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Measurement and Evaluation of Machinability Characteristics in Turning of Train Wheel Steel via CVD Coated-RCMX Carbide Tool

Recep DEMİRSÖZ[1*], Mehmet BOY[2]

[1*] *Karabük Üniversitesi, Mühendislik Fakültesi, Karabük, Türkiye*

[2] *Karabük Üniversitesi, TOBB Teknik Bilimler MYO, Karabük, Türkiye*

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ABSTRACT

ER7 quality steels produced according to EN13262 standard used in European railway lines can be produced at Kardemir A.Ş Railway Wheel Production Facilities. These wheels, which are produced by pressing and rolling, are included in the machining process to be brought to their final dimensions after the production process. In this experimental study, the effects of cutting speed (CS) and feed rate (FR) on surface roughness (SR), power consumption (PC) and cutting temperature (CT) were investigated during turning of ER7 wheel material with 1mm depth of cut value under dry test conditions using MT-TiCN+Al_2O_3 CVD coated-RCMX 1606M0 K15 quality tool. Analysis of Variance (ANOVA) method was used to determine the effect rates of the input parameters on the results. In addition, estimation equations were obtained using the Response Surface Method (RSM). As a result of this study, the effective parameter for SR is FR with 57.158%, while the effective parameter for PC and CT is found to be CS, and it is found to be 58.071% and 64.977%, respectively.

CVD Kaplamalı-RCMX Karbür Takım ile Tren Tekerleği Çeliğinin Tornalanmasında İşlenebilirlik Özelliklerinin Ölçülmesi ve Değerlendirilmesi

MAKALE BİLGİSİ

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ÖZET

Avrupa demir yolu hatlarında kullanılmakta olan EN13262 standardına göre üretilmiş ER7 kalite çelikleri Kardemir A.Ş Demir Yolu Tekeri Üretim Tesislerinde üretilebilmektedir. Pres ve haddeleme ile üretilen bu tekerlekler üretim prosesinin ardından nihai ölçülerine getirilmek üzere talaşlı imalat sürecine girmektedir. Bu çalışmada MT-TiCN+Al_2O_3 CVD kaplamalı-RCMX 1606M0 K15 kalite takım kullanılarak kuru test koşullarında ER7 tekerlek malzemesinin 1mm kesme derinliği değeri ile tornalanması sırasında ilerleme hızı (FR) ve kesme hızı (CS) parametrelerinin yüzey pürüzlülüğü (SR), güç harcaması (PC) ve kesme sıcaklığı (CT) üzerindeki etkileri araştırılmıştır. Giriş parametrelerinin sonuçlar üzerindeki etki oranlarının tespitinde varyans analizi (ANOVA) yöntemi kullanılmıştır. Ayrıca Cevap Yüzey Metodu kullanılarak tahmin denklemleri elde edilmiştir. Bu çalışmanın sonucunda yüzey pürüzlülüğü için etkili parametre %57.158 ile ilerleme hızı olurken, güç harcaması ve kesme sıcaklığı için etkili parametrenin kesme hızı olduğu tespit edilmiş olup sırası ile %58.071 ve %64.797 olarak bulunmuştur.

1. INTRODUCTION (GİRİŞ)

By using a vacuum degassing process and continuous casting method, the semi-finished products (thick round) of the items to be manufactured are created in the necessary steel quality (ER7) [1]. One of the most encountered problems in railway management is wheel flats. "Flat spots" or "wheel flats" are a defect that occurs in railway wheels. There are many factors in the formation of flattening points and wheel flats [2]. To eliminate these factors, dry machining of these train wheels via round insert are performed to obtain much better surface quality. While coolant is used in most

***Corresponding author, e-mail:** *recepdemirsoz@karabuk.edu.tr*
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Nomenclature

Adj. MS	Adjusted mean squares	FR	Feed rate (mm/rev)
Adj. SS	Adjusted sums of squares	MT	Medium temperature (°C)
ANOVA	Analysis of variance	PC	Power consumption (W)
CNC	Computer numeric control	PCR	Parameter contribution rate (%)
CS	Cutting speed (m/min)	RCMX	Round shape cutting tool
CT	Cutting temperature (°C)	RSM	Response surface method
CVD	Chemical vapor deposition	SR	Surface roughness (μm)
DF	Degree of freedom	TOBB	The Union of Chambers and Commodity Exchanges of Turkey
EN	European norm		

machining applications, some applications do not use coolant. Since cutting fluid is not used in the machining method, which it can be describe as dry machining, this method is considered a clean production method. Elimination of the negative effects of cutting fluids on human health and the environment while it has advantages such as reduction of overall processing costs by eliminating filtration, cleaning and disposal costs; and a cleaner working environment [3]. For these reasons, the dry machining method without using cutting fluid is becoming more and more popular. Even if the negative effects of cutting fluids are eliminated in dry machining, it is very difficult to abandon the use of cutting fluids due to high efficiency and performance advantages in machining [4], [5]. In dry machining, there is relatively more friction and adhesion and higher temperatures at the cutting tool and workpiece interface [6]. If a good machining is to be mentioned in the case of dry machining, the correct selection of parameters such as machining process, cutting tool and workpiece material is important [7]. Polycrystalline diamond, ceramic, etc., with high temperature hardness and high wear resistance in dry machining. It would be appropriate to prefer materials such as the material properties of the cutting tool, the geometry of the cutting tool is an important parameter, and it should be selected in the geometry suitable for the work to be done and with optimum properties suitable for the workpiece. Coated tools can also be preferred to increase the performance and life of the tool in machining. The coatings on the tools act as a lubricant, reducing the friction between the tool and the workpiece and preventing the tool from sticking [8]. Because of these effects, it affects the tool life positively. There is a need for the development of new technology tool coatings, which prevent the coating of the tool to be used during long working periods, making it economical as well as improving the product quality [9].

