Iğdır Üniversitesi Fen Bilimleri Enstitüsü Dergisi, 13(4), 2973-2985, 2023
Journal of the Institute of Science and Technology, 13(4), 2973-2985, 2023

ISSN: 2146-0574, eISSN: 2536-4618

Metalurji ve Malzeme Mühendisliği / *Metallurgical and Materials Engineering* **DOI: 10.21597/jist.1310601**

Araştırma Makalesi / *Research Article*

Geliş tarihi / *Received*: 06.06.2023 **Kabul tarihi / *Accepted*: 12.07.2023**

Atıf İçin: Yaka, H. ve Engin, K. E. (2023). AISI D2 Soğuk İş Çeliğinin Delinmesinde Deneysel ve Sonlu Elemanlar Analizi Yoluyla Delik Kalitelerinin İyileştirilmesi ve İşleme Parametrelerinin Optimizasyonu. *Iğdır Üniversitesi Fen Bilimleri Enstitüsü Dergisi*, 13(4), 2973-2985.

To Cite: Yaka, H. & Engin, K. E. (2023). Improvement of Hole Qualities and Optimization of Machining Parameters Through Experimental and Finite Element Analysis in Drilling Of AISI D2 Cold Work Steel. *Journal of the Institute of Science and Technology*, 13(4), 2973-2985.

AISI D2 Soğuk İş Çeliğinin Delinmesinde Deneysel ve Sonlu Elemanlar Analizi Yoluyla Delik Kalitelerinin İyileştirilmesi ve İşleme Parametrelerinin Optimizasyonu

Harun YAKA[1*], Kaan Emre ENGİN[2]

Öne Çıkanlar:
- İtme kuvveti
- Optimizasyon
- Yüzey pürüzlülüğü

Anahtar Kelimeler:
- AISI D2
- ANOVA
- Delme
- Sonlu eleman
- Yüzey pürüzlülüğü
- Taguchi

ÖZET:

Son yıllarda artan tedarik sorunları birçok alanda maliyetlere olumsuz yansımaktadır. Global çapta meydana gelen krizlerden dolayı ham madde fiyatları artmış ve imalat sektörü de ciddi etkilenmiştir. İmalat sektöründe zararları minimize etmek için üretim planlaması ve malzeme tasarrufu doğru yapılmalıdır. Üretim giderlerini düşürmenin en verimli yolu da uygun kesici takım kullanmak ve doğru işleme parametrelerini seçmektir. Bu çalışmada kalıp sektöründe yaygın olarak kullanılan AISI D2 çeliğinin delinmesi incelenmiş ve optimum işleme parametreleri belirlenmiştir. Delme işlemleri için TiN kaplamalı matkaplar kullanılmıştır. İşleme parametrelerinin yüzey pürüzlülüğü (Ra) ve itme kuvveti (Fz) üzerindeki etkileri Taguchi ve ANOVA ile incelenmiştir. Delme işleminde oluşan yüzey pürüzlülüğü ve itme kuvveti değerleri ölçülmüştür. Ayrıca itme kuvveti değerleri sonlu elemanlar (FE) yöntemi ile de sayısal olarak incelenmiştir. Düşük ilerleme ve kesme hızlarında Ra ve Fz düşük çıkmıştır. Ra' ya en çok ilerleme oranı etki ederken Fz'ye en çok kesme hızı etki etmiştir. En düşük Ra ve Fz, 30 mm/dak. ilerleme oranı ve 25 m/dak. kesme hızında olmuştur. ANOVA analizine göre, belirlenen işleme parametrelerinin hem Ra hem de Fz üzerinde etkili olduğu tespit edilmiştir. Ra ve Fz için R^2 değerleri %95'in üzerinde hesaplanmıştır.

Improvement of Hole Qualities and Optimization of Machining Parameters Through Experimental and Finite Element Analysis in Drilling Of AISI D2 Cold Work Steel

Highlights:
- Thrust force
- Optimization
- Surface roughness

Keywords:
- AISI D2
- ANOVA
- Drilling
- Finite Element
- Surface roughness
- Taguchi

ABSTRACT:

Increasing supply chain problems in recent years have a negative impact on costs in many areas. Due to the global crisis, raw material prices increased and the manufacturing sector was seriously affected. Production planning and material saving should be done correctly in order to minimize the losses in the manufacturing sector. The most efficient way to reduce production costs is to use suitable cutting tools and choose the right machining parameters. In this study, the drilling of AISI D2 steel, which is widely used in the mold industry, was examined and optimum machining parameters were determined. TiN coated drills are used for drilling operations. The effects of machining parameters on Surface Roughness (Ra) and Thrust Force (Fz) were investigated by Taguchi and ANOVA. Surface roughness and thrust force values during drilling were measured. Thrust force values were also analyzed numerically by the Finite Element (FE) method. Ra and Fz were also low at low feed rate and low cutting speeds. While the feed rate affected Ra the most, the Fz affected the cutting speed the most. The lowest Ra and Fz were at 30 mm/min feed rate and 25 m/min cutting speed. According to the ANOVA, it was determined that the machining parameters were effective on both Ra and Fz. R^2 values for Ra and Fz are calculated over 95%.

