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Investigation of the Impacts of Cutting Parameters on Power Usage in Cryogenic-Assisted Turning of AISI 52100 Bearing Steel by FEM

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ABSTRACT

In this study, the effects of dry, cryogenic cooling (LN_2/CO_2) environments and different cutting parameters on power consumption in turning AISI 52100 bearing steel with finite element analysis (FEA) were investigated. ThirdWave AdvantEdge software was used for FEA. In the analyzes, dry and cryogenic cooling (LN_2/CO_2) as the processing medium, three different cutting speeds (100 m/min, 150 m/min and 200 m/min), three different feed rates (0.1 mm/rev, 0.15 mm/rev and 0.2 mm/rev) and a fixed depth of cut (0.5 mm) were selected as machining parameters. According to the FE analysis results, it was observed that the power consumption in turning of AISI 52100 bearing steel in cryogenic cooling (LN_2/CO_2) environment decreased compared to dry environment in all cutting parameters. In the turning experiments performed in dry and cryogenic cooling (LN_2/CO_2) environments, it was observed that the minimum power consumption was measured at low cutting speeds and high feed rates. In this context, the lowest power consumption was measured as 72 W at 100 m/min cutting speed, 0.2 mm/rev feed rate in LN_2 environment, while the highest power consumption was 217.3 W at 200 m/min cutting speed, 0.1 mm/rev feed rate in dry environment.

AISI 52100 Rulman Çeliğinin Kriyojenik Destekli Tornalama İşleminde Kesme Parametrelerinin Güç Tüketimi Üzerine Etkilerinin FEM ile İncelenmesi

MAKALE BİLGİSİ

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Anahtar Kelimeler:
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Kriyojenik işleme
Güç tüketimi
Sonlu elemanlar metodu

ÖZET

Bu çalışma, sonlu eleman analizi (FEA) ile AISI 52100 rulman çeliğinin tornalanmasında güç tüketimi üzerine kuru, kriyojenik soğutma (LN_2/CO_2) ortamlarının ve farklı kesme parametrelerinin etkileri incelenmiştir. FEA ThirdWave AdvantEdge yazılımı kullanılmıştır. Analizlerde işleme ortamı olarak kuru ve kriyojenik soğutma (LN_2/CO_2) ile işleme parametresi olarak üç farklı kesme hızı (100 m/min, 150 m/min ve 200 m/min), üç farklı ilerleme miktarı (0.1 mm/rev, 0.15 mm/rev ve 0.2 mm/rev) ve sabit kesme derinliği (0.5 mm) seçilmiştir. FE analiz sonuçlarına göre, tüm kesme parametrelerinde kriyojenik soğutma (LN_2/CO_2) ortamında AISI 52100 rulman çeliğinin tornalanmasında güç tüketimi kuru ortama göre azaldığı görülmüştür. Kuru ve kriyojenik soğutma (LN_2/CO_2) ortamlarında yapılan tornalama deneylerinde düşük kesme hızlarında ve yüksek ilerleme miktarlarında minimum güç tüketiminin ölçüldüğü görülmüştür. Bu bağlamda en düşük güç tüketimi 100 m/min kesme hızında, 0.2 mm/rev ilerleme miktarında ve LN_2 ortamında 72 W ölçülürken, en yüksek güç tüketimi 200 m/min kesme hızında, 0.1 mm/rev ilerleme miktarında ve kuru ortamda 217.3 W olmuştur.

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1. INTRODUCTION (GİRİŞ)

Future generations should be concerned about the rise in individual and industrial consumption of the planet finite resources due to the world constantly growing population. Important research is being conducted both in academia and the industry to create sustainable energy resources and production processes to maximize the use of energy resources, which is one of the primary resources, and to limit their impacts on human and environmental health. The manufacturing area constitutes approximately half of energy consumption [1].

