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An Investigation on the Performance of the Ultrasonic Atomization-Based Cutting Fluid (uACF) Spray System

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ABSTRACT

Nowadays, due to limited resources and manufacturers desire to keep manufacturing costs at the lowest level, minimum quantity lubrication systems stand out. Ultrasonic atomisation based cutting fluid (uACF) spraying system, which is one of the minimum quantity lubrication methods, has been compared with conventional cooling systems on different performance parameters. The study concluded that the uACF system can outperform or compete with other cooling conditions in all performance outputs with the right choice of cutting parameter combination.In addition, the study also revealed the effects of cutting speed and feed rate levels on performance outputs under different cooling conditions. In the light of the data obtained from the study, it is concluded that the uACF system, which has a much lower installation cost compared to complex MQL methods, provides good performance under real cutting conditions with a low amount of cutting fluid consumption (0.5 ml/min) and has a high utilisation potential.

Ultrasonik Atomizasyona Dayalı Kesme Sıvısı (uACF) Püskürtme Sisteminin Performansı Üzerine Bir Araştırma

MAKALE BİLGİSİ

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Anahtar Kelimeler:
Atomizasyon tabanlı kesme sıvısı
Minimum miktarda yağlama
Kesme kuvveti
Kesme sıcaklığı
Ortalama yüzey pürüzlülüğü
Talaş büzüşme katsayısı

ÖZET

Günümüzde, kaynakların sınırlı olması ve üreticilerin imalat maliyetlerini en düşük seviyede tutmak istemesi sebebiyle minimum miktarda yağlama sistemleri ön plana çıkmaktadır. Minimum miktarda yağlama yöntemlerinden biri olan ultrasonik atomizasyon tabanlı kesme sıvısı (uACF) püskürtme sistemi geleneksel soğutma sistemleri ile farklı performans parametreleri üzerine mukayese edilmiştir. Gerçekleştirilen çalışma ile, uACF sisteminin doğru kesme parametre kombinasyonu seçimiyle bütün performans çıktılarında diğer soğutma şartlarına karşı üstünlük sağladığı veya rekabet edebileceği sonucuna varılmıştır. Bununla birlikte, çalışma neticesinde kesme hızı ve ilerleme oranı seviyelerinin farklı soğutma şartları altında performans çıktıları üzerine etkileri de ortaya çıkarılmıştır. Çalışmadan elde edilen veriler ışığında, karmaşık MMY yöntemlerine göre çok daha düşük kurulum maliyetine sahip uACF sisteminin düşük miktarda kesme sıvısı tüketimiyle (0.5 ml/dak) gerçek kesme şartları altında iyi bir performans sağladığı ve yüksek bir kullanım potansiyeline sahip olduğu sonucuna ulaşılmıştır.

1. INTRODUCTION (GİRİŞ)

Cooling and lubrication are very important factors in machining applications, especially in the machining of heavy metals such as titanium and steel [1]. The application of cutting fluids to provide cooling and lubrication with the right parameters has a direct effect on machining process stability and production cost. The positive effects of cutting fluid use on different performance parameters such as reducing cutting forces, reducing friction and temperature in the cutting zone, increasing cutting tool life and reducing surface roughness values have been proven by numerous academic studies. However, it is also known that cutting fluid creates a serious cost burden for manufacturers and harms human health. Studies have shown that the cost of cutting fluid occupies a