[1]Harun YAKA (**Orcid ID:** 0000-0003-4859-9609), Amasya University, Mechanical Engineering Department, Amasya, Türkiye
[2]Kaan Emre ENGİN (**Orcid ID**: 0000-0002-6439-7700), Adıyaman University, Mechanical Engineering Department, Adıyaman, Türkiye

***Sorumlu Yazar/*Corresponding Author**: Harun Yaka, e-mail: harun.yaka @amasya.edu.tr

INTRODUCTION

Cold work tool steels are a type of steel that is characterized by high carbon content and relatively low levels of manganese, tungsten, molybdenum, and chromium. The material exhibits favorable dimensional stability and hardenability, abrasion resistance, high tensile strength, and thermal softening resistance. Machining operations aim to achieve high surface quality and accuracy, reduce energy consumption, and prolong tool life. Cold work tool steels have a distinct machining behavior compared to other materials. The materials' high strength affects the cutting tool during chip removal, hindering the use of optimal cutting techniques. (Anthony, 2015). The need to optimize the machinability of these steels arises as a result of the current situation.

AISI D2 is a cold work tool steel that is gaining attention in die fabrication. Drilling is an important part of die manufacturing, used to make assembly easier or create cooling channels within the die (Shapiro, 2009). Assessing surface roughness and thrust forces is important when drilling AISI D2 material.

Surface roughness is a crucial indicator of drilling precision. Several factors influence surface roughness, including the properties of the drilling bit (geometry, materials coating etc.) and cutting conditions (cutting speed, feed rate, shape of chips and process temperature, etc.). Any change in these parameters directly affect surface roughness (Çiçek et al., 2012).

Thrust force is another significant output factor to consider in drilling. Thrust forces impact energy consumption and surface outcomes such as hole diameter errors, roundness, and surface roughness. (Duran&Acır, 2004; Akıncıoğlu et al., 2013). Metal-cutting process can achieve high speeds with advanced coating technology. Tool coatings enhance tool life, surface smoothness, and decrease thrust forces. Titanium nitride (TiN) coatings have improved drilling tools by providing better crater wear resistance, low friction, chemical stability, and longer tool life. (Chou & Liu, 2000; Sharif & Rahim, 2007). Consequently, it is important to provide optimal cutting parameters to obtain lower thrust forces (Çakır, 2000; Basavarajappa et al., 2008).

The machinability of AISI D2 has become an important research topic due to its increasing use in manufacturing and the tool industry, particularly in drilling operations. Experimental studies are conducted and optimization techniques are applied by other researchers. The study focuses on Taguchi method and the Analysis of Variance (ANOVA) as an optimization approach. The Taguchi method is a statistical approach used for optimizing design problems by determining the significance of various factors for the target function. The methodology can be used for various research paradigms, including experimental, numerical, and theoretical methods (Bademlioglu et al., 2020). The ANOVA method is a well-established technique that is commonly used in conjunction with the 'Taguchi' approach to determine the proportionate impact of each process parameter on the desired outputs (Mustapha et al., 2021).

Aized and Amjad deep drill AISI D2 material. Peck-drilling technique is used during drilling and its effect on drilling parameters such as speed, feed rate, and depth of drilling step is assessed for roundness, cylindricity, diameter errors, and surface roughness. The response surface methodology is used to optimize drilling efficiency. It is found out that spindle speed and feed rate have a significant impact on the quality of a drilled hole (Aized & Amjad, 2013).

Akıncıoğlu et al. (2013), conducted experiments using various drill bit coatings and cutting parameters to drill AISI D2 workpiece with a fixed depth of cut. ANN is used to predict hole diameters and thrust forces. They state that TiAlN/TiN multi-layer coated drills are the most effective in reducing thrust forces and hole diameters.

Akıncıoğlu et al. (2017), use the Taguchi method to optimize drilling parameters for AISI D2 workpiece with carbide drills. Three types of drill bits, untreated, cryo-treated, and cryo-treated and tempered, are used for experiments. CTT drills outperform in Ra and Fz based on experimental findings. Carbide drills show improved wear resistance after undergoing cryogenic treatment. Feed rate has the highest impact on Ra and Ff parameters, with a significant percentage contribution of 66.97% and 80.07%, respectively, according to the ANOVA analysis.

Osman et al. (2017), perform dry drilling on an AISI D2 workpiece to determine the optimal parameters for creating holes with high accuracy of diameter. Spindle speeds of 482, 550, and 627 RPM are used for drilling. Feed rates are set at 68 mm/min, 103 mm/min, and 146 mm/min. Different drill bit materials are used, including High Speed Steel (HSS) coated with TiN, HSS coated with Titanium Carbon Nitride (TiCN), and HSS coated with TiAlN. Taguchi method and ANOVA are used for output analysis. Drill bit coating has the most significant influence on diameter accuracy, followed by feed rate and spindle speed. Optimal parameters are achieved by using TiCN-coated HSS, with a feed rate of 103 mm/min and spindle speed of 627 RPM. Coated drill bits provide the best performance results.

Osman et al. (2018), investigate the dry drilling of AISI D2 using drill bits with a diameter of 10 mm and different coatings (uncoated TiN and TiCN) at three spindle speeds and feed rates. The authors use a L9 array, S/N ratio, and ANOVA to determine the importance of each parameter for achieving minimal surface roughness. Drilling tools have the greatest influence on surface roughness at 95%, followed by spindle speed at 3% and feed rate at 0.4%. The optimal combination for HSS-TiCN drilling tools is found to be a spindle speed of 680 rpm and a feed rate of 206.25 mm/min, as revealed by ANOVA.

Ulaş (2018) conduct an experimental study on the relationship between drilling parameters (cutting speed, feed rate, drill bit, and workpiece material) and maximum thrust force and torque. The author drills AISI D2 and AISI D3 cold work tool steels using uncoated HSS and carbide drill bits. The drilling process is done without coolant, using a CNC vertical machining center at different cutting speeds and feed rates. Carbide drill bits result in less thrust force than HSS drill bits. He states that feed rate affects maximum thrust forces, but cutting speed does not. AISI D3 cold work tool steel requires higher forces in drilling than AISI D2 cold work tool steel.

