İmalat Teknolojileri ve Uygulamaları
Cilt: 3, No: 3, 2022 (8-19)
Araştırma Makalesi
e-ISSN: 2717-7475

Manufacturing Technologies and Applications
Vol: 3, Issue: 3, 2020 (8-19)
Research Article
e-ISSN: 2717-7475

Analyzing the Effects of Cutting Parameters on Machinability Criteria in Milling of 17-4PH Stainless Steel under Dry Environment

Hakan YURTKURAN[1,*], Mustafa GÜNAY[2]

[1] *Yozgat Bozok University, Akdağmadeni Vocational School, Yozgat, Turkey*

[2] *Karabük University, Faculty of Engineering, Karabük, Turkey*

ARTICLE INFORMATION

Received: *28.09.2022*
Accepted: *10.11.2022*

Keywords:
17-4 PH
Milling
Cutting force
Energy consumption
Surface roughness

ABSTRACT

17-4PH steel is a martensitic precipitation hardening stainless steel with an excellent convenience of good corrosion resistance and high mechanical properties. At the same time, it has been determined from the literature that very little research has been done on the milling of this steel, which is one of the materials that are difficult to process. Therefore, an experimental research was focused on the milling of the steel with coated carbide inserts in a dry cutting environment, which is an eco-friendly cutting regime. In the experiments performed with the up milling technique, the changes in the resultant cutting force (*Fr*), surface roughness (Ra) and total cutting power or energy consumption (Pc_T) during machining were investigated. Experiments were performed according to the L_9 experimental design by choosing three different cutting speeds (*V*), feed rate (*f*) and cutting depth (*ap*). *Fr* values were calculated with the help of cutting force components measured with Kistler brand dynamometer and equipment. The magnitude of *Fr* mostly depends on the cutting depth (64.92%) and then the feed rate (30.26%), and it was determined that the forces relatively decreased with the increase in cutting speed. While Ra was mainly affected by the feed rate (65.52%), it was observed that the cutting speed had a substantial positive effect (33.78%). According to the Pc_T results, although the energy consumption owing to the spindle speed increased at high cutting speed without changing the chip cross-section, the decrease in material strength as a result of the increased cutting temperature led to a decrease in the total energy consumption. However, the lowest value was obtained at the smallest levels of the machining parameters.

17-4PH Paslanmaz Çeliğin Kuru Ortamda Frezelenmesinde Kesme Parametrelerinin İşlenebilirlik Kriterlerine Etkilerinin İncelenmesi

MAKALE BİLGİSİ

Alınma: *28.09.2022*
Kabul: *10.11.2022*

Anahtar Kelimeler:
PH 17-4
Frezeleme
Kesme kuvveti
Enerji tüketimi
Yüzey pürüzlülüğü

ÖZET

17-4PH çelik, iyi korozyon direnci ve yüksek mekanik özelliklerin olağanüstü bir uyumuna sahip olup martensitik çökeltme ile sertleşen bir paslanmaz çeliktir. Aynı zamanda, işlenebilirliği zor olan malzemelerden olan bu çeliğin özellikle frezelenmesi üzerine yok denecek kadar az araştırma yapıldığı literatürden belirlenmiştir. Bu nedenle, söz konusu çeliğin kaplamalı karbür uçlar ile çevreye duyarlı bir kesme rejimi olan kuru kesme ortamında frezelenmesi üzerine deneysel bir araştırmaya odaklanılmıştır. Zıt yönlü frezeleme tekniği ile yapılan deneylerde, işleme sırasında ortaya çıkan bileşke kesme kuvveti (*Fr*), yüzey pürüzlülüğü (Ra) ve toplam kesme gücü veya enerji tüketiminin (Pc_T) kesme parametrelerine göre değişimleri araştırılmıştır. Üç farklı kesme hızı (*V*), ilerleme oranı (*f*) ve kesme derinliği (*ap*) seçilerek L_9 deneysel tasarıma göre deneyler yapılmıştır. Kistler marka dinamometre ve ekipmanları ile ölçülen kesme kuvveti bileşenleri yardımıyla *Fr* değerleri hesaplanmıştır. *Fr*'nin büyüklüğü daha çok kesme derinliği (%64.92) ve ardından ilerleme miktarına (%30.26) bağlı olup, kesme hızının artmasıyla kuvvetlerin nispeten azaldığı belirlenmiştir. Ra ise esasen ilerleme oranı (%65.52) etkilenirken, kesme hızının küçümsenmeyecek düzeyde olumlu bir etkiye (%33.78) sahip olduğu görülmüştür. Pc_T sonuçlarına göre, talaş kesiti değişmeksizin, yüksek kesme hızında

***Sorumlu yazar, e-posta:** *hakan.yurtkuran@bozok.edu.tr*
To cite this article: *H. Yurtkuran, M. Günay, Analyzing the Effects of Cutting Parameters on Machinability Criteria in Milling of 17-4PH Stainless Steel under Dry Environment, Manufacturing Technologies and Applications, 3(3), 8-19, 2022. https://doi.org/10.52795/mateca.1181213,* *This paper is licensed under a CC BY-NC 4.0*

fener mili devir sayısına bağlı enerji tüketimi artmasına rağmen, artan kesme sıcaklığı yüzünden malzeme dayanımındaki azalma toplam enerji tüketiminin azalmasını sağlamıştır. Bununla birlikte, en düşük Pc_T değeri kesme parametrelerinin en küçük seviyelerinde elde edilmiştir.