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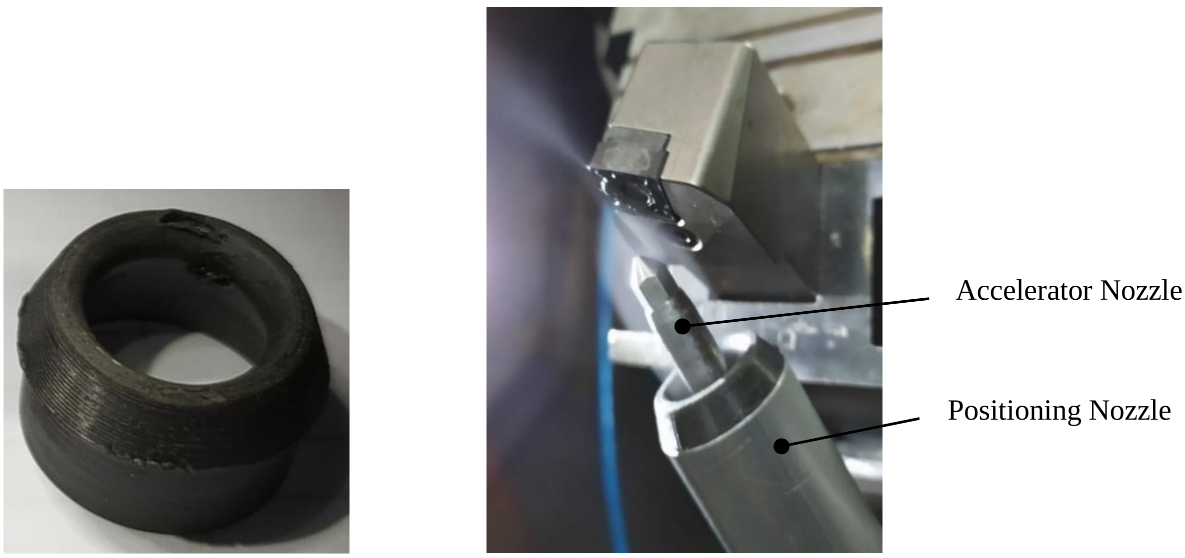
significant volume of 14% in production costs [2]. Cutting fluid can also harm human health by causing skin and respiratory diseases such as dermatitis, skin cancer, skin infections, lung and respiratory tract irritations [3]. In this context, researchers have conducted numerous studies on the consumption of cutting fluid at a minimum level while keeping cutting efficiency at the highest level. Systems that atomize a small amount of cutting fluid with air mixture at high pressure and apply it to the cutting zone are called minimum quantity lubrication (MQL). These systems are also called near dry cooling and lubrication because only 2% of the applied cutting fluid adheres to the chip. However, traditional cooling methods consume approximately 1000 times more cutting fluid than MQL lubrication systems (0.1 ml/min-2ml/min) [4]. The demands of manufacturers to increase product performance and reduce production cost, as well as the desire to create an eco-friendly production and sustainable production ecosystem in the metal industry, make it attractive for researchers to work in the field of minimum amount lubrication. Studies have shown that minimum quantity lubrication systems can compete with conventional cooling methods in terms of various performance parameters under the right conditions and with the right cutting parameters. Ngoc [5] stated that the Al_2O_3/MoS2 hybrid nanofluid MQL system increases the cutting tool life and surface quality by cooling and lubricating much more effectively than other cooling conditions in the heavy turning process. Khanna [6] observed the effects of different cooling conditions on different performance parameters in drilling VT-20 alloy material. As a result of the study, it was evaluated that hybrid nanoparticles (NPs) immersed electrostatic minimum quantity lubrication (HNPEMQL) system gave highly competitive results on the basis of different performance parameters. Shukla [7] compared the soybean-containing MQL system with dry machining in the turning of AISI 304 steel. The lubrication provided by the MQL system in reducing the cutting forces resulted in a more effective result than dry cutting. Liaoa [8] determined that the effective cooling provided by the MQL system increased the cutting tool life and surface quality compared to traditional cooling methods. Davim [9] compared the minimum quantity lubrication system with flood cooling in terms of cutting forces, power consumption, surface roughness and chip form. As a result of the study, it was seen that the MQL system gave better or similar results in terms of relevant performance parameters. Attanasio [10] found that if the MQL application was applied to the flank surface, it effectively lubricated, reducing cutting tool wear and increasing cutting tool life. Hoyne [11] concluded that the ACF system effectively penetrates the cutting zone and forms a thin film layer compared to the use of conventional cutting fluid, effectively reduces the friction coefficient and the temperature in the cutting zone, and therefore increases the life of the cutting tool. Sivalingam [12] stated that the fine droplets transferred to the cutting zone by the ACF system remove heat from the zone, reduce the friction coefficient and prevent BUE formation, thus significantly reducing cutting tool wear compared to dry conditions. In addition, the ACF system provides better surface roughness results due to these parameter improvements. Dhar [13] found that the MQL system was more successful in reducing the temperature in the cutting zone than traditional cooling methods and prevented the formation of BUE. Vikram [14] concluded that the MQL method effectively penetrates the cutting zone, regulates the friction distribution and reduces the cutting forces. The result that the MQL method reduces surface roughness and cutting forces, especially in low cutting parameter combinations, was discussed in Rahman's [15] study. Khan [16] found that the MQL application reduces cutting tool flank wear and prevents notch wear much more effectively than traditional cooling methods, and thus the best surface roughness is obtained. It is thought that the oil mist produced by minimal quantity lubrication systems penetrates and adheres to the cutting zone more effectively due to its small size. The ultrasonic-based minimal lubrication method is one of the minimum quantity lubrication systems that converts the cutting fluid into particles ranging from 10-50 µm by means of ultrasonic components [17]. In this respect, conventional MQL systems differ from ultrasonic atomization-based minimal lubrication systems in terms of the method of atomizing the cutting fluid. Ultrasonic based cutting fluid application system has been chosen as the subject of research due to the limited number of studies on it and its evaluation as a unique system open to development. The main objective of the study is to demonstrate the effectiveness of the ultrasonic-based coolant spray (uACF) system under real cutting conditions in comparison with other conventional cooling methods and to reveal the optimum cutting parameters. In addition, this comprehensive study, which comparatively demonstrates a large number of performance parameters, is intended to be a reference for subsequent studies.