The turning process is frequently the preferred manufacturing method among all the manufacturing methods in many industries. The conversion of a significant portion of the energy used in turning into heat can cause various issues, including shortened tool life. During the processing of materials that are called difficult-to-cut materials, much more heat generation and therefore, energy consumption is observed compared to conventional materials. The most commonly used method in the processing of such materials is hot processing, in which local heat is applied to the workpiece with various heat sources [2-4]. Although the processing of difficult-to-cut materials is facilitated by this method, the applied heat causes the cutting tool life to be shortened and the surface quality reduction. While increasing the processing capability of difficult-to-cut materials, another method to eliminate these handicaps caused by hot processing is to decrease the cutting temperature [5, 6]. In addition, processing these materials in a dry environment is not economical since it will cause tool wear [7]. For this purpose, high-pressure water jet coolant is applied to diminish the cutting temperature at the insert [8]. On the other hand, the cooling capacity of the water jet is not sufficient to reach the industrial quality level in the turning of difficult-to-machine materials. For this reason, cryogenic fluid-assisted turning has been frequently used to reduce the risk of high tool wear and improve surface quality [9, 10]. The literature has seen that the turning of nickel-based superalloy materials with the help of cryogenic liquid has been examined in detail both experimentally and numerically [11, 12]. In a recent thesis study, cryogenic treatment on Inconel 625 material was compared with the dry method and its effects on surface roughness were investigated [13]. Apart from nickel-based superalloys, cryogenic machining of materials such as Ti, Tantalum, and steel has been extensively studied [14-16] while the scope of this study is to examine the energy consumption of AISI 52100 steel. Similarly, the effects of cryogenic turning of Inconel 718 material on the residual stress were investigated and the direct effect of liquid nitrogen on the residual stress was presented experimentally and numerically [17]. Umbrello and Rotella et al. studied the surface changes of AISI 52100 steel by cryogenic processing. The study results show that the surface integrity properties can be enhanced, and the white layer is partially deducted under cryogenic cooling conditions and certain process parameters. Rapidly falling cutting temperatures, which prevent martensitic phase transitions, have been credited as the reason why cryogenic processing is successful at minimizing the thickness of white layers [18, 19]. Biček et al. investigated the effects of ceramic and cubic boron nitride (CBN) on tool life and surface integrity. The results showed that cryogenic coolant increases efficiency of AISI 52100 machining processes [20].

While titanium, tantalum, and other metals extensively investigated in the literature, limited studies have been conducted about numerical analysis of AISI 52100 bearing steel throughout cryogenic turning. This study aims to investigate the effects of dry, liquid nitrogen (LN_2), and carbon dioxide (CO_2) cooling environments and different cutting parameters on power consumption in turning AISI 52100 bearing steel through finite element (FE) analysis.

2. MATERIAL AND METHOD (MATERYAL VE YÖNTEM)

2.1. Finite Element Method (Sonlu Elemanlar Metodu)

FEM is a numerical approach method that enables mathematical solutions by transforming complex structures into idealized structures to be divided into nodes and elements [21]. A variety of software programs such as ANSYS LS-DYNA, ABAQUS, DEFORM, Third Wave AdvantEdge are used in order to run FEM. Although programs such as DEFORM, ABAQUS, or ANSYS LS-DYNA are generally simulation software for the plastic deformation process, Third Wave AdvantEdge is a software used for investigating machining simulations with FEM [7]. In this study, the effect of cutting parameters on power consumption was investigated by using Third Wave AdvantEdge software in the turning of bearing steel of AISI 52100, which is a difficult to cut material, under dry and cryogenic cooling conditions. Table 1 shows the mechanical and thermal parameters of the AISI 52100 bearing steel material utilized in the investigation.