1. INTRODUCTION (GİRİŞ)

The developments in the aviation industry have enabled the development of factors such as correct use of time in machinability and appropriate cost by reviewing production technologies, especially material quality. Accurate analysis of the machinability processes of PH (precipitation hardening) stainless steels, which are particularly difficult to process and weld, plays an important role in reducing the machinability costs [1,2]. 17-4PH stainless steel is a martensitic PH type, which has the great strength of martensitic stainless steel along with superb corrosion resistance of austenitic stainless steel. Aircraft engine parts, gears, chemical apparatus, nuclear reactor and ship board components etc. Many important apparatuses in industrial applications such as these are produced by shaping this material [3]. It is becoming a quite new and progressively popular material for medical devices, as well as being frequently used in the defense industry and aerospace industry due to its superior mechanical properties and high corrosion resistance. In particular, many of the surgical and orthopedic instruments can be produced using conventional or unconventional manufacturing methods [4,5].

On the other side, the machinability of 17-4PH material is poor due to bad surface quality as well as chip formation with built up edge creation in carbide tools due to high cutting temperatures during machining [6]. As is known, one of the key factors defining the efficacy of material use is surface topography. Biomedical material has an important effect on the working properties of parts, especially on wear and corrosion characteristics [7]. However, changing cutting parameters during machining operations such as turning, milling, drilling, etc. can seriously alter surface integrity properties for example surface roughness, residual stress, and microstructure. It has been proven that surface properties can significantly affect the facility performance of components such as fatigue life and corrosion resistance [8,9]. Besides, the milling method is often used in the production of various machine parts, especially in the aerospace, automotive, aerospace, molding and cutting tool industries. Depending on the milling kinematics, two types of milling operations are applied as down milling and up milling, and the surface roughness and cutting forces change according to these milling types [10]. At the same time, estimation or measurement of cutting forces is an important factor for reducing power consumption in machining process. By optimizing the cutting parameters such as cutting speed, cutting depth and feed rate, reducing the cutting force can directly regulate the energy consumption in the metal cutting industry, resulting in a greener and more environmentally friendly production process [11]. In general, estimation models developed for calculating cutting forces require a measured cutting force profile [12]. Literature studies show that the direct measurement of cutting force is more convenient than the data obtained from cutting simulations based on material models, and advanced cutting force measurement dynamometers are used for these studies, which can make simultaneous measurements throughout the machining process and can be adapted to any machine tool [11,13]. It provides substantial records about the procedure, such as cutting forces, design of bench tools, machining equilibrium, and even estimation of tool wear and energy consumption. Machine tools have great influence for energy efficiency advances and carbon emission reduction. Because a 1% drop in energy consumption with processing activities can save ~55 kWh/year. In addition, reducing energy consumption in the processing process is a way to minimize the environmental effect of production [14]. In this context, researches on the power consumption of bench tools and the surface quality is very important, and with existing processing equipment in the manufacturing industry, ensuring energy-saving production while advancing surface quality in machining is a critical issue in reducing energy consumption [15]. Some of the recent works on the machining of PH stainless steels are summarized below.