Kumar et al. (2018) conduct abrasive assisted high-speed drilling on AISI D2 cold work tool steel. Abrasive slurry containing SiC and Al_2O_3 with mesh sizes of 800, 1200, and 1500 is used. Slurry concentrations vary from 20% to 35%. The study aims to optimize surface roughness and material removal rate by investigating process factors such as abrasive type, abrasive mesh size, spindle speed, slurry concentration, and feed rate using an L18 orthogonal array. The surface roughness of the hole is significantly affected by the type and concentration of the abrasive, as shown by ANOVA analysis. The feed rate and type of abrasive used have a significant impact on the material removal rate.

Drilling parameter optimization is usually based on empirical data from experimental outcomes, as shown in existing literature. Performing experiments for each condition type is expensive, time-consuming, and inefficient. Finite Element (FE) analysis has the potential to decrease these manufacturing expenses and time requirements, making it a feasible choice for implementation. (Uğur et al., 2022; Luo et al., 2021). FE analysis can simulate drilling under different conditions, including various drill bit types and workpiece materials.

The present study involves the drilling process of AISI D2 cold work tool steel, which has a thickness of 15 mm. The drilling operation is carried out using a carbide drill coated with Titanium Nitride (TiN), having a diameter of 6 mm and a tip angle of 118°. The drilling process involves perforating the material from end to end, while utilizing a coolant consisting of 10% boron oil. The study employs three distinct sets of cutting speeds (15, 20, 25 m/min) and three varying feed rates (30, 40, 50 mm/min). Simultaneously, finite element analyses are performed to simulate identical process conditions and materials with the aim of comparing the outcomes with experimental data. The experimental thrust force values were compared with those obtained through FE analysis. Furthermore, the Taguchi method and ANOVA are utilized for optimization purposes in order to identify the optimal parameters.

MATERIALS AND METHODS

Experimental Work

The experimental study employs AISI D2 steel, which has a size of 150x48x15 mm as illustrated in Figure 1. The process involves drilling holes along the entire thickness of the material, while utilizing a coolant containing 10% boron oil. The chemical composition of the AISI D2 steel used in the experiments is given in Table 1.

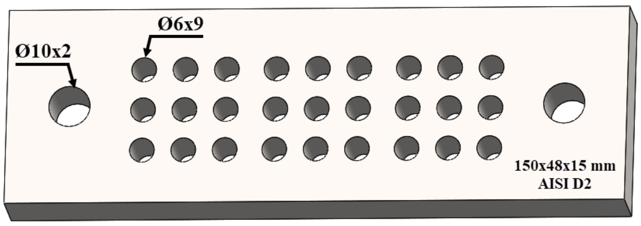


Fıgure 1. Illustration AISI D2 cold work steel and related hole diameters

Table 1. Chemical Composition of AISI D2

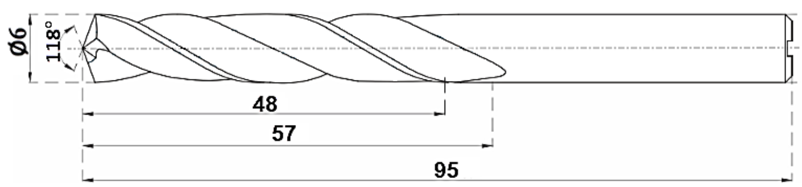
Element	C	Mn	Si	Cr	Ni	Mo	V
Weight %	1.40-1.60	0.6	0.6	11-13	0.3	0.7-0.12	1.1

In the experiments, Karcan brand M8DF060095 coded Titanium Nitride (TiN) coated carbide drill bit with a diameter of 6 mm and a point angle of 118° supplied from Karcan Cutting Tools company is used. Table 2 presents the specifications of the drill utilized in the experiments.

Experiments are conducted using the TAKUMA brand JVH710 CNC vertical machining center maintained by Amasya University. A bench and a test set are used for the experiments use, as shown in Figure 2. Drilling factors are adjusted according to cutting tool catalog specifications and literature review findings. Drilling of AISI D2 workpiece is carried out at 15 mm cutting depth with 3 different cutting speeds (15, 20, 25 m/min) and 3 feed rates (30, 40, 50 mm/min). The experiments have been performed on three plates under the same conditions. Experimental results are obtained by averaging measured Ra and Fz values. Cutting parameters used for hole drilling are shown in Table 4.

Table 2. Technical Specifications of the Drill Used in the Experiments

Helix angle	30°
Coating type	TiN
Point angle	118°
Coating thickness	0.25-1.2 Micron
Coating method	PVD
Coating melting Temperature	2950°C



The surface roughnesses of the specimens are measured using a Mitutoya SJ-310S surface roughness measuring device, which abides by ISO 1997 standards. The device has a measuring length of 8 mm and a measuring speed of 0.5 mm/sec. The hole surface is measured from three distinct points, and subsequently, the means of these measurements are recorded. An S type loadcell manufactured by

Puls Elektronik is utilized to measure the thrust forces generated during the drilling process under varying process factors. It is positioned beneath the workpiece to facilitate the measurements.