Table 1. The mechanical and thermal properties of the AISI 52100 (AISI 52100'ün mekanik ve termal özellikleri)

Properties	Workpiece Material (AISI 52100 Steel)
Density (kg/cm^3)	7.8
Poisson's Ratio	0.3
Young's Modulus (GPa)	210
Thermal Conductivity Coefficient (W/m°C)	46.6
Specific Heat (J/kg/°C)	476.975
Thermal Expansion(**µm/m**°C)	1.19

To employ the finite element approach in simulations of metal cutting operations, boundary conditions are required. These criteria may be used to compute the deformation rate, understand how the workpiece's material will behave during plastic deformation, and model metal cutting processes by selecting the appropriate modeling technique and modeling the material. To represent the dynamic behavior of the model, the strain rate and temperature impacts of the constitutive equations must be determined. The yield stress of a metallic material changes with strain, strain rate, and temperature [22-24]. The mechanical behavior of the workpiece was described using the Johnson-Cook (JC) yield surface forming material model in this study. The flow stress of the workpiece is calculated using Equation 1 in the Johnson-Cook material model.

$$\sigma = \underbrace{[A + B\varepsilon^{n}]}_{\text{Elasto-Plastic}} \underbrace{\left[1 + C\ln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)\right]}_{\text{Viscosity}} \underbrace{\left[1 - \left(\frac{T - T_{room}}{T_{melt} - T_{room}}\right)^{m}\right]}_{\text{Thermal Softening}} \tag{1}$$

AdvantEdge™ uses a coefficient of friction defined by the Coulomb friction given in Equation 2:

$$F_f = \mu F_n \tag{2}$$

Figure 1 depicts the overall geometric framework for finite element analysis with Third Wave AdvantEdge. As a turning method, 3D turning is favored.

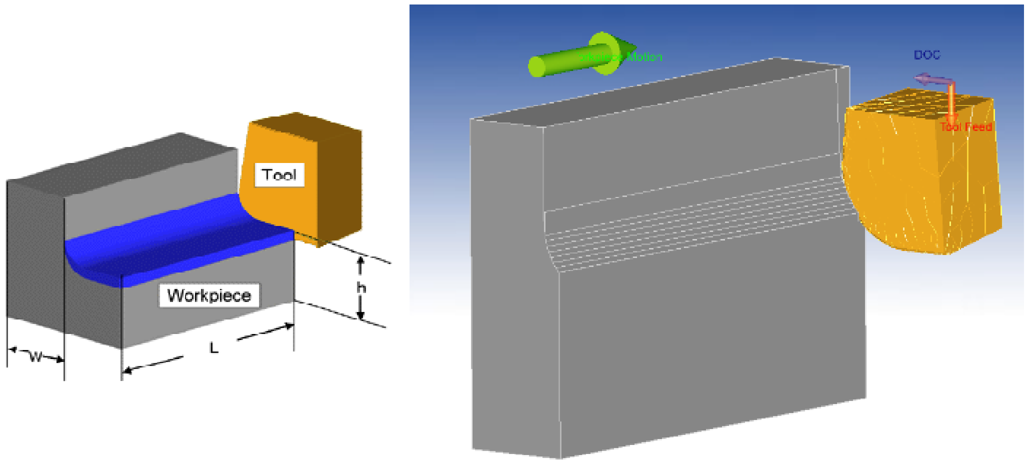

Figure 1. General geometric structure for FEM (FEM için genel geometrik yapı)

In the first stage of the analysis, the dimensions of the workpiece material 1x1x3 mm were used. Tool geometry properties and tool material parameters were defined in the program. The JC parameters and refractive constants used by Pawar et al. were used as shown in Table 2. [25]. The cutting tool geometry used in the analysis is shown in Figure 2.

Table 2. JC parameters of AISI 52100 bearing steel [25] (AISI 52100 rulman çeliğinin JC parametreleri)

	AISI 52100 Steel
A (MPa)	2482.4
B (MPa)	1498.5
N	0.19
C	0.027
M	0.66
Tmelt (^{0}C)	1487