Soft materials such as aluminum are not recommended for dry machining, as they cause chip accumulation on the tool and risk affecting the surface quality during machining [10]. Although dry machining is an environmentally friendly option, it has some disadvantages in processing [11]–[13]. The biggest disadvantage is the high temperature generated during machining, which causes tool wear [14], [15]. In addition, there is a possibility of reducing the tool life and decreasing the surface quality due to the possibility of accumulation of chips generated during machining in the machining area and especially at the tool tip. Due to these disadvantages, it is important to determine the cutting parameters and the machining process correctly [16], to match the material of the workpiece and the cutting tool, and to optimize the cutting process. To summarize the problems related to dry processing [17]. Tool wear that may occur due to friction, poor dimensional tolerance and surface quality, low CS and production speed values to increase tool life, accumulation of chip to low CS, lack of advantages in chip removal, difficult to machine materials [18], [19].

It has been observed that machining operations such as turning, drilling and milling are more suitable for dry machining than closed surface machining, due to the easy evacuation of chip formed in open surface machining. In addition, in closed surface machining such as tapping and drilling, efficient dry machining cannot be performed due to the chip evacuation problem and therefore the possibility of damage to the workpiece surface [20].

2. MATERIAL AND METHOD (MATERYAL VE YÖNTEM)

EN 13262 standard is used to determine the characteristics of train wheels used in European railway networks. In this standard, four different steel grades, ER6, ER7, ER8 and ER9, are defined for use in train wheels. These grades have low carbon content (0.55% C) and pearlitic and ferritic structures. After the train wheels are produced by forging method, they are processed on special vertical CNC lathes due to their geometric shape, size and weight. Since there is not enough lathe in size for the machining of the commercially produced train wheel in the university laboratories, ER7 quality material with the dimensions of 170x50mm was taken from the wheel hub to be used as a test workpiece. The chemical composition of ER7 quality steel used in turning experiments is shown in Table 1. The test workpieces were obtained from Kardemir A.Ş., which manufactures and commercially sells train wheels.

Table 1. The chemical composition of ER7 steel (wt%) (ER7 çeliğinin kimyasal bileşimi (%ağ.)

C	Mn	Si	S	P	Cr	Ni	Cu	Mo	V	Cr+Ni+Mo	H.ppm
0.52	0.80	0.40	0.015	0.020	0.30	0.30	0.30	0.080	0.060	0.50 max	2.0 max

In the experiments, MT-TiCN+Al_2O_3 CVD coated-RCMX 1606M0 K15 quality tool and suitable tool holder were used in accordance with ISO standards of Korloy company. The experiments were carried out on the TTC-550 CNC lathe located in TOBB Technical Sciences Vocational School Laboratory at Karabük University. Fixed depth of cut (1mm), three different CS (200, 250, 300 m/min) and three different FR (0.15, 0.20, 0.30 mm/rev) were used in the experiments. The temperatures on the cutting tool and workpiece during turning were measured with the Fluke TI400 infrared camera. The infrared camera has automatic focusing, a temperature measuring range of 0 °C to 1200 °C and a measurement accuracy of ±2 °C. KAEL Network Analyzer with three 60/5A current transformers was used to precisely measure the PC of the CNC lathe during turning. After each machining parameter, the SR of the workpiece was measured with the Mahr M300 roughness device. For each measurement, the workpiece was rotated approximately 70° and measured from five different regions and evaluated by taking the average value. The experimental setup is shown in Figure 1.

In the study, an experimental design was made with RSM and SR (Ra), PC (W), temperature (°C) values were taken as basis as quality properties. Control factors were determined as FR(f) and CS (V). Each control factor was defined at three levels and the RSM L9 index was used. RSM-based second-order estimation models have been developed. Analysis of variance (ANOVA) was performed using Minitab software to examine the interaction of the processing parameters separately and with each other.

3. RESULTS and DISCUSSION (SONUÇLAR ve TARTIŞMA)

The study on train wheel material turning, two different variables, CS and FR, and three different values determined according to the preliminary experiments for each variable were used and the results were evaluated on the SR, PC during machining and machining temperature outputs. The cutting depth value was kept constant as 1 mm in the experiments. Experimental results are listed in Table 2. Estimation equations developed using Response Surface Method (RSM) are given in Table 3.