Leksycki et al. analyzed changes in chip forms and surface structure in machining 17-4PH steel in dry, wet and near-dry machining for a certain range of feed and cutting speeds. Under dry, wet, minimum quantity lubrication (MQL) and high pressure MQL environments, small curved chips suitable for the cutting speed of 456 m/min and feed rate of 0.27 mm/rev were obtained. Matched to dry machining, there was a 38-48% reduction in the parameters Sa, Sq, and Sz for the near-dry condition. Depending on the processing conditions, it was determined that different textures were formed on the machined surfaces, especially with anisotropic mixture and periodicity. Surface isotropy was found in the range of ~6-10% under all studied cooling conditions, with Sa= 0.8–15.0 mm [16]. Palanisamy et al. investigated the performance of three types of tools; conventional, horizontal texture and diamond texture on tangential cutting force, surface roughness, and insert wear in semi-solid lubrication (MoS_2) condition when turning 15-5PH stainless steel. It has been detected that the diamond-textured cutting tool performs better in reducing cutting force and tool wear, and also improves surface quality [17]. Sivaiah and Chakradhar investigated the effects of LN_2 coolant and process parameters on temperature (T), tool wear, MRR, surface topography and microhardness during machining 17-4PH material. Test results shown that Mode-I (modified toolholder cooling) reduced T and tool wear by up to 61% and 29%, respectively, compared to Mode-II (classical cryogenic cooling). In addition, it was emphasized that Mode-I approach positively affects surface properties according to Mode-II approach and this will lead to a significant improvement in final product performance [1]. Liu et al. investigated the insert damage process and its effects on machined surface roughness in high speed milling of 17-4PH stainless steel. Although fracture, adhesive and diffusion wears contribute to insert damage, it has been found that the insert is more prone to damage from fatigue fracture at lower cutting speed and from peeling when speed is increased. During the machining, the mean roughness and deflection from the processed surface increased considerably after notch wear. The spindle vibration caused by bit damage and the large clearance between the tool edge and the workpiece cause severe chip wrapping as well as scratches and ridges [18]. Basmacı et al. examined the effects of feed rate, cutting depth and insert radius on surface roughness and cutting force when turning 17-4PH steel in dry cutting condition with wiper and conventional inserts. While test results verify the efficiency of wiper tips in providing excellent surface roughness, the most useful factor for Ra is feed. In terms of cutting force, depth of cut was found to be the main factor for both cutter geometries. On the other hand, tip radius is a secondary factor for surface roughness after feed [19]. Ondin et al. investigated the changes in surface topography and insert wear during turning of PH13-8 Mo steel by PVD TiAlN-$(AlCr)_2O_3$ tool in dry, pure-MQL and nanofluid-MQL cutting regimes. Comparing the dry cutting, about 5% and 12% lower surface roughness was obtained with MQL and nanofluid-MQL, respectively. Similarly, flank wear was 40.2% and 69% lower under MQL and nanofluid-MQL. On the other hand, they emphasized that nanofluids have some disadvantages such as high production cost, machining steadiness, uniform distribution of nanoparticles, increased pumping power and pressure fall [20]. Liu et al. conducted a study on fatigue performance after machining 17-4PH stainless steel using surface integrity changes and three-point bending tests. Fatigue performance generally tended to decrease with increasing cutting speed due to increased plastic deformation and strain hardening. The fatigue performance of the machined samples decreased rapidly at first as the cutting depth increased due to the ever-increasing plastic deformation. Because of the curved propagation tracks, the effects on fatigue life were overshadowed when the surface roughness changes were small [21]. Popovici and Dijmărescu analyzed the effect of cutting parameters (axial and radial cutting depth, cutting and feed speed) on surface quality once machining 17-4PH steel with the same direction milling regime using carbide end mills. Experimental results showed that the biggest effect on the Ra belonged to the radial cutting depth, and Ra increased by the rise of cutting parameter. It was stated that the smallest effect on the surface roughness belonged to the cutting speed [22].

When the literature is evaluated, it has been determined that the researches on surface quality, cutting force, tool wear and energy consumption in the processing of PH group steels are mostly done by using the turning method. However, in rare studies on milling 17-4PH steel, it is understood that only the effects of cutting parameters on surface roughness were investigated. Therefore, the presented research investigated the changes in cutting force, surface quality and energy consumption during milling of 17-4PH stainless steel in dry cutting regime. Accordingly, it is aimed to contribute to sustainability by optimizing the amount of energy consumed in the milling of a material that is difficult to process.

2. EQUIPMENT AND RESEARCH METHODOLOGY (EKİPMANLAR VE ARAŞTIRMA METODOLOJİSİ)

2.1. Material and Tool (Malzeme ve Takım)

In this study, 17-4PH (630 quality) stainless steel in sizes of 120 × 100 × 20 mm without any heat treatment was used as workpiece. This steel is used for production of parts plays critical roles in many industrial areas, especially in the aerospace and defense industry due to very high mechanical strength and corrosion resistance. The chemical composition and mechanical properties of its in line with the information received from the supplier (Birçelik A.Ş.) are given in Table 1 and Table 2, respectively.

Tablo 1. Chemical composition of 17-4PH steel (wt.%) (17-4PH çeliğin kimyasal bileşimi)

C	Mn	Si	P	S	Cu	Mo	Nb	Cr	Ni
0.07 (max)	1.0	0.7	0.04	0.03 (max)	3-5	0.6 (max)	0.15-0.35	15-17	3-5

Tablo 2. Mechanical specification of 17-4PH steel (17-4PH çeliğin mekanik özellikleri)

Tensile strength (MPa)	Yield strength (MPa)	Percentage elongation (%)	Hardness (HRC)
1094	910	15	36

In the machining experiments, coated carbide inserts with the code APMT11T0308PDSR-MM supplied from KORLOY were used as cutting tools (Figure 1a). As the tool holder, a KORLOY product holder with the code AEM90-AP11-D20-W20-L150-Z03-H was used, which enables the rigid attachment of the cutting tools (Figure 1b).