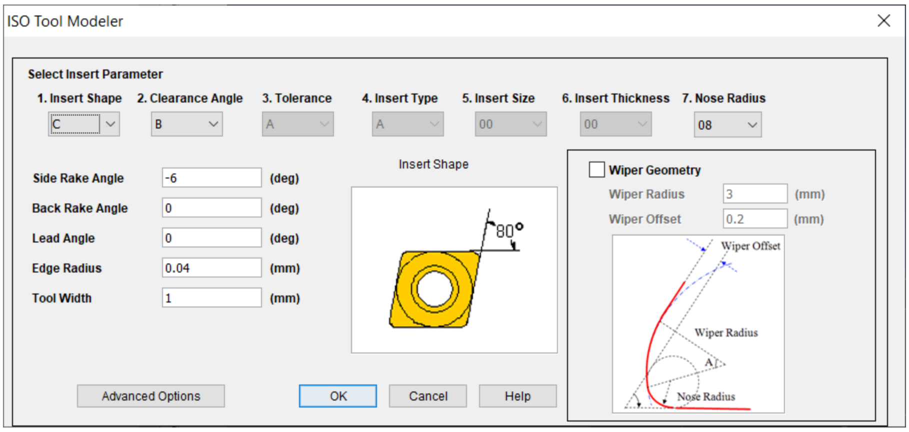

Figure 2. Cutting tool parameters (Kesici takım parametreleri)

2.2. Cooling systems (Soğutma Sistemi)

The study of low temperature environments is known as cryogenics [26]. Low temperatures were achieved for the analyses using LN_2 and CO_2. LN_2 and CO_2 were approved as having cryogen temperatures of 196.5 °C and 78.5 °C, respectively. Additionally, it was agreed that the heat transfer coefficients for CO_2 and LN_2 were 309 W/m^{2}K and 165 W/m^{2}K, respectively [27].

2.3. Cutting parameters (Kesme Parametreleri)

In order to determine the cryogenic effect in the machining of AISI 52100 bearing steel, the cutting parameters were obtained from the manufacturer's catalogs and previous studies. Table 3 shows the cutting parameters determined. In addition, the cutting depth was determined as 0.5 mm in all analyzes.

Table 3. Cutting parameters and levels (Kesme parametreleri ve seviyeleri)

Cutting parameters		Levels		
		Low -1	Medium 0	High +1
Cutting Speed (m/min)	V	100	150	200
Feed Rate (mm/rev)	*f*	0.1	0.15	0.2
Cooling Conditions		Dry	LN_2	CO_2
Depth of Cut (mm)	ap		0.5	

3. RESULTS AND DISCUSSION (BULGULAR VE TARTIŞMA)

As a result of 3D turning analyses with Thirdwave Advantage software, power consumptions of different cutting parameters in dry and LN_2 and CO_2 cooling conditions were simulated. Figure 3 shows the change in power usage based on cutting settings and cooling conditions.

Figure 3 shows that as cutting speed increased, so did power consumption in all cutting zones and feed rates. For example, with a cutting speed of 100 m/min, dry machining condition, and feed rate of 0.1 mm/rev, the power consumption was 199.2 W. It was observed that the power consumption increased by 8.7% and 11.32%, respectively, by subtracting the cutting speed of 150 m/min and 200 m/min in dry machining conditions and 0.1 mm/rev feed rate, respectivelyIn other cutting settings and feed rates, the rise in power usage paralleled the increase in cutting speed. Lower power usage has been claimed to be possible only at slower cutting speeds [28]. It is seen that power consumption decreases with increasing feed rate at all cutting speeds and cutting conditions. It has been observed that the power consumption is 109 W at 100 m/min cutting speed, LN_2 cutting condition, and 0.1 mm/rev feed rate. It was observed that power consumption decreased by 22.02% and 33.95%, respectively, by increasing the feed rate of 0.15 m/rev and 0.2 mm/rev at 100 m/min cutting speed and LN_2 cutting condition. It has been stated that low cutting speed and high feed rate values provide minimum energy consumption of the machine tool during the cutting process [29].