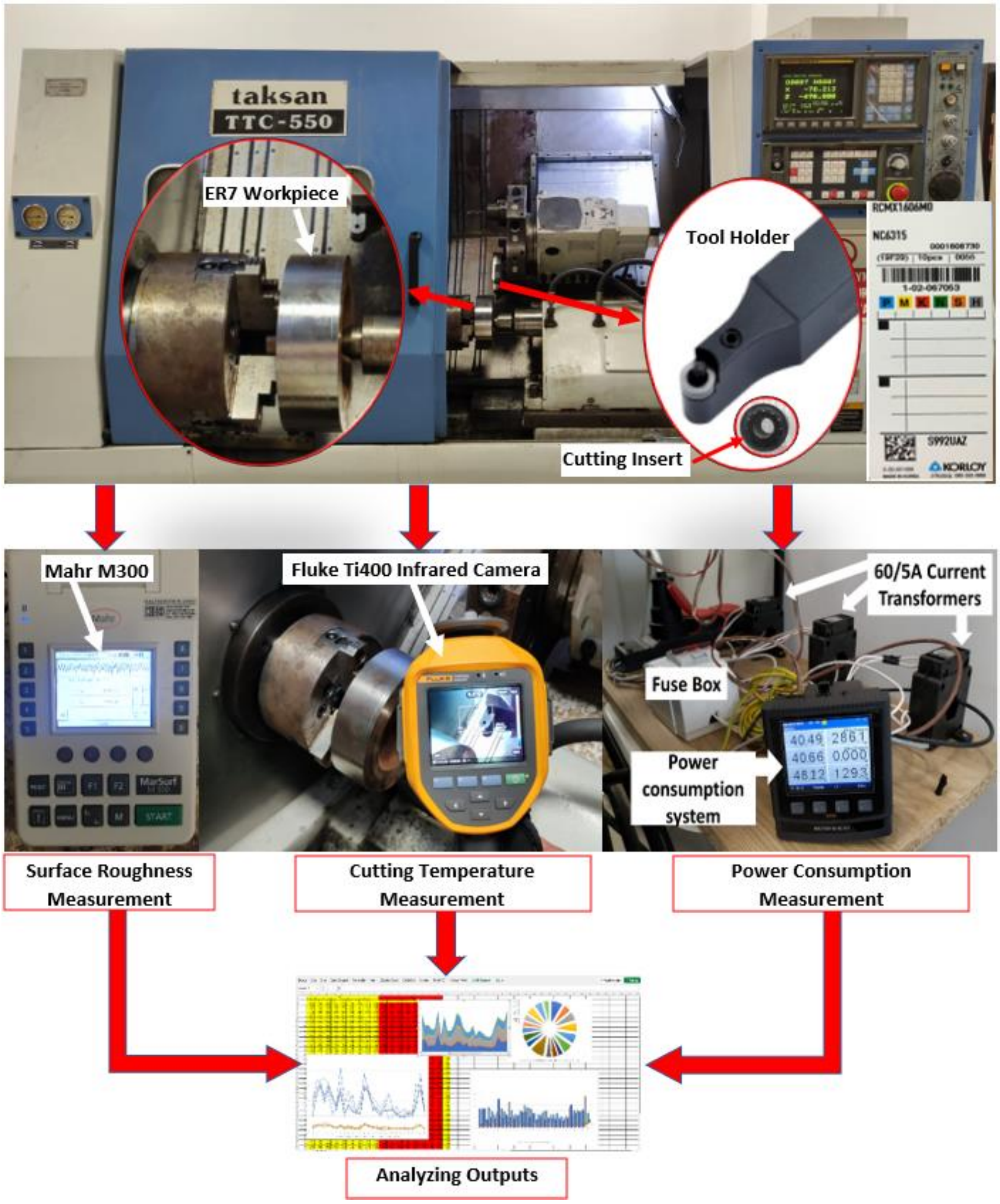

Figure 1. Experimental setup (Deneysel kurulum)

Table 2. Table of experimental and estimated results (Deneysel ve tahmini sonuçlar tablosu)

	Exp. No.	CS (V) [m/min]	FR (f) [mm/rev]	SR (Ra) [μm]	Regression Results SR (Ra) [μm]	PC [W]	Regression Results PC [W]	CT [̊C]	Regression Results CT [̊C]
RCMX Tool	1	200	0.15	0.635	0.603	342.3	344.078	277	283.556
	2	200	0.2	0.663	0.681	390.3	387.078	376	360.889
	3	200	0.25	0.752	0.758	434.3	435.744	393	401.556
	4	250	0.15	0.521	0.541	400.3	397.411	406	405.556
	5	250	0.2	0.591	0.619	432.3	437.411	466	470.889
	6	250	0.25	0.729	0.696	485.3	483.078	504	499.556
	7	300	0.15	0.496	0.479	450.3	451.411	461	454.889
	8	300	0.2	0.544	0.557	490.3	488.411	498	508.222
	9	300	0.25	0.638	0.634	530.3	531.078	529	524.889

Table 3. Equations developed by RSM (RSM ile geliştirilen denklemler)

RCMX	Ra [µm] =	$1.370 - 0.00322*V - 3.73*f + 0.000003*V^2 + 11.62*f^2 + 0.00253*V*f$
	Total Power [W] =	$6 + 1.187*V + 703*f + 0.00013*V^2 + 1133*f^2 - 1.200*V*f$
	Temperature [℃] =	$-1527 + 9.7*V + 5073*f - 0.01453*V^2 - 7333*f^2 - 4.8*V*f$

3.1. Surface Roughness (Yüzey Pürüzlülüğü)

The roughness values of the surfaces that emerge after machining are very important in terms of manufacturing quality and are an output that is closely followed by the manufacturers. Roughness values of the processed material, toughness, strength, and abrasion resistance, etc. reflects its mechanical properties, as well. The main purpose in machining is to obtain surfaces with as low roughness as possible. For this reason, researchers focused on reducing the SR values.