Figure 2. CNC vertical machining center and experimental set

Taguchi Method

The analysis's effectiveness depends on choosing process parameters that are correlated with the objective function. The established parameters and levels for statistical analysis are given in Table 3. The Taguchi method is used to optimize machining parameters for minimizing surface roughness and thrust force during the drilling of AISI D2 cold work tool steel. Ra and Fz outcomes are converted into Signal-to-Noise (S/N) ratio. S/N ratio calculation involves three performance characteristics. Jena et al. (2021) identifies three categories: smallest best, largest best, and nominal best. Smallest best is chosen as the performance characteristic to minimize Ra and Fz values. Equation 1 is used to compute S/N ratios based on the smallest best.

$$SNRs = -10log\frac{1}{n}\left[\sum_{i-1}^{n} y_i^2\right] \quad (1)$$

Table 3. Drilling Factors and Factor Levels

Factors	Unit	Code	Factor levels		
Drill bit				TiN Coated Drill	
Cutting speed (Vc)	m/min	A	15	20	25
Feed rate (f)	mm/min	B	30	40	50

Finite Element (FE) Analysis

Deform-3D Machining Software Package (Def3D-Machsp), developed by STFC, is used to generate finite element models based on implicit Lagrangian for simulating manufacturing processes like turning, milling, boring, and drilling. Simulating the drilling process in Def3D-Machsp is a time-intensive task due to the complexity of chip formation and the need to simulate both rotational and linear displacement movements. The paper only analyzes stresses on the drill and does not study heat transfer or related configurations hence the simulation methodology employed entails the acquisition of thrust forces.

SolidWorks software is used to create 3D models of the workpiece and the drill. A cylindrical workpiece with a diameter of 10 mm and a thickness of 15 mm is modeled to decrease computing time and mesh number. Drills are modeled using data from the tool manufacturer's catalogue considering all important aspects. Solid models are imported into Def3D-Machsp. The X, Y, and Z axes orientations are determined. The software is programmed with movement parameters such as feed rate and cutting speeds. The selection of the object type for the workpiece is plastic. The software's material library provides data on coated drills, such as coating thickness, modulus of elasticity, and Poisson's ratio. The drills are made of cemented carbide (WC). The drill is coated with TiN layers of 5 µm thickness.

Def3D-Machsp generates multiple meshes during metal drilling simulation due to material and mesh distortion. Novel meshes are created based on user-specified parameters to maintain fine elements in high-resolution areas and coarse elements in other regions.

The size ratio determines the dimensions of significant elements in areas where additional details are unnecessary. A size ratio of 10 is commonly used in metal cutting simulations and the same trend is followed for the study. The mesh number for AISI D2 workpiece is 26.128 with an element size of 0.025 mm. Drill bit's minimum element size is 0.2 mm with a mesh number of 20,000. Figure 3 shows the figure obtained from the Deform software.

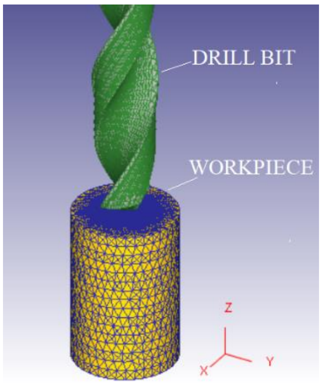


Figure 3. FE modelling of drilling in Deform-3D machining package

The speed of the workpiece in the X, Y, and Z axes is set to 0 in three directions during the boundary condition setting to restrict the workpiece's motion. The drill operates in the -Z orientation and revolves about the Z-axis. Simultaneously, the surfaces of the tool and workpiece, as well ambient temperatures are assumed to be 20°C, while the heat transfer coefficient and convection coefficient of coolant are determined to be 45 kW/m^{2}K and 0.02 kW/m^{2}K, respectively. The workpiece is subject to a contact condition characterized by shear friction, with a corresponding friction coefficient of 0.6 (Raju & Swamy, 2012; Li et al., 2017). The drill bit is not subject to any tool wear condition carrying the purpose to reduce computation time. Johnson and Cook constitutive equation is used as the plasticity model. Johnson and Cook equation is given in Equation 2 as;

$$\sigma = (A + B\varepsilon^n)\left\{1 + C\log(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0})\right\}\left\{1 - (\frac{T-293}{T_m-293})^m\right\} \quad (2)$$

which A, B, C are material constants, n is the strain hardening index, ε and $\dot{\varepsilon}$ are the strain and strain-rate, $\dot{\varepsilon}_0$ is the initial strain rate, T is the operating temperature, Tm is the melting temperature of the material and m the strain rate sensitivity exponent.

ANOVA Method

ANOVA is carried out to assess the reliability of the experimental study (Çırakoğlu et al., 2021). In studies applying variance analysis, it is common practice to consider the confidence level of the model to be 95%. It is anticipated that the experimental study's confidence level will either meet or approach this threshold. The significance of the factor can be assessed by utilizing the p-value presented in the table. A factor is considered statistically significant if its p-value is less than 0.05. (Nyugen et al., 2014; Malo and Yaka, 2023).

RESULTS AND DISCUSSION

Experimental Results

Machining operations can cause surface roughness that negatively affects the durability of the workpiece material. Processing defects such as excessive surface roughness and micro cracks can occur due to insufficient determination of processing parameters and cutting conditions. Exposure to high temperatures or significant forces can cause rapid corrosion and wear in susceptible components. Optimizing machining parameters is crucial to address these issues (La Monaca et al., 2021). The Taguchi method is employed in the present investigation to optimize the thrust forces and surface roughness. Table 4 presents the test list generated using Taguchi L9 sequencing and the corresponding Ra and Fz values. The Ra values range from 2.04 to 1.53 µm. The experimental results indicate that the lowest surface roughness value of 1.53 µm is obtained in the seventh experiment. The minimum Fz value of 370 N is observed in the 7th experiment, while the maximum value of 625 N is recorded in the 3rd experiment.