2. MATERIAL AND METHOD (MATERYAL VE YÖNTEM)

2.1. Ultrasonic Atomization-based Cutting Fluid Sprey System (uACF) (Ultrasonik Atomizasyon Tabanlı Kesme Sıvısı Püskürtme Sistemi (uACF))

Ultrasonic atomization-based cutting fluid spraying system is a minimal amount lubrication method that atomizes the cutting fluid into droplets of 10-50 μm in size by means of piezoceramic components, forming a thin film layer in the cutting zone for cooling and lubrication. Compared to complex MQL systems, this uACF system is a much more cost-effective and accessible system built with ultrasonic-based components, with minimal lubrication characteristics. uACF system has potential to be an important green production method due to its very low consumption (0.5 ml/min) of cutting fluid. In addition to this, there is no cutting fluid disposal and cycle cost since the low amount of cutting fluid used is vaporised in the cutting zone. The ultrasonic atomization-based cutting fluid spray system used in the experiment and developed, manufactured and tested by Kafkas [17] basically consists of two main parts. These parts are ultrasonic mist generator and nozzle system. The ultrasonic mist generator consists of a reservoir, atomization chamber, fan, mist generating piezoceramic discs, drive circuit and DC power unit. The cutting fluid in the reservoir turns into small droplets by vibration of piezoceramic discs (0.7 mm thickness, 113 kHz resonance frequency) fixed on a thin stainless-steel foil with micro holes (0.15 mm thickness, 5 μm hole size, 1000 pores). The mist formed by the piezoceramic discs is collected in the atomisation circle to be discharged and then conveyed to the nozzle system through flexible hoses by a fan providing a low-speed air flow. The nozzles fixed to the tool turret include a positioning nozzle and an accelerating nozzle. There is an orifice with a hole diameter of 1 mm in the outlet part of the acceleration nozzle located in the centre of the positioning nozzle and a high-speed air jet is created with the help of high-pressure air. At the outlet of the system, there is a replaceable nozzle tip attached to the positioning nozzle. The interchangeable nozzle tip is shown in Figure 1a. The nozzle tip used in the experiment is called flat-wide nozzle and this nozzle was selected by considering the optimum parameters obtained in the study conducted by Kafkas [17]. The nozzle parameters used in the study are presented in Table 1. As can be seen in Figure 1b, the mist transmitted at low speed by the positioning nozzle is combined with the pressurised air jet provided by the accelerator nozzle at the exit and is transmitted to the cutting zone as a high-speed aerosol.



(a) **(b)**

Figure 1. (a) Flat-wide nozzle Tip and (b) uACF nozzle components and position of cutting tool-uACF system

Table 1. Nozzle Parameters (Nozul Parametreleri)

Parameter	Value
Liquid Concentration	5%
Nozzle Diameter	0.8 mm
Horizontal Nozzle Angle	30 deg
Vertical Nozzle Angle	45 deg
Nozzle Distance	30 mm
Air Pressure	6 bar
Mist Flow Rate	0.5 ml/min
Nozzle Type	Flat-wide nozzle