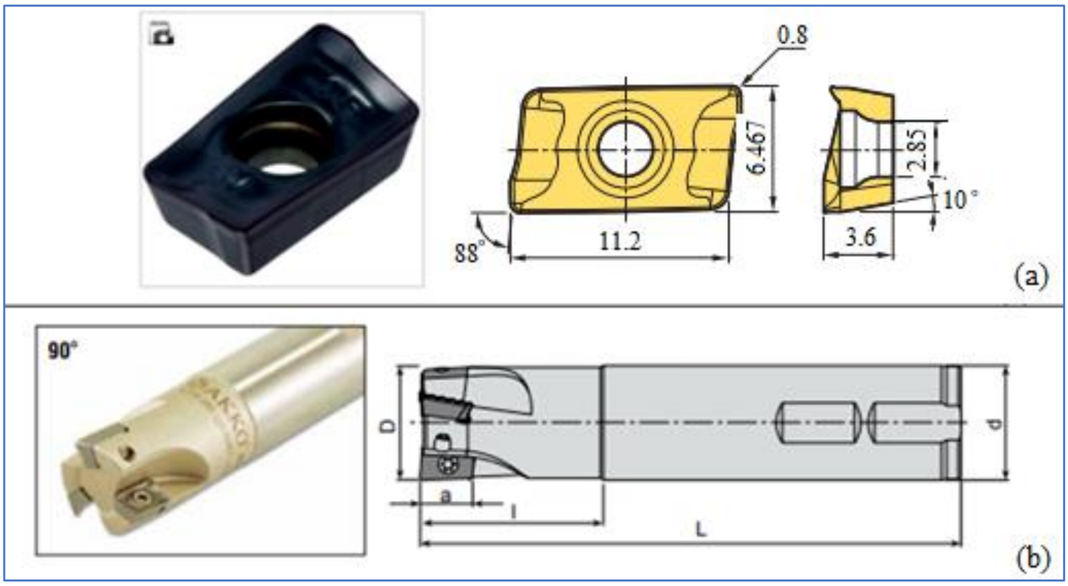

Figure 1. a) Cutting tool and b) Tool holder (a) Kesici takım ve b) Takım tutucu)

2.2. Machinability Criteria Measurement (İşlenebilirlik Kriterleri Ölçümü)

In the milling of 17-4PH stainless steel, cutting force, surface roughness and cutting power are based on machinability criteria. While the resultant force (*Fr*) was taken as the basis for the evaluation of the cutting forces, the average roughness value (Ra) was taken as the basis for the surface roughness. In the analysis of cutting power, the total energy consumption during chip removal was taken into account. The experiments were carried out on the VMC-550 model industrial CNC milling machine. The 5 kW machine can operate at a maximum of 6000 rpm.

Cutting force measurements were performed using a Kistler 9257B piezoelectric dynamometer and a 5070A type amplifier. Then, the cutting force data was converted into graphics using Dynoware software. Experiments were carried out using the up milling method (Figure 2). Though three inserts can be mounted to the holder, a single insert was milled to clearly observe the tool quality performance. Symmetrical face milling operations were applied in a dry cutting rejime and machining length was 100 mm. Here, the *Fx* component (force in the X direction), the *Fy* component (force in the Y direction) and the *Fz* component (force in the Z direction) are the cutting forces occurring in the three axes. The experimental setup used to measure cutting forces is shown in Figure 2.