Table 4. Experimental results of Ra and Fz Values

Exp. No	A	B	Ra 1	Ra 2	Ra 3	Average Ra (µm)	Fz 1	Fz 2	Fz 3	Average Fz (N)
E1	15	30	1.78	1.81	1.93	1.84	399	410	403	404
E2	15	40	1.88	2.01	1.87	1.92	515	499	498	504
E3	15	50	1.94	2.10	2.08	2.04	639	624	612	625
E4	20	30	1.74	1.57	1.55	1.62	372	374	364	373
E5	20	40	1.69	1.80	1.79	1.76	430	429	443	434
E6	20	50	1.90	1.75	1.78	1.81	531	515	520	522
E7	25	30	1.49	1.52	1.58	1.53	376	379	364	370
E8	25	40	1.56	1.76	1.52	1.61	416	399	427	414
E9	25	50	1.59	1.77	1.68	1.68	512	481	486	493

Figure 4 shows the Ra and Fz values obtained during the L9 test using line and bar graphs. Ra and Fz increase at E1-E3, E4-E6, and E7-E9. The phenomenon is due to an increase in the feed rate. Ra andFz show a positive correlation with progression. Fz increases at lower cutting speeds in experiments. Fz decreases with increased cutting speeds. Figure 5 presents the impact of cutting speed and feed rates on Ra and Fz. Upon examination of Figure 5a, it is evident that an increase in the feed rate has an adverse impact on Ra. Furthermore, it is observed that Ra exhibited a greater value under conditions of low cutting speeds. The minimum surface roughness (Ra) is observed at a cutting speed of 25 m/min and a feed rate of 30 mm/min. The maximum surface roughness (Ra) is observed at a cutting speed of 15 m/min and a feed rate of 50 mm/min.

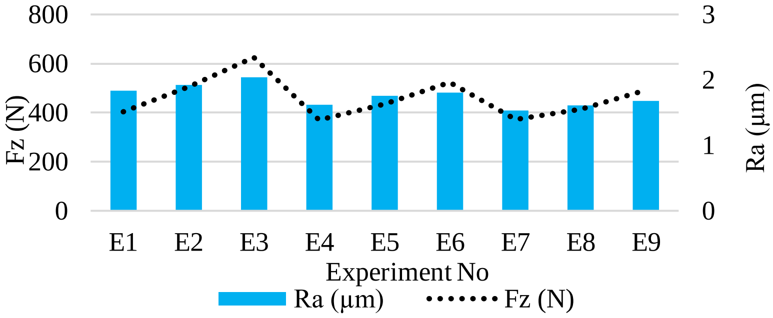
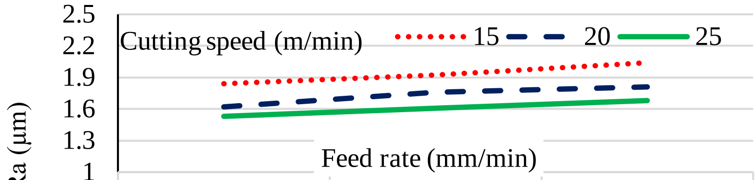


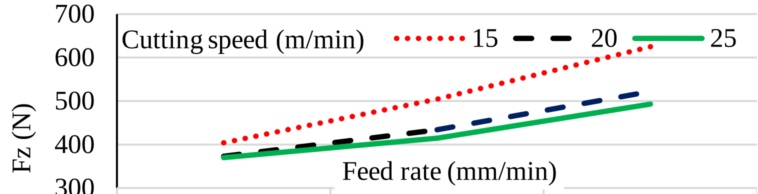
Figure 4. Graph of Fz and Ra values gathered from experiments

It is generally observed that an increase in cutting speed during machining operations leads to a reduction in surface roughness (Akıncıoğlu et al., 2013a; Akkuş and Yaka, 2021; Özlü et al., 2023). This phenomenon can be attributed to the reduction in Fz at moderate cutting speeds, which has a beneficial impact on the surface roughness (Shapiro, 2009; Özlü, 2021). Fz increases with higher feed rate and lower cutting speed, as shown in Figure 5b. The Ra measurement shows that the minimum Fz occurs at a cutting speed of 25 m/min and a feed rate of 30 mm/min.



	30	40	50
15	1.84	1.92	2.04
20	1.62	1.76	1.81
25	1.53	1.61	1.68

(a)



	30	40	50
15	404	504	625
20	373	434	522
25	370	414	493

(b)

Figure 5. Effect of cutting speed according to feed rate a) Effect on Ra b) Effect on Fz

Finite Element (FE) Results

Experimental and simulation results are compared for maximum thrust forces. It has been observed that there is a difference of about 7%-8% between the results obtained from the simulation and experimental data. Figure 6 shows the thrust force distribution along the -Z axis for a cutting velocity of 15 m/min and a feed rate of 30 mm/min. Table 5 shows the results.