2.2. Experimental Design (Deneysel Tasarım)

In the experiments, the turning process was carried out on a Johnford TC-35 horizontal CNC lathe. This lathe, which has a Fanuc control unit, has a power of 13 kW and a maximum speed of 3.500 rpm. The turning process was carried out with a Sumitomo brand SNMG 120408-NGU cutting tool. The cutting tool has a multilayer (Al2O3 + TiCN) coating produced by the CVD method. A new replaceable cutting tip was used for each cutting combination. Hot-rolled ∅100x500 mm cylindrical AISI 1050 steel with a hardness of 135 HB was selected as the workpiece material. This material, which is called manufacturing steel, contains 0.50% carbon and is widely preferred in bolts, shafts, low life tools and mould sets. Before starting the experiments, the workpiece was pre-turned to a diameter of 94 mm to create a clean entry surface and to eliminate possible runout. In the study, a semi-synthetic and water-based cutting fluid with an oil content of 5% by volume was used.

The experimental study plan was designed according to Taguchi L_9 (3x3) orthogonal arrangement. In accordance with this arrangement, three different levels of cutting speed (100 m/min, 130 m/min, 170 m/min) and feed rate (0.15 mm/rev, 0.2 mm/rev, 0.25 mm/rev) were selected. Medium level of cutting speed (100 m/min) and feed rate (0.2 mm/rev) were selected according to recommended cutting tool (Sumitomo brand SNMG 120408-NGU) value in the catalog. To observe the effect of cutting speed and feed rate changes on the performance parameters, the medium level parameters were significantly increased and decreased between 25-30%. Table 2 shows the working parameters and their levels in a tabular form. Cutting speed is symbolized as "*Vc*" and feed rate is symbolized as "*f*". In order to observe the effects of cooling conditions and cutting parameters on the performance parameters, all cutting speed and feed rate combinations were repeated for different cooling conditions. These cooling conditions are: spray cooling (SPR), ultrasonic atomization-based cutting fluid spray (uACF), compressed air cooling (AIR) and dry cutting (DRY). Cooling conditions are presented in Table 3. Thirty-six different experimental combinations were performed in the study, including three different levels of cutting speed, three different levels of feed rate and four different cooling conditions. The parameter combinations of the experimental studies and the experimental plan according to the L_9 orthogonal arrangement are shown in Table 4. Cutting force (*Fc*), cutting temperature (*Tc*), average surface roughness (*Ra*) and chip shrinkage coefficient (ξ) were considered as performance characteristics. The aim of the study is to demonstrate the effectiveness of uACF, which has a much lower cutting fluid consumption (0.5 ml/min) compared to its counterparts, against alternative cooling methods on the considered performance characteristics.

Table 2. Experimental parameters and levels (Deneysel parametreler ve seviyeleri)

Symbol	Parameter	Level 1	Level 2	Level 3
Vc	Cutting Speed (m/min)	100	130	170
f	Feed rate (mm/dev)	0.15	0.2	0.25

Table 3. Cooling condition parameters and levels (Soğutma şartı parametreleri ve seviyeleri)

		Level			
Symbol	**Parameter**	**1**	**2**	**3**	**4**
CC	Cooling Condition	SPR	uACF	AIR	DRY

Table 4. L_9 (3^2) * 4 orthogonal array of experimental studies (Deneysel çalışmaların L_9 (3^2) * 4 ortogonal dizini)