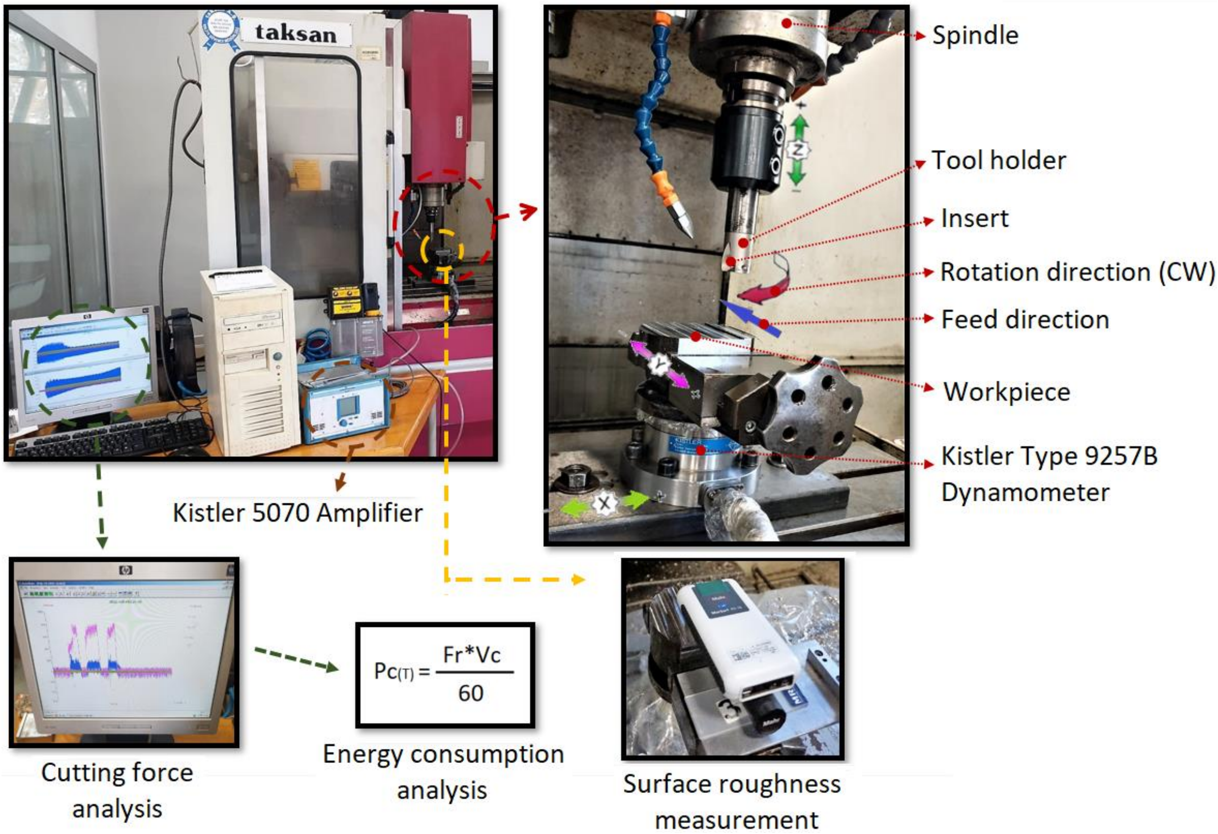

Figure 2. Experiment and analysis processes (Deney ve analiz işlemleri)

In milling, the oblique cutting theory is valid, and naturally there are three force components. Instant cutting forces in *Fx*, *Fy* and *Fz* directions were recorded when the cutting tool reached the maximum chip height using Dynoware software. Also, the force in the Z direction (*Fz*) has a value that cannot be underestimated due to the radius at the insert. Therefore, the resultant cutting force (*Fr*) resulting from the three force components was calculated (Eq.1).

$$Fr = \sqrt{(Fx^2 + Fy^2 + Fz^2)} \quad (1)$$

The surface roughness (Ra) was selected as the secondary machinability criterion, and was measured according to the international norm (ISO 4287). Ra values were recorded by MarSurf M300 device by applying a cutting and sampling length, 0.8 mm and 5 mm, respectively. The roughness measurements were made from three regions (front, middle and end) along the cutting length and evaluated by averaging them.

Energy or power consumption, which is the third machinability criterion in the presented research, is an important tool that can be measured or calculated to contribute to sustainability in metal cutting processes. On the other hand, the cutting power (Pc) in the bench tool mostly depending on the machining parameters. Reducing the cutting force by optimizing the cutting parameters can directly regulate the power consumption in machining applications, thus enabling a greener and more eco-friendly production process. So, the specific cutting energy can be used to estimate the total power consumption of the bench tool in machining. This expression is labeled as the power or energy required to remove 1 mm^3 of material. In brief, specific energy consumption is the ratio of Pc to MRR, which is a function of cutting parameters. In this context, Pc is one of the main machinability criterions that affect tool life, dimensional precision of part and machining efficiency. Energy consumption can be measured as well as calculated using cutting force data. Eq.2 is usually applied to calculate the power (in kW) required for removing the material in milling [23].

$$Pc = (ae * ap * Vf * ks)/(60 * 10^6 * n) \quad (2)$$

Here, cutting depth (ap in mm), cutting width (ae in mm), table feed speed (Vf in mm/min), specific cutting force or energy (ks in J/mm^3) and machine efficiency (n) has been determined. The ks value is the specific cutting resistance of the material and varies according to the cutting parameters. In this context, in turning and milling operations, the power consumption can be obtained as an occupation of the cutting force (Fc) and cutting speed (Vc) (Eq.3). In the presented study, the total cutting power or energy consumption for each test condition was calculated using Eq.4.

$$Pc = (Fc * Vc)/60 \quad (3)$$

$$Pc_T = (Fr * Vc)/60 \quad (4)$$

2.3. Experimental Design and Analysis (Deney Tasarımı ve Analiz)

The cutting parameters and values to be used in the experimental design are given in Table 3. Cutting speed, feed rate and cutting depth were determined by considering the recommendations of the tool manufacturer and the machinability properties of PH group steels in the literature. Accordingly, three different cutting speeds (90-150 m/min), feed (0.05-0.15 mm/rev) and cutting depth (0.5-1.5 mm) were selected. Milling experiments were done using the Taguchi L_9 orthogonal array (Table 3).

Table 3. Experimental design (Deney tasarımı)

Exp.no	*V*, m/min	*f*, mm/rev	*ap*, mm
1	90	0.05	0.5
2	90	0.1	1
3	90	0.15	1.5
4	120	0.05	1
5	120	0.1	1.5
6	120	0.15	0.5
7	150	0.05	1.5
8	150	0.1	0.5
9	150	0.15	1

In addition, variance analysis at 95% significance level was applied to analyze the influence ranks of cutting parameters on the machinability criteria taken into account in the milling of 17-4PH steel. Minitab software was used for experimental design and statistical analysis.

3. RESULTS AND ASSESSMENT (SONUÇLAR VE DEĞERLENDİRME)

In this study, the changes in cutting forces, surface roughness and energy consumption versus the cutting parameters were analyzed in the machining of 17-4PH steel with the counter milling technique. With the help of the data obtained as a result of the experiments, interaction graphs were drawn depending on the cutting parameters for all machinability criteria.