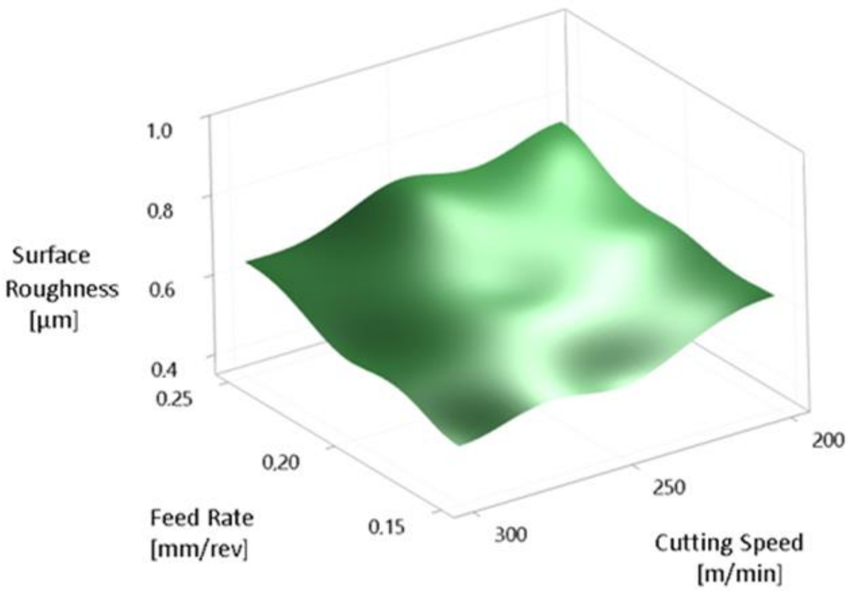

Figure 2. 3D-SR value graph under interactions of process parameters for RCMX cutting tool (RCMX kesici takım için proses parametrelerinin etkileşimleri altında 3B yüzey pürüzlülük değer grafiği)

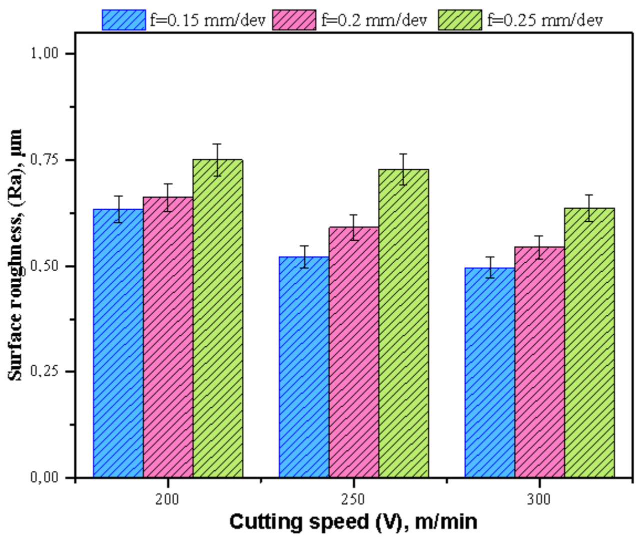

Figure 3. Graph of SR values obtained according to different parameters (Farklı parametrelere göre elde edilen yüzey pürüzlülüğü değerleri grafiği)

In this study, SR values were measured at different SC and FR after the experiments. These roughness values were taken from three different points on the machined surface and were given as average values. It is seen that the SR values decrease as the CS increases and increase as the FR increases (Figure 2). The test conditions in which the highest SR value is 200 m/min CS and 0.25 mm/rev FR. The experimental conditions at 0.15 mm/rev FR and 300 m/min CS give the lowest roughness values. When the graph given in Figure 3 is evaluated with the RCMX cutting tool, the SR value is 0.496 µm at 0.15 mm/rev FR and 300 m/min CS, and the SR value is 0.544 µm at 0.20 mm/rev FR. It is measured as 0.638 µm at a FR of 0.25 mm/rev. When the FR value increases from 0.15 to 0.20 mm/rev and from 0.15 to 0.25 mm/rev, the increases in the SR value are 9.7% and 28.63%, respectively. About the RCMX cutting tool, the SR value is measured as 0.663 µm at 0.20 mm/rev FR and 200 m/min CS, 0.591 µm at 250 m/min CS and 0.544 µm at 300 m/min CS. When the CS value increases from 200 to 250 m/min and from 200 to 300 m/min, the reductions in the SR value are 10.86% and 17.95%, respectively. The surface roughness increases with increasing feed rate depending on that surface roughness is mainly a function of the feed rate due to increasing load per unit cutting zone by increasing too-chip contact area as as shown in many investigations. Moreover, surface roughness decreases with increasing cutting speed due to decreasing friction coefficient any easier to cut by higher cutting speed [7], [21].