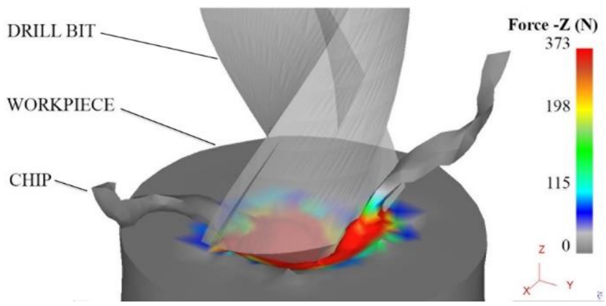


Figure 6. The visualization of thrust force generated by Deform- 3D Machining software package

Table 5. The comparison of maximum thrust force values between experimental and simulation results

Exp. No	Vc (m/min)	f (mm/min)	Thrust force (N)-Experimental	Thrust force (N)-Simulation	Percentage Error
E1	15	30	404	373	8.31 %
E2	15	40	504	464	8.62 %
E3	15	50	625	581	7.57%
E4	20	30	370	340	8.82 %
E5	20	40	434	403	7.69 %
E6	20	50	522	485	7.63 %
E7	25	30	373	343	8.75 %
E8	25	40	414	381	8.66 %
E9	25	50	493	459	7.41 %
Total Average	-	-	459.89	425.45	8.09 %

Table 5 illustrates that the simulation outcomes exhibit a minor deviation from the experimental findings. The occurrence of disparities between numerical and experimental findings is a frequently observed phenomenon in the literature (Nosouhi et al., 2017, Luo et al., 2021). The observed phenomenon can be attributed to the external factors that impact the experimental apparatus, such as inaccuracies in load cell measurements, compression of the chips, vibrations, and additional friction in the tools. It is worth noting that the simulation environment is devoid of these extraneous effects. Numerical analysis has been found to be a more efficient and cost-effective method for examining the impact of process parameters on thrust force during drilling, compared to experimental approaches. Implementing an experimental methodology requires a special setup, considerable effort, resource allocation, and material consumption. The approach lacks economic efficiency. The study shows that numerical analysis eliminates the need for the previously mentioned requirements. The main drawback of numerical analysis is the lengthy time needed to run simulations for approximating real operating conditions outcomes.

Taguchi Results

The experimental list's Ra and Fz values are converted into signal-to-noise (S/N) ratio using the Taguchi method. The objective is to optimize the cutting factors, as shown in Table 6. The S/N ratio is chosen as smallest best for achieving the lowest values in both outcomes. In the 7th experiment, the maximum S/N ratio value of -3.69383 dB for Ra is found to be the most significant. The experiment yields a Fz measurement of -51.3640 dB.

Table 6. Experimental Ra and Fz Values

Exp. No	A	B	Ra (µm)	Ra (µm) - S/N (dB)	Fz (N)	Fz (N) - S/N (dB)
E1	15	30	1.84	-5.29636	404	-52.1276
E2	15	40	1.92	-5.66602	504	-54.0486
E3	15	50	2.04	-6.19260	625	-55.9176
E4	20	30	1.62	-4.19030	370	-51.4342
E5	20	40	1.76	-4.91025	434	-52.7498
E6	20	50	1.81	-5.15357	522	-54.3534
E7	***25***	***30***	***1.53***	***-3.69383***	***373***	***-51.3640***
E8	25	40	1.61	-4.13652	414	-52.3400
E9	25	50	1.68	-4.50619	493	-53.8569

Taguchi's findings on the order of effectiveness of the shear factors concerning Ra and Fz are presented in Table 7. The study reveals that the feed rate (B) has the greatest impact on surface roughness (Ra), while the cutting speed (A) is the most significant factor in determining Fz.

Table 7. Signal-to-Noise (S/N) Ratio Response Table by Smallest Best

	Ra					Fz (N)				
Control factors	**Level 1**	**Level 2**	**Level 3**	**Delta**	**Rank**	**Level 1**	**Level 2**	**Level 3**	**Delta**	**Rank**
S/N (dB)										
Cutting speed (A)	-5.718	-4.751	-4.112	1.606	1	-54.03	-52.85	-52.52	1.51	2
Feed rate (B)	-4.393	-4.904	-5.284	0.891	2	-51.64	-53.05	-54.71	3.07	1
Means										
Cutting speed (A)	1.933	1.730	1.607	0.327	1	511.0	443.0	425.7	85.3	2
Feed rate (B)	1.663	1.763	0.180	0.180	2	382.3	450.7	546.7	164.3	1

Figures 7 and 8 present the optimal parameter values for Ra and Fz. Figure 7 illustrates that the optimal cutting speed (A) for achieving Ra is 25 m/min, while the optimal feed rate (B) is 30 mm/min.

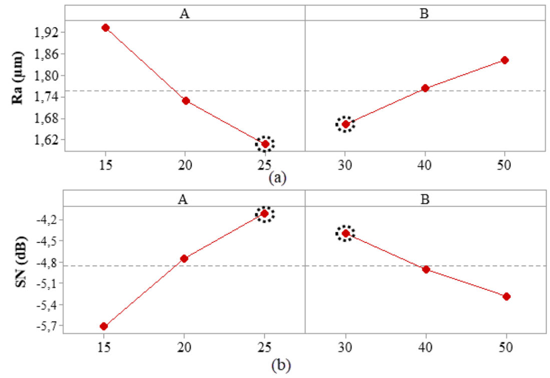


Figure 7. Optimum levels of control factors on Ra

The optimal values for the Fz can be observed in Figure 8, where a cutting speed of 25 m/min (A) and a feed rate of 30 mm/min (B) were found to be ideal, as indicated by the Ra values. The A3B1 index for Ra and Fz can be derived from the obtained results, indicating the sequence of optimal control factor levels.