3.1. Resultant Cutting Force (Bileşke Kesme Kuvveti)

Cutting forces offers valuable data on processes such as project of machine tools, machining stability, and even predicting tool wear and energy consumption. In this context, the arithmetical averages were taken for each force component (*Fx, Fy* and *Fz*) measured as a result of repeated experiments. Later, the resultant cutting forces were calculated via the force components measured in the milling process with a coated carbide insert. In Figure 3, the variation of cutting parameters and *Fr* values is presented graphically.

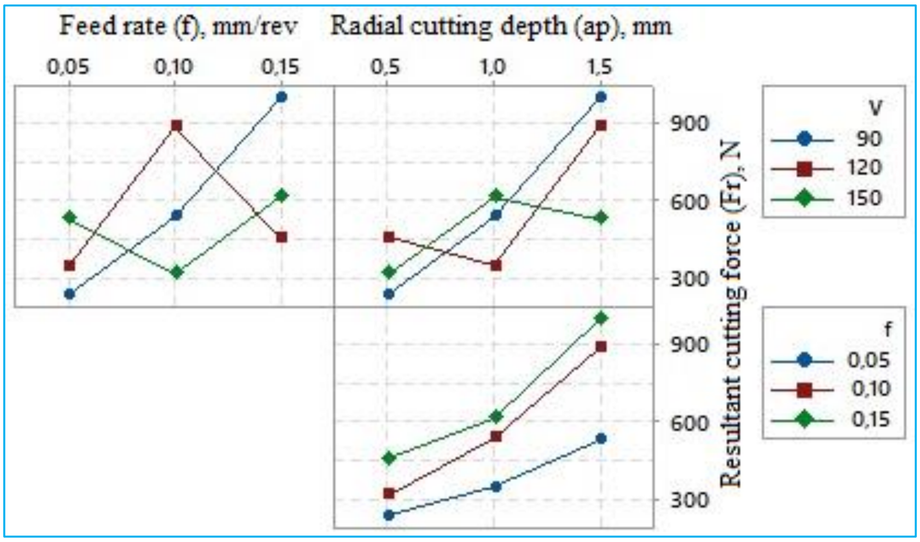

Figure 3. Variation of Fr versus cutting parameters (Kesme parametrelerine karşılık Fr'nin değişimi)

As can be seen from the interaction graphs in Figure 3, when the cutting speed is kept constant, the changes in the resultant force can be clearly seen in the feed rate-cutting depth interaction. The highest *Fr* value (883.07 N) obtained in the experiments was reached at the lowest cutting speed and the highest feed and cutting depth (*f*=0.1 mm/rev, *ap*=1.5 mm). It is expected that the resultant cutting force will increase with the increase of cutting depth and feed rate. This outcome is ascribed to the increase in the chip cross-sectional area (*ap* x *f*) with the increase in the feed rate, similar to the studies in the literature [24, 25]. In other words, the cutting area gradually enlarges with increasing the cutting depth and feed rate, and therefore increasing the overall deformation resistance or raising the power necessary for chip formation [26]. When the graph is examined, it can be said that the changes in *Fr* in the cutting speed-cutting depth and cutting-feed speed interactions have a complex trend except for the cutting speed of 90 m/min. This is mainly dependent on the experimental design and may be partly related to the cutting temperature, which varies by the cutting speed. For example, although the chip cross-section was the same in the 5th and 9th experiments, which can be understood Table 3, *Fr* was measured lower at 150 m/min cutting speed. The reason for this is the drop in material strength owing to high cutting temperature at the higher cutting speed, as mentioned in Ref. [27]. At the same time, especially in the machining of ductile materials, the built-up edge (BUE) creation is reduced once high cutting speed is applied, and the cutting force is stabilized. In the milling of 17-4PH steel, the smallest *Fr* value was obtained as 235.25 N under the 1st experiment condition.

3.2. Surface Roughness (Yüzey Pürüzlülüğü)

The changes in the mean surface roughness (Ra) according to the cutting parameters during the milling of 17-4PH steel in the dry cutting regime are shown in the graphs in Figure 4.

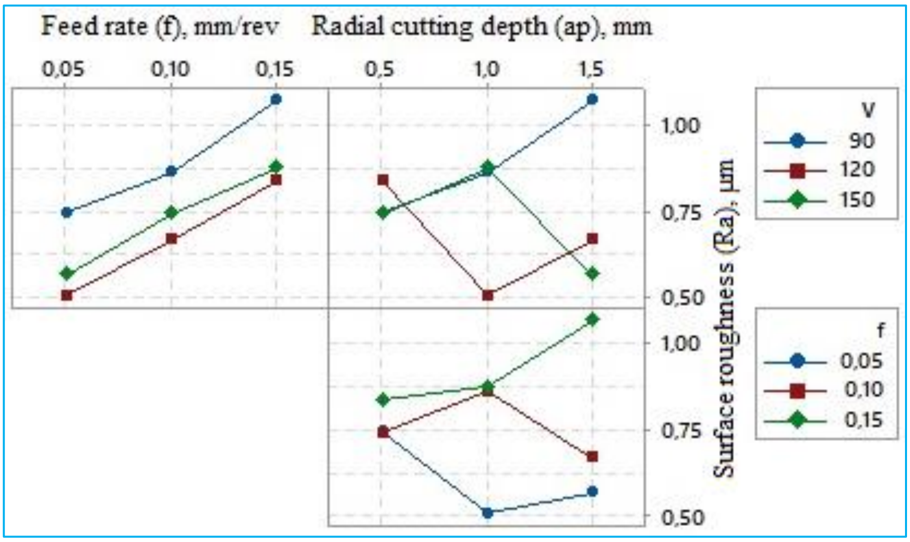

Figure 4. Variation of Ra versus cutting parameters (Kesme parametrelerine karşılık Ra'nın değişimi).