Table 4. ANOVA results according to SR values for RCMX cutting tool (RCMX kesici takım için yüzey pürüzlülük değerlerine göre ANOVA sonuçları)

Source	DF	Adj SS	Adj MS	F-Value	P-Value	PCR (%)
CS - V [m/min]	1	0.023023	0.023023	32.75	0.0110	36.412
FR - f [mm/rev]	1	0.036141	0.036141	51.41	0.0060	**57.158**
V*V	1	0.000109	0.000109	0.16	0.7200	0.172
f*f	1	0.001688	0.001688	2.40	0.2190	2.670
V*f	1	0.000160	0.000160	0.23	0.6650	0.253
Error	3	0.002109	0.000703			3.335
Total	8	0.063230				100

When the variance analysis results given in Table 4 according to the RCMX cutting tool are examined, it is seen that the FR parameter is more effective than the CS parameter. While the effect rate in the FR is 57.158%, this rate is 36.412% for the CS. For a parameter to be statistically significant, the P-value must be less than 0.05 [22]. When the squares of the parameters and the P values of their interaction are examined, it is seen that the results are not significant. On the other hand, the results obtained are significant because the mentioned P values of the parameters are less than 0.05. In the RCMX cutting tool, the results are found to be not significant when the P values obtained from the squares of the parameters and their interaction are examined. CS and FR values are statistically significant. As a result, in cases where good SR is expected, when working with RCMX cutting tools, it will be appropriate to work with 300 m/min and 0.15 mm/rev values to obtain the best SR value. When the error values are examined, it can be said that these values may be caused by bench vibrations, vibrations from the ground or the microstructure of the material. The error value is obtained as 3.335% for the RCMX cutting tool.

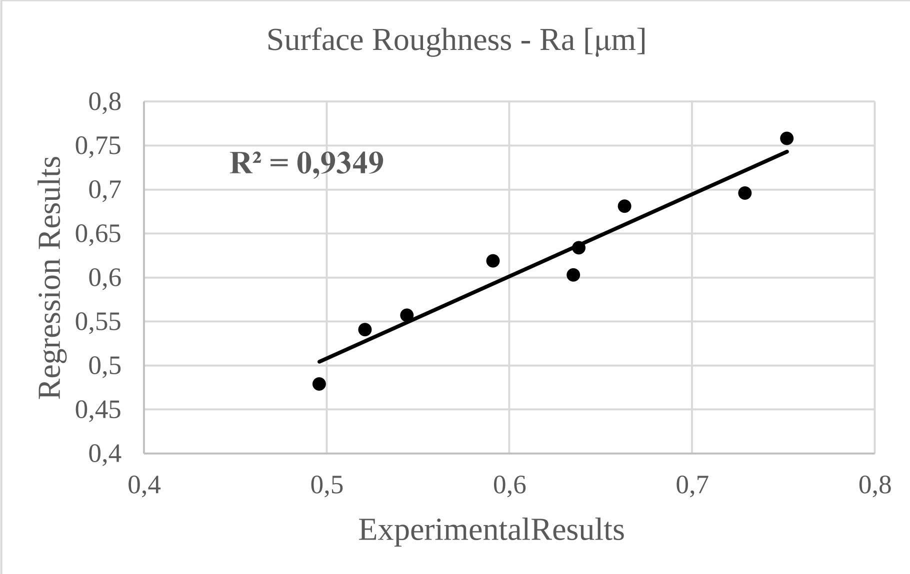

Figure 4. Regression graph of SR results (Yüzey pürüzlülük sonuçlarının regresyon grafiği)

When the graph obtained from the RSM given in Figure 4 for SR is examined, it is seen that the experimental results and the results obtained from the model estimation are in good agreement. R^2 values expressing the agreement of the results were found to be 0.9349.

3.2. Power Consumption (Güç Tüketimi)

The total power value measured during the machining on the CNC lathe where the experiments were carried out was obtained from the sum of the linear power, idle mode power, spindle power and machining power values. According to the tool used during the experiments, the total power values at different CS and FR were measured. The test conditions with the highest power values are 0.25 mm/rev FR and 300 m/min CS (Figure 5). Moreover, the experimental conditions at a CS of 200 m/min and a FR of 0.15 mm/rev give the lowest power values.

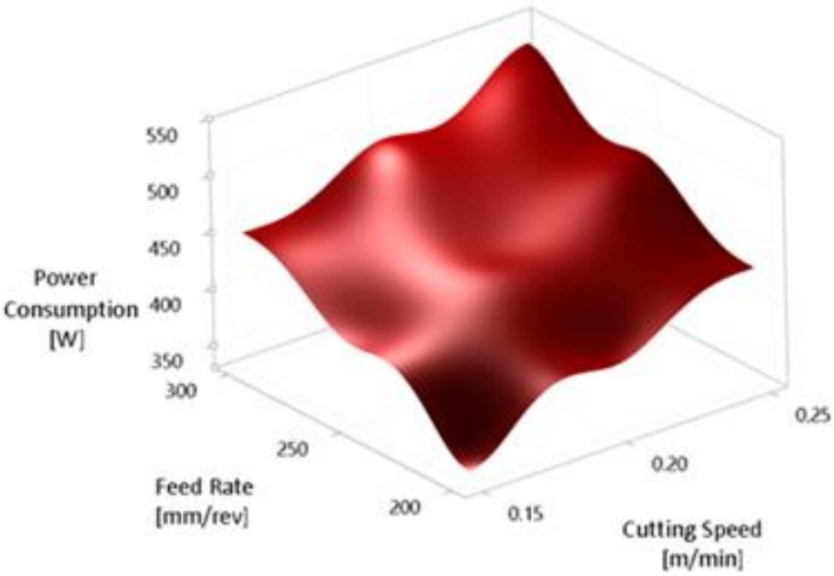

Figure 5.3D-PC graph under interactions of process parameters for RCMX cutting tool (RCMX kesici takım için proses parametrelerinin etkileşimleri altında 3B güç tüketim değerleri grafiği)