Non-Coded Values				**Coded Values**				**Non-Coded Values**				**Coded Values**			
No	***CC***	***Vc***	***f***	**No**	***CC***	***Vc***	***f***	**No**	***CC***	***Vc***	***f***	**No**	***CC***	***Vc***	***f***
1	SPR	100	0.15	**1**	1	1	1	**19**	AIR	100	0.15	**19**	3	1	1
2	SPR	100	0.2	**2**	1	1	2	**20**	AIR	100	0.2	**20**	3	1	2
3	SPR	100	0.25	**3**	1	1	3	**21**	AIR	100	0.25	**21**	3	1	3
4	SPR	130	0.15	**4**	1	2	1	**22**	AIR	130	0.15	**22**	3	2	1
5	SPR	130	0.2	**5**	1	2	2	**23**	AIR	130	0.2	**23**	3	2	2
6	SPR	130	0.25	**6**	1	2	3	**24**	AIR	130	0.25	**24**	3	2	3
7	SPR	170	0.15	**7**	1	3	1	**25**	AIR	170	0.15	**25**	3	3	1
8	SPR	170	0.2	**8**	1	3	2	**26**	AIR	170	0.2	**26**	3	3	2
9	SPR	170	0.25	**9**	1	3	3	**27**	AIR	170	0.25	**27**	3	3	3
10	uACF	100	0.15	**10**	2	1	1	**28**	DRY	100	0.15	**28**	4	1	1
11	uACF	100	0.2	**11**	2	1	2	**29**	DRY	100	0.2	**29**	4	1	2
12	uACF	100	0.25	**12**	2	1	3	**30**	DRY	100	0.25	**30**	4	1	3
13	uACF	130	0.15	**13**	2	2	1	**31**	DRY	130	0.15	**31**	4	2	1
14	uACF	130	0.2	**14**	2	2	2	**32**	DRY	130	0.2	**32**	4	2	2
15	uACF	130	0.25	**15**	2	2	3	**33**	DRY	130	0.25	**33**	4	2	3
16	uACF	170	0.15	**16**	2	3	1	**34**	DRY	170	0.15	**34**	4	3	1
17	uACF	170	0.2	**17**	2	3	2	**35**	DRY	170	0.2	**35**	4	3	2
18	uACF	170	0.25	**18**	2	3	3	**36**	DRY	170	0.25	**36**	4	3	3

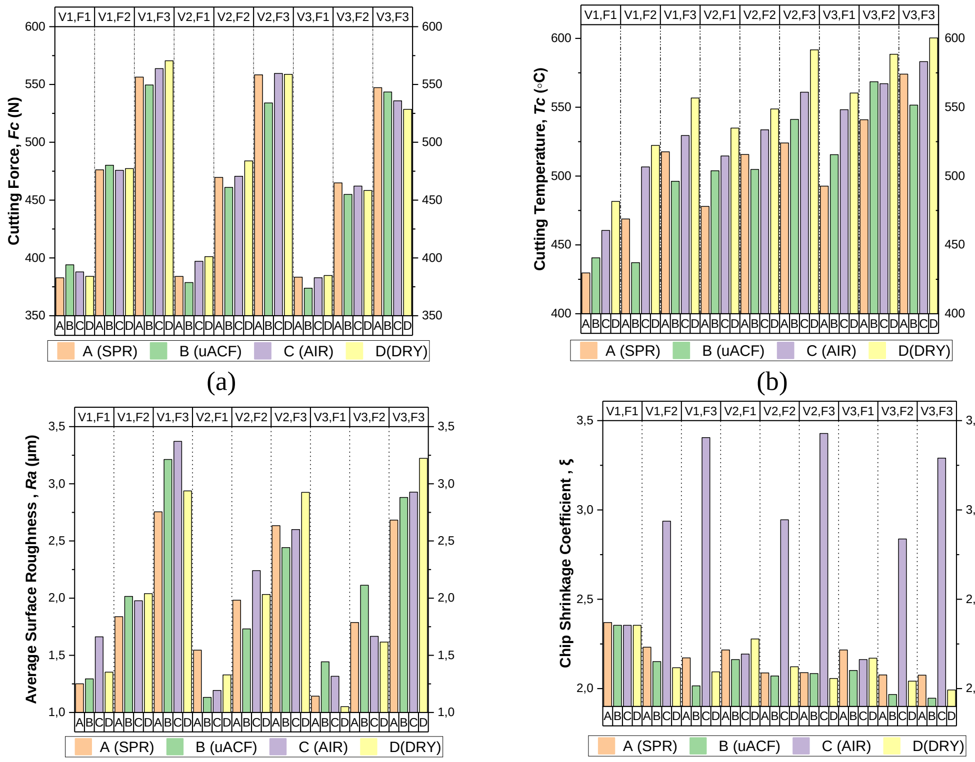
The cutting force (*Fc*) was measured with a three-component piezoelectric dynamometer (Kistler 9257A). The signals received by the dynamometer were amplified with a load amplifier (Kistler 5019) and transmitted to the Dynoware 2825AI-2 software and recorded. The cutting temperature (*Tc*) was measured with a Raytek-MI31002MSF1 brand non-contact infrared (IR) pyrometer device. The pyrometer device, which was placed at a distance of 20 cm behind the tool tip, was precisely fixed to the tool turret. The pyrometer device was adjusted in a position to take precise measurements from the tool tip where the cutting temperature was maximum. The temperature detection range of the IR pyrometer is 250–1400 ºC, its spectral response is 1.6 µm, its optical resolution is 100:1, its response time is 10 ms, and its reading accuracy is ±2 ºC. The data obtained by the thermometer were transferred to the "DataTempMultidrop" software and recorded. After the turning process was completed, Mitutoyo SJ-201 portable surface profilometer was used to measure the average surface roughness (*Ra*) value. The measurements were taken from a 2.5 mm sample length and the device was calibrated with a standard calibration gauge before each measurement. In order to determine the chip shrinkage coefficient (ζ), the chips that underwent plastic deformation during the turning process were measured with a digital caliper with 0.01 mm sensitivity and then the chip shrinkage coefficient (ζ) was calculated by taking into account the "ratio of the cut chip thickness ($a2$) to the uncut chip thickness ($a1$)" ($\zeta = a2/a1$, $a1 = f{\cdot}sin(\varphi)$, f: feed rate-mm/rev, φ: angle of cutting tool approach -degree).