When the surface roughness changes are examined, it is clearly seen that the Ra values increase with the increase in the feed rate, similar to the results obtained in the processing of various materials [28, 29]. This result is similar in all machining methods and is clearly evident in milling, where an interrupted cutting operation takes place. On the other hand, it is seen from the *V-f* interaction that the cutting speed has a positive effect on the surface roughness up to a certain value. At the same time, this positive effect was clearly felt at the middle value of the depth of cut, as can be seen from the *V-ap* interaction. Therefore, the smallest Ra value was measured as 0.427 µm at cutting speed of 120 m/min, the smallest feed rate and cutting depth of 1 mm. This result indicates that the tool holder runout and vibrations are optimum at the mentioned cutting parameters levels. Besides, increasing cutting temperature with increasing cutting speed reduces vibrations, helping to create a more stable cutting, as can be mentioned in literature [26]. From this it can be concluded that a more stable cutting process is experienced up to a certain point at a depth of cut greater than the tool radius. Namely, when the *ap* value is smaller than the tool radius, the cutting process will be rubbing, which will make plastic deformation difficult and increase tool vibrations [23, 30]. As a result, an increase in surface roughness is inevitable. At the same time, the increased cutting forces in both cases contribute to the worsening of the surface quality, especially in up-milling. As a result, an unstable cutting process caused an irregular structure in the surface profile, resulting in an increase in Ra. As can be seen from Figure 4, the highest Ra value was found at the cutting speed of 90 m/min and the highest values of feed rate and cutting depth.

3.3. Energy Consumption (Enerji Tüketimi)

Optimizing energy consumption in production technologies helps both reduce processing costs and create a cleaner environment. So, it is extremely important to calculate the energy consumption spent during the machining of material groups that require experience and time to be processed. In recent years, researchers have focused on the analysis of processing costs of materials that are difficult to process, such as superalloys and PH stainless steels. The fact that there are not enough studies on the milling of PH group steels in the literature reveals that this area needs to be investigated. In Figure 5, the relations between the theoretically calculated total energy consumption (Pc_T) and machining parameters in milling of the 17-4PH stainless steel are given graphically.

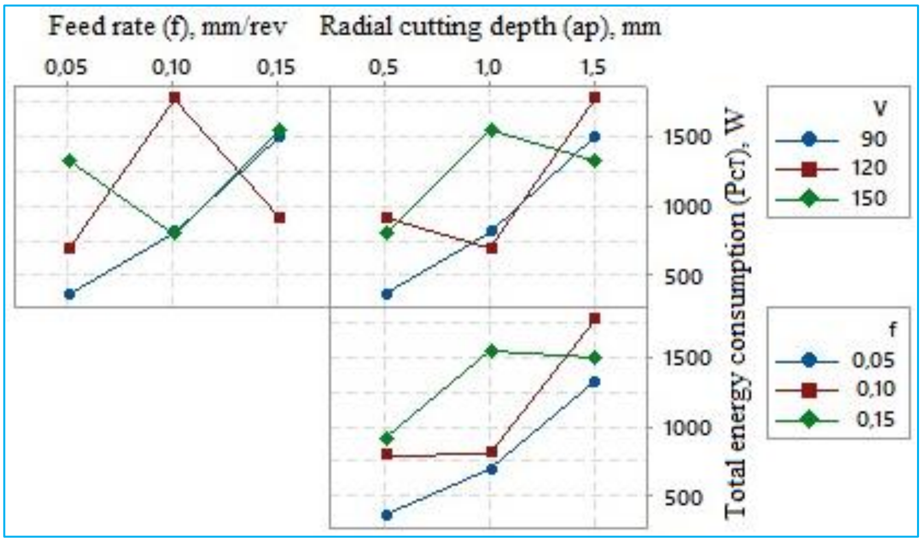

Figure 5. Variation of Pc_T versus cutting parameters (Kesme parametrelerine karşılık Pc_T'nin değişimi).