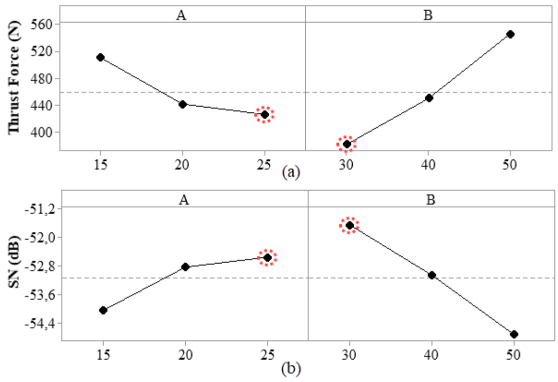


Figure 8. Optimum levels of control factors on Fz

ANOVA Results

Table 8 presents the ANOVA outcomes for Ra and Fz. The table displays the percentage effect degree of the cut-off factors for each factor. The cutting speed (A) contributes to 76.22% of Ra, while the feed rate (B) contributes for 22.78%. The contribution of feed rate (B) to Fz is 73.42%, while cutting speed (B) contributes 21.92%. All factors are found to be significant for both Ra and Fz. In ANOVA results, cutting speed contributed the most to Ra (Yaka 2021), feed rate contributed the most to Fz (Sur and Erkan 2018).

Table 8. Analysis of Variance (ANOVA) Results

Source	Degree of Freedom (df)	Contribution %	Sum of squares (SS)	Mean square (MS)	F Value	P
Ra						
A	2	76.22	0.163267	0.081633	153.06	0.0002
B	2	22.78	0.048800	0.024400	45.75	0.0018
Error	4	1.00	0.002133	0.000533		
Total	8	100.00				
Fz						
A	2	21.92	12206	6103.1	9.41	0.031
B	2	73.42	40891	20445.4	31.53	0.004
Error	4	4.66	2594	648.4		
Total	8	100.00	55691			

Table 9 presents a concise overview of the results obtained from the analysis of variance. The R^2 value presented in Table 9 indicates the degree of confidence in the model. The model developed for Ra was established with a confidence level of 99%, while the model for the Fz was established with a confidence level of 95.34%. Given that the aforementioned values exceed the 95% confidence threshold, it is reasonable to assert that the research is reliable.

Table 9. Summary of ANOVA Model

	S	R^2	R^2 mean	PRESS	R^2 (pred)	AICc	BIC
Fz	25.4646	95.34%	90.69%	13131	76.42%	130.51	89.70
Ra	0.0230940	99.00%	98.01%	0.0108	94.96%	4.42	-36.40

CONCLUSION

This study examines the experimental and finite element analysis of drilling AISI D2 cold work steel using a TiN coated drill. The Fz values during drilling were evaluated and compared with the Fz values obtained in the finite element analysis. In addition, as a result of the experimental study, the surface roughness of the hole surfaces was measured. Machining parameters were determined for minimum Ra and Fz.

• Fz values measured by the finite element method were 7% and 8% lower than the Fz values obtained by experimental results. In the experimental study, the high Fz was caused by the compression of the chips during drilling, the tool wear and vibrations.

- The cutting speed (A) was the most significant factor in determining Fz.
- The feed rate (B) was the greatest impact on surface roughness (Ra).
- Ra and Fz values were smaller at low feed rate and high cutting speeds.
- The results obtained for the Fz measurements were close to the experimental and simulation results.

Conflict of Interest

The article authors declare that there is no conflict of interest between them.

Author's Contributions

The authors declare that they have contributed equally to the article.

REFERENCES

Aized, T., & Amjad, M. (2013). Quality improvement of deep-hole drilling process of AISI D2. *The International Journal of Advanced Manufacturing Technology*, 69, 2493-2503.

Akıncıoğlu, S., Mendi, F., Çiçek, A., & Akıncıoğlu, G. (2013). Prediction of thrust forces and hole diameters using artificial neural networks in drilling of AISI D2 tool steel with cemented carbide tools. *Academic Platform-Journal of Engineering and Science*, 1(2), 11-20.

Akıncıoğlu, G., Mendi, F., Çiçek, A., & Akıncıoğlu, S. (2017). Taguchi optimization of machining parameters in drilling of AISI D2 steel using cryo-treated carbide drills. *Sādhanā*, 42, 213-222.

Akkuş, H., & Yaka, H. (2021). Optimization of cutting parameters in turning of titanium alloy (grade 5) by analysing surface roughness, tool wear and energy consumption. *Experimental Techniques*, 1-12.

Anthony, X. M. (2015). Analysis of cutting force and chip morphology during hard turning of AISI D2 steel. *Journal of Engineering Science and Technology*, 10(3), 282-290.

Bademlioglu, A. H., Canbolat, A. S., & Kaynakli, O. (2020). Multi-objective optimization of parameters affecting Organic Rankine Cycle performance characteristics with Taguchi-Grey Relational Analysis. *Renewable and Sustainable Energy Reviews*, 117.

Basavarajappa, S., Chandramohan, G., & Davim, J.P. (2008). Some studies on drilling of hybrid metal matrix composites based on Taguchi techniques. *Journal of Materials Processing Technology*, 196, 332–338.

Chou, C.W.C., Liu, X.D. (2000). Study on the various coated twist drills for stainless steels drilling. *Journal of Materials Processing Technology*, 99, 226-230.

Çakır, M.C. (2000). *Modern talaşli imalat yöntemleri*. Bursa: Vipaş.

Çırakoğlu, F., Özlü, B., Demir, H. (2021). Hardox 450 çeliğinin lazerle delinmesinde kesme parametrelerinin delik kalitesi üzerine etkisinin incelenmesi ve kesme parametrelerinin optimizasyonu. *Bilecik Şeyh Edebali Üniversitesi Fen Bilimleri Dergisi*, 8(2), 913-923.