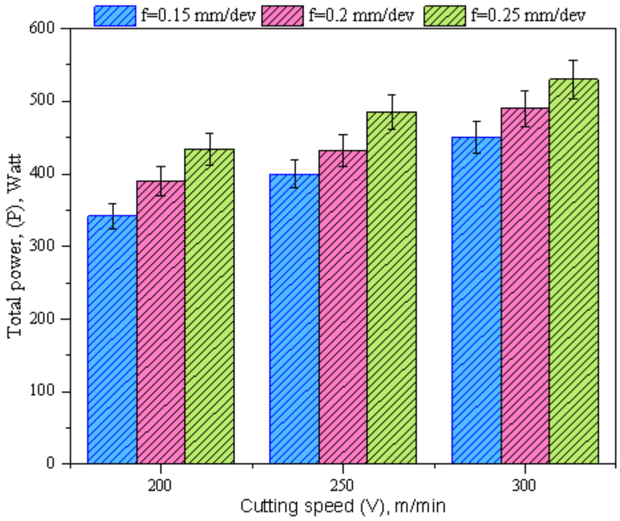

Figure 6. Graph of PC values obtained according to different parameters (Farklı parametrelere göre elde edilen güç tüketim değerleri grafiği)

When the graph given in Figure 6 is evaluated regarding the RCMX cutting tool, the PC value is 450.3 W at 0.15 mm/rev FR and 300 m/min CS, PC value is 490 at 0.20 mm/rev FR. It is measured as 530.3 W at a FR of 3 W and 0.25 mm/rev. The increases in PC are 8.88% and 17.76%, respectively, when the FR value increases from 0.15 to 0.20 mm/rev and from 0.15 to 0.25 mm/rev. The PC value is measured as 434.3 W at a FR of 0.25 mm/rev and a CS of 200 m/min, 485.3 W at a CS of 250 m/min and 530.3 W at a CS of 300 m/min. The increases in PC are 11.74% and 22.10%, respectively, when the CS increases from 200 to 250 m/min and from 200 to 300 m/min. This can attributed that the power consumption increases with increasing feed rate depending on that it is mainly a function of the feed rate due to increasing load per unit cutting zone by increasing too-chip contact area like in surface roughness [23], [24]. Moreover, cutting speed has also rising effect on power consumption due to its increasing influence on spindle speed and spindle power [23].

Table 5. ANOVA results according to PC values for RCMX cutting tool (RCMX kesici takım için güç tüketim değerlerine göre ANOVA sonuçları)

Source	DF	Adj SS	Adj MS	F-Value	P-Value	PCR (%)
CS - V [m/min]	1	15402.7	15402.7	764.47	0.00010	**58.072**
FR - f [mm/rev]	1	11008.2	11008.2	546.36	0.00017	41.503
V*V	1	0.2	0.2	0.01	0.92299	0.001
f*f	1	16.1	16.1	0.80	0.43780	0.061
V*f	1	36	36	1.79	0.27365	0.136
Error	3	60.4	20.1			0.228
Total	8	26523.6				100

When the variance analysis results given in Table 5 regarding the RCMX cutting tool are examined, it is seen that the CS parameter is more effective than the FR parameter regarding the power values. While the rate in FR is 41.503 %, this rate increases to 58.072 in CS. When the squares of the parameters and the P values of their interaction are examined, it is seen that the results are greater than 0.05 and therefore cannot be statistically significant. On the other hand, the results obtained are statistically significant because the mentioned P values of the parameters are much smaller than 0.05. When the P values obtained for the squares of the parameters in the RCMX cutting tool, are examined, it is seen that the results are meaningless. However, it is significant because the P-value obtained for the interaction of the parameters is less than 0.05. The CS and FR values are also statistically significant. As a result, if it is desired to work with lower energy consumption values, it will be appropriate to work with 200 m/min and 0.15 mm/rev values to obtain the lowest power value in case of working with RCMX cutting tools. When the error values are examined, it can be said that these values may be caused by reasons such as bench vibrations, vibrations from the floor or the microstructure of the material, which are not considered in this study. These error values are obtained as 0.228% for the RCMX cutting tool.