As can be understood from Figure 8, it is understood that energy consumption exhibits an uneven trend in all interactions of the cutting parameters, except for the experiments performed at a cutting speed of 90 m/min. This is mainly due to the random distribution of the ap value in the last six experiments due to the experimental design (Table 3). However, it is observed that Pc_T is constantly increasing in the feed rate-cutting depth interaction. This result is possible to attribute to the increasing chip cross-section with increasing the feed rate and cutting depth, and therefore the need for more cutting power for chip formation [11]. Therefore, it is inevitable to measure the lowest Pc_T (352.8 W) at the smallest values of the cutting parameters. On the other hand, although the chip cross-section is the same (5th and 9th experiments), the highest total energy consumption is 1766.15 W at 120 m/min. This result can be explained by the energy consumed by the machine spindle and the heat generated during cutting. The increase of cutting speed means the increase in energy consumption due to the increase in the spindle speed of the machine, as can be seen in literature [31]. At the same time, the high cutting temperature caused by the increase in cutting speed causes the material to soften, resulting in a decrease in deformation resistance. From this, it is understood that increasing the cutting speed decreases the cutting force on the one hand and increases the energy consumption on the other hand. Similar results have been obtained in the literature [14], revealing the need for optimum use of cutting speed. As a result, even if the rise in cutting speed increments the energy consumed in the spindle, the decrease in the energy required to form the chip with the decrease of material strength caused Pc_T to be lower at high cutting speed.

3.4. ANOVA for Machinability Criteria (İşlenebilirlik Kriterleri için ANOVA)

In the above sections, the resultant cutting force, surface roughness and energy consumption changes in the interaction of cutting parameters are tried to be explained. However, learning how effective these parameters are on the machinability criteria will be of significant benefit to optimizing the cutting process. At this point, the results of ANOVA applied to determine the effect levels of the parameters in the milling process of 17-4PH steel are given in Table 4.

Table 4. ANOVA for machinability criteria (İşlenebilirlik kriterleri için ANOVA)

Variable	Degree of freedom	Sum of square	Mean of square	F-value	%PCR
Resultant cutting force					
Cutting speed	2	17138	8569	2.18	3.31
Feed speed	2	156909	78454	20	30.26
Cutting depth	2	336633	168316	42.91	64.92
Error	2	7845	3922		1.51
Total	8	518525			100
Surface roughness					
Cutting speed	2	0.08028	0.04014	176.73	33.78
Feed speed	2	0.1557	0.07785	342.78	65.52
Cutting depth	2	0.00121	0.00061	2.66	0.51
Error	2	0.00045	0.00023		0.19
Total	8	0.23764			100
Energy consumption					
Cutting speed	2	173917	86958	1.79	9.78
Feed speed	2	422782	211391	4.34	23.78
Cutting depth	2	1083854	541927	11.13	60.96
Error	2	97389	48694		5.48
Total	8	1777941			100

The ANOVA results indicates that the most effective parameter on Fr and Pc_T is the depth of cut with 64.92% and 60.96% PCR, respectively. The most active parameter for surface roughness is the feed with 65.52% PCR. On the other side, cutting speed was found to be a secondary important cutting parameter for Ra in the machining of 17-4PH steel. The secondary important parameter for Fr and Pc_T was the feed rate, and the effect rates were calculated as 30.26% and 23.78%, respectively. At the same time, it is seen that the cutting speed has an effect of about 10% on the Pc_T. This value has revealed the necessity of optimizing the cutting speed in terms of total energy consumption, especially in the milling of difficult-to-process materials. Because high cutting speed increases the energy consumption depending on the number of revolutions on the one hand, and reduces the energy consumption by providing material softening on the other hand. However, it should be noted that high cutting speed accelerates tool wear, increasing both tool costs and energy consumption, thus negatively affecting sustainable machining.

4. CONCLUSIONS AND SUGGESTIONS (SONUÇLAR VE ÖNERİLER)

The results obtained in dry milling of 17-4PH stainless steel with a coated carbide insert bit are summarized below.

- It has been detected that the resultant cutting force (Fr) increases with increasing the feed rate (f) and the cutting depth (ap), and declines to a certain extent with increasing the cutting speed. This is an expected result; it was found that Fr was most affected by cutting depth according to the ANOVA result. The lowest Fr value was obtained with cutting parameters namely V=90 m/min, f=0.05 mm/rev and ap=0.5 mm.

- According to the surface roughness (Ra) results, the surface quality is significantly affected by the cutting speed as well as the feed rate. At the same time, more stable chip formation that occurs at a certain cutting speed and ap>tool radius minimizes possible tool vibrations and ensures optimum surface roughness. The smallest Ra value (0.427 mm) was obtained at V=120 m/min, f=0.05 mm/rev and ap=1 mm.

- Total energy consumption (Pc_T) naturally increased due to the interaction of the main parameters (*ap* and *f*) forming the chip section. In addition, in the case of the same chip cross-section, although the energy consumed by the machine spindle increases at high cutting speed, the decrease in material strength due to the increase in temperature during machining led to a decrease in total energy consumption. From this, it was concluded that cutting speed is an important parameter to be considered in terms of energy consumption as well as tool wear, especially in milling difficult-to-machine materials.

- The results obtained from the study showed that cutting parameters should be optimized and used in this type of milling operations. In the future, in order to contribute to sustainable processing, it will be useful to conduct research comparing environmentally friendly cutting regimes such as dry cutting and minimum quantity lubrication, vegetable-based cutting oil in terms of processing efficiency in the processing of PH stainless steels.

ACKNOWLEDGMENT (TEŞEKKÜR)

This research was supported by a project carried out within the scope of TÜBİTAK 2209-A.

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