3. RESULTS AND DISCUSSION (SONUÇLAR VE TARTIŞMA)

The experimental study was carried out according to the Taguchi L9 experimental design plan given in Table 4. Table 5 shows the results of cutting force (*Fc*), cutting temperature (*Tc*), average surface roughness (*Ra*) and chip shrinkage coefficient (ζ) obtained according to the experimental plan in Table 4. In order to understand the effects of the operating parameters and cooling conditions on the performance parameters by making preliminary evaluations of the operating parameters and cooling conditions, the results were plotted as shown in Figure 2. In Figure 2, the effect of cutting speed and feed rate combinations on different performance parameters under different cooling conditions is expressed as a bar graph.

Table 5. Experimental results (Deneysel sonuçlar)

Experimental results									
No	***Fc***	***Tc***	***Ra***	**ξ**	**No**	***Fc***	***Tc***	***Ra***	**ξ**
1	382.79	429.66	1.25	2.37	**19**	387.91	460.49	1.66	2.35
2	476.21	468.80	1.84	2.23	**20**	475.78	506.65	1.98	2.94
3	556.38	517.65	2.76	2.17	**21**	563.70	529.49	3.37	3.40
4	384.03	477.96	1.55	2.22	**22**	397.12	514.65	1.19	2.19
5	469.59	515.70	1.98	2.09	**23**	470.61	533.60	2.24	2.94
6	558.39	524.07	2.63	2.09	**24**	559.53	560.96	2.60	3.43
7	383.39	492.71	1.14	2.22	**25**	382.90	548.22	1.32	2.16
8	464.89	540.90	1.79	2.08	**26**	462.13	567.13	1.67	2.84
9	547.24	574.10	2.68	2.08	**27**	535.84	583.17	2.93	3.29
10	394.07	440.62	1.29	2.35	**28**	384.08	481.57	1.35	2.35
11	480.14	437.09	2.02	2.15	**29**	477.29	522.26	2.04	2.12
12	549.60	496.21	3.21	2.02	**30**	570.53	556.73	2.94	2.09
13	378.70	503.89	1.13	2.16	**31**	401.09	534.89	1.33	2.28
14	461.02	504.83	1.73	2.07	**32**	483.88	548.79	2.03	2.12
15	534.00	541.14	2.44	2.08	**33**	558.81	591.70	2.93	2.06
16	373.82	515.56	1.44	2.10	**34**	384.82	560.36	1.05	2.17
17	454.91	568.54	2.11	1.97	**35**	458.30	588.49	1.62	2.04
18	543.52	551.53	2.88	1.95	**36**	528.50	600.39	3.22	1.99



(b) (d)

Figure 2. Variation graphs of performance characteristics: (a) cutting force, (b) cutting temperature, (c) average surface roughness, (d) chip shrinkage coefficient

3.1. Evaluation of Cutting Forces (Kesme Kuvvetlerinin Değerlendirilmesi)

Cutting forces are generated when the cutting tool removes chips from the workpiece. The largest force occurring in the turning process is the 'main cutting force (Fc)' and this force occurs tangent to the direction of rotation. The high level of cutting forces negatively affects the machining and product performance and increases the energy consumed. With the analyses, the effect of cutting speed, feed rate and cooling condition changes on the cutting force has been revealed.

Table 6. ANOVA results table for cutting forces (Kesme kuvvetleri için ANOVA sonuç tablosu)