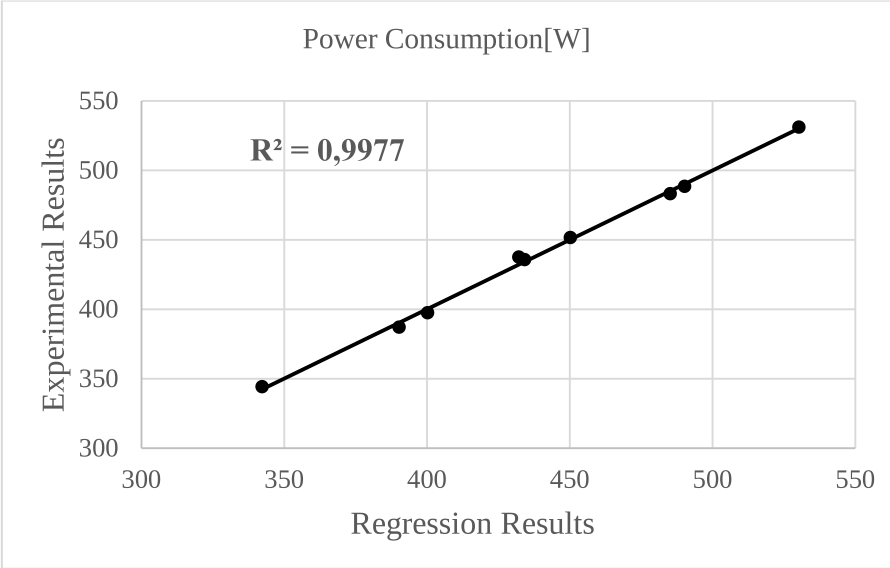

Figure 7. Regression graph of PC results (Güç tüketim sonuçlarının regresyon grafiği)

When the graph obtained from the RSM given in Figure 7 for PC is examined, it is seen that the experimental results and the results obtained from the model estimation are in good agreement. R^2 values expressing the agreement of the results were found to be 0.9977.

3.3. Cutting temperature (Kesme Sıcaklığı)

In almost all machining processes, mechanical energy converts into heat energy. Some of the heat generated is in the processed material, some of it stays on the tool, and some of it is removed with the material chips. During the experiments, the temperature values that occurred because of heat are measured separately at different CS and FR. The test conditions with the highest temperature value are 300 m/min CS and 0.25 mm/rev FR. The lowest temperature value is found at a FR of 0.15 mm/rev and a CS of 200 m/min. With the increase of the CS, the temperature values also increase (Figure 8). The increase in the FR causes an increase in temperature. The increase in CTs directly affects the tool life.

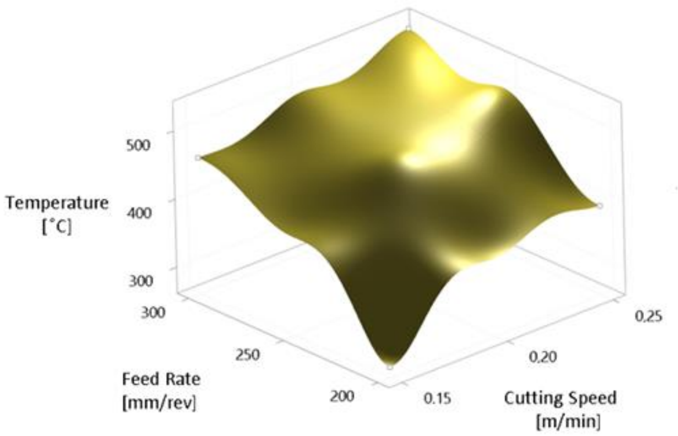

Figure 8. 3D-CT graphs under interactions of process parameters for RCMX cutting tool (RCMX kesici takım için proses parametrelerinin etkileşimleri altında 3B kesme sıcaklığı değer grafiği)

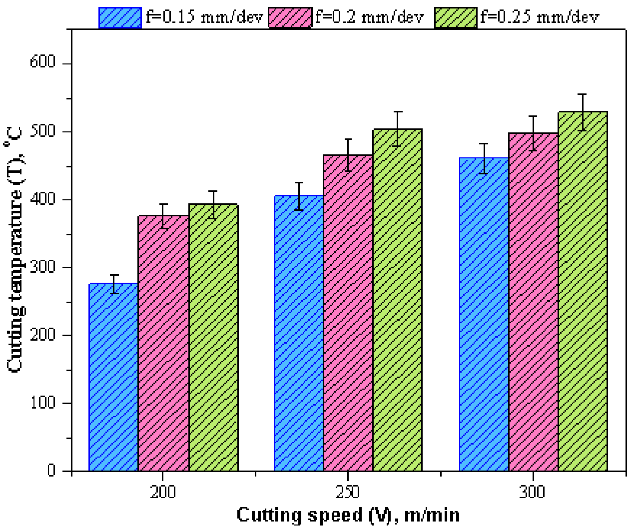

Figure 9. Graph of CT values obtained according to different parameters (Farklı parametrelere göre elde edilen kesme sıcaklığı değerleri grafiği)

Looking at the graph in Figure 9, the temperature value occurring at a FR of 0.15 mm/rev and a CS of 300 m/min is 461 °C, the temperature value is 498 °C at a FR of 0.20 mm/rev and 0.25 mm/rev. At rev FR, it is measured as 529° C. When the FR value increases from 0.15 to 0.20 mm/rev and from 0.15 to 0.25 mm/rev, the increases in temperature value are 8% and 14.75%, respectively. For the RCMX cutting tool, the temperature value was measured as 393 °C at a FR of 0.25 mm/rev and a CS of 200 m/min, 504 °C at a CS of 250 m/min, and 529 °C at a CS of 300 m/min. When the CS value increases from 200 to 250 m/min and from 200 to 300 m/min, the rate of increase in temperature value is 28.24% and 34.61%, respectively. Because of the increased load per unit cutting zone caused by an increase in too-chip contact area, as shown in surface roughness and power, it can be concluded that the cutting temperature rises with increasing feed rate based on the fact that it is mostly a function of the feed rate. Furthermore, cutting speed has a growing impact on cutting temperature as a result of its increasing influence on spindle speed and spindle power, which are both increasing with cutting speed.