Çiçek, A. Kıvak, T. & Samtaş, G. (2012). Application of Taguchi method for surface roughness and roundness error in drilling of AISI 316 stainless steel”. *Strojniški Vestnik - Journal of Mechanical Engineering*, 58(3), 165-174.

Duran, A.& Acır, A. (2004). HSS torna kalemindeki talaş açisinin kesme kuvvetlerine etkisi. *Polytechnic Journal*, 211-215.

Jena, S. P., Mahapatra, S., & Acharya, S. K. (2021). Optimization of performance and emission characteristics of a diesel engine fueled with Karanja biodiesel using Grey-Taguchi method. *Materials Today: Proceedings*, 41, 180-185.

Kumar, P., Singh, G., Jain, V., & Gupta, D. (2018). Optimization of process parameters for improving drilling quality and machining performance of abrasive assisted drilling on AISI D2 steel. *Indian Journal of Engineering & Materials Sciences*, 25, 33-41.

La Monaca, A., Murray, J. W., Liao, Z., Speidel, A., Robles-Linares, J. A., Axinte, D. A., ... & Clare, A. T. (2021). Surface integrity in metal machining-Part II: Functional performance. *International Journal of Machine Tools and Manufacture*, 164, 103718.

Li, G., Huang, Z., & Wang, X. (2017). The FEM simulation on end mill of plastic doors and windows corner cleaning based on deform-3D. *In IOP Conference Series: Materials Science and Engineering*, 272(1), 012009.

Luo, H., Fu, J., Wu, T., Chen, N., & Li, H. (2021). Numerical simulation and experimental study on the drilling process of 7075-t6 aerospace aluminum alloy. *Materials*, *14*(3), 553.

Malo, Y., Yaka, H. (2023). Evaluating the parameters for electrode wear rate in electrical discharge machining of H13 steel. *Selcuk University Journal of Engineering Sciences*, 22(1), 33-37.

Mustapha, A. N., Zhang, Y., Zhang, Z., Ding, Y., Yuan, Q., & Li, Y. (2021). Taguchi and ANOVA analysis for the optimization of the microencapsulation of a volatile phase change material. *Journal of Materials Research and Technology*, 11, 667-680.

Nosouhi, M., Nosouhi, R., Paktinat, H., & Amini, S. (2017). Finite element analysis and experimental investigation on the conventional and vibration assisted drilling. *Journal of Modern Processes in Manufacturing and Production*, *6*(4), 23-33.

Nguyen, T. C., Miska, S., Saasen, A., & Maxey, J. (2014). Using Taguchi and ANOVA methods to study the combined effects of drilling parameters on dynamic barite sag. *Journal of Petroleum Science and Engineering*, 121, 126-133.

Raju, B. P., & Swamy, M. K. (2012). Finite element simulation of a friction drilling process using deform-3D. *International Journal of Engineering Research and Applications*, 2(6), 716-721.

Shapiro, A. (2009). Finite element modeling of hot stamping. *Steel Research International*, 80, 658.

Sharif, S., & Rahim, E.A. (2007). Performance of coated and uncoated-carbide tools when drilling titanium alloy-Ti–6Al4V. *Journal of Materials Processing Technology*, 185, 72-76.

Osman, M. H., Hadzley, M., Tamin, N. F., Mohamad, N. J., Wahid, M. K., Ahmad, M. N., ... & Ab Rahman, M. H. (2017). Optimization of drilling parameters in diameter accuracy on dry drilling process of AISI D2 tool steel. *Proceedings of Mechanical Engineering Research Day*, 105-106.

Osman, M. H., Tamin, N. F., Ahmad, M. N., Rahman, M. A., Wahid, M. K., Maidin, N. A., ... & Azahar, A. A. (2018). Effect of cutting parameters on surface roughness in dry drilling of AISI D2 tool steel by using Taguchi method. *Journal of Advanced Manufacturing Technology (JAMT),* 12(1 (2)), 535-546.

Özlü, B. (2021). Investigation of the effect of cutting parameters on cutting force, surface roughness and chip shape in turning of Sleipner cold work tool steel. *Journal of the Faculty of Engineering and Architecture of Gazi University,* 36(3), 1241-1251.

Özlü, B., Çelik, U., Demir, H. (2023). Serbest Formlu İnce Cidarlı AA 5083-H111 Alaşımının Frezelenmesinde Kesme Parametrelerinin Yüzey Pürüzlülüğü Üzerine Etkilerini Deneysel ve İstatiksel Değerlendirilmesi. *Afyon Kocatepe Üniversitesi Fen ve Mühendislik Bilimleri Dergisi*, 23(2), 512-522.

Sur., G., Erkan, Ö. (2018). Cutting tool geometry in the drilling of CFRP composite plates and Taguchi optimisation of the cutting parameters affecting delamination. Sigma Journal of Engineering and Natural Sciences, 36(3), 619-628.

Uğur, L., Kazan, H., Özlü, B. (2022). Investigation of the Impacts of Cutting Parameters on Power Usage in Cryogenic-Assisted Turning of AISI 52100 Bearing Steel by FEM. *İmalat Teknolojileri ve Uygulamaları*, 3(3), 55-61.

Ulaş, H. B. (2018). AISI D2 ve AISI D3 soğuk iş takım çeliklerinin delinmesinde kesme parametrelerinin kesme kuvvetleri üzerindeki etkisinin incelenmesi. *Polytechnic Journal*, 21(1), 251-256.

Yaka, H. (2021). Measurement of Surface Quality and Optimization of Cutting Parameters in Slot Milling of Gfrp Composite Materials with Different Fiber Ratios Produced by Pultrusion Method. *Surface Review and Letters*, 28(10), 2150095.