Kesme Kuvvetlerinin Tahmini ve Analizi", ***Politeknik Dergisi***, 25(1) : 157-167, (2022).

[43] Kuntoğlu M. and Aslan A., "AISI 5140 Çeliğinin Tornalanması Esnasında Yaklaşma Açısı ve Kesme Parametrelerinin İşlenebilirliğe Etkisinin İncelenmesi", ***Politeknik Dergisi***, 25(1): 145-155, (2021)