Table 6. ANOVA results according to CT values for RCMX cutting tool (RCMX kesici takım için kesme sıcaklığı değerlerine göre ANOVA sonuçları)

Source	DF	Adj SS	Adj MS	F-Value	P-Value	PCR (%)
CS - V [m/min]	1	32560.7	32560.7	178.54	0.001	**64.797**
FR - f [mm/rev]	1	13254	13254	72.68	0.003	26.376
V*V	1	2640.2	2640.2	14.48	0.032	5.254
f*f	1	672.2	672.2	3.69	0.151	1.338
V*f	1	576	576	3.16	0.174	1.146
Error	3	547.1	182.4			1.089
Total	8	50250.2				100

When the variance analysis results given for the RCMX cutting tool in Table 6 are examined, it is seen that the FR parameter is less effective than the CS parameter regarding the temperature values. While the rate in FR is 26.376%, this rate increases to 64.797% in CS. When the P values for two separate parameters and the square of the CS are examined, it is seen that the results are less than 0.05 and therefore statistically significant. On the other hand, the results obtained are statistically insignificant because the square of the FR and the P values for the interaction of cutting and FR are greater than 0.05. If it is desired to work with lower temperature values, in case of working with RCMX cutting tools, it will be appropriate to work with 200 m/min and 0.15 mm/rev values to obtain the lowest temperature value. The error values can be explained by variables not considered in this study, such as bench vibrations, floor vibrations or the microstructure of the material. These error values were calculated as 1.089% for the RCMX cutting tool.

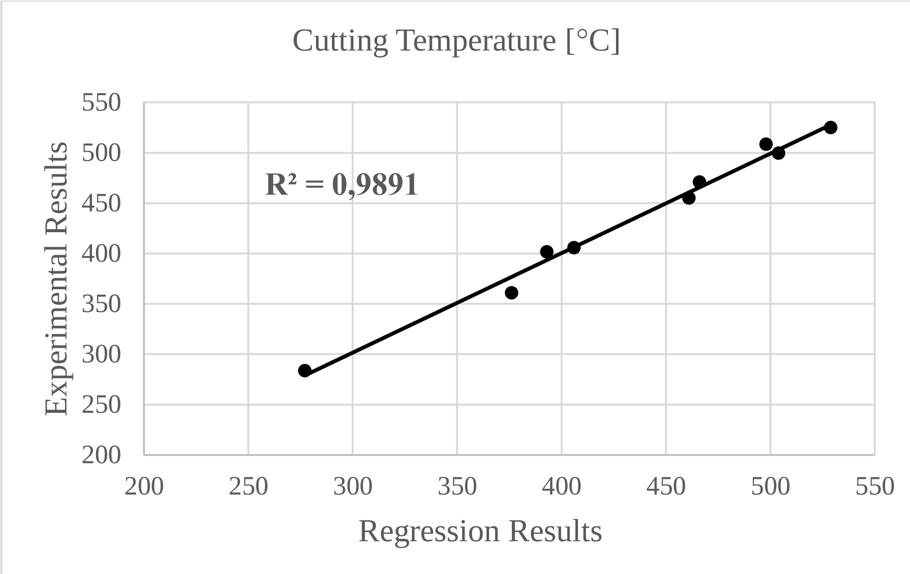

Figure 10. Regression graph of CT results (Kesme sıcaklığı sonuçlarının regresyon grafiği)

When the graph obtained from the RSM given in Figure 10 for CT is examined, it is seen that the experimental results and the results obtained from the model estimation are in good agreement. R^2 values expressing the agreement of the results were found to be 0.9891.

4. CONCLUSIONS (SONUÇLAR)

In this experimental study, the effects of FR and CS parameters on SR, PC and CT values were investigated in the processing of ER7 train wheels with CRMX cutting tool using ANOVA and RSM methods. Appropriate processing parameters were determined by determining the relationship between input parameters and outputs. Experiment results were analyzed using the ANOVA method. Obtained results are given below:

1. According to the analysis of variance, the parameter affecting the SR was the FR with 57.158%. The effect rate of CS is 36.412%. The results for FR and CS are statistically significant as the P-Value value is less than 0.05. In addition, the agreement between the values calculated using the equation obtained by the RSM method and the experimental results was found to be 93.49%. The operating parameters that give the lowest SR value are 0.15 mm/rev FR and 300 m/min CS. As the FR increases, the SR increases, and as the CS increases, the SR decreases.
2. According to the analysis of variance, the parameter affecting the PC was the CS with 58.072%. The impact rate of the FR is 41.503%. The results for FR and CS are statistically significant as the P-Value value is less than 0.05. In addition, the agreement between the values calculated using the equation obtained by the RSM method and the experimental results was found to be 99.77%. The operating parameters that give the lowest PC value are 0.15 mm/rev FR and 200 m/min CS. As CS and FR increase, PC increases.
3. According to the analysis of variance, the parameter affecting the CT was 64.797% CS. The impact rate of the FR is 26.376%. The results for FR and CS are statistically significant as the P-Value value is less than 0.05. In addition, the agreement between the values calculated using the equation obtained by the RSM method and the experimental results was found to be 98.91%. The

operating parameters that give the lowest SR are 0.15 mm/rev FR and 200 m/min CS. As the FR and the CS increase, the CT increases.

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