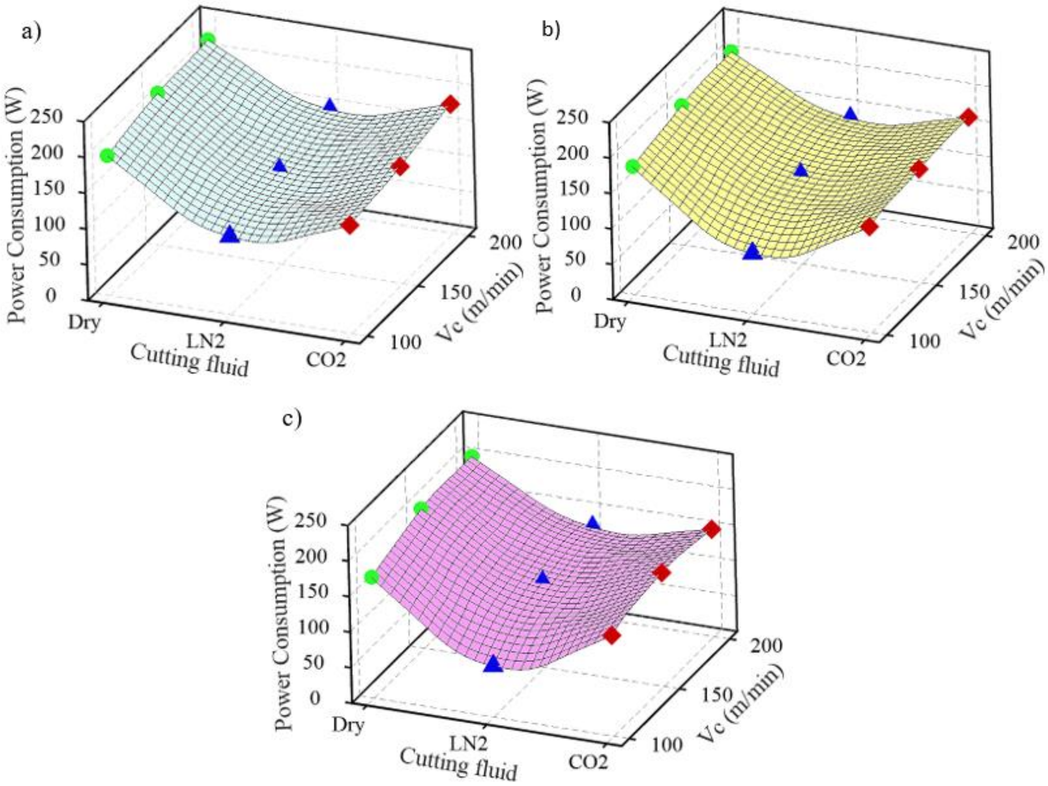

Figure 3. Power consumptions based on cutting parameters and conditions a) 0.1 mm/rev, b) 0.15 mm/rev, c) 0.2 mm/rev (Kesme parametrelerine ve koşullarına dayalı güç tüketimleri a) 0,1 mm/dev, b) 0,15 mm/dev, c) 0,2 mm/dev)

As can be seen in Figure 3, the power consumption for all conditions in cryogenic fluid-assisted turning is reduced compared to dry turning. In addition, it is seen that the lowest power consumption occurred in the experiments performed in the LN_2 environment in all process parameters. The lowest cutting speed (100 m/min), highest feed rate (0.2 mm/rev), and minimum power consumption with 72 W in the LN_2 machining environment were measured. In the studies in the literature, it has been stated that machining processes using coolant reduce the surface roughness, tool wear, and power consumption values in general [28].

4. CONCLUSIONS (SONUÇLAR)

In this study, the effects of power consumption on turning AISI 52100 steel at different cutting parameters under dry and cryogenic LN_2/CO_2 cooling conditions were investigated using Third Wave AdvantEdge software. The outstanding results of this study can be summarized as follows:

- ✓ Power consumption increased with the increasing cutting speed in all cutting conditions and feed rates.
- ✓ When all experimental conditions were compared, the minimum power consumption was obtained in the LN_2 cooling turning process, and the highest power consumption was obtained in the dry environment.

- ✓ In the LN_2 environment, the cutting parameter combination is 100 m/min cutting speed and 0.2 mm/rev feed rate for the lowest power consumption which is 72 W.
- ✓ The cutting parameter combination with the highest power consumption was measured at 200 m/min cutting speed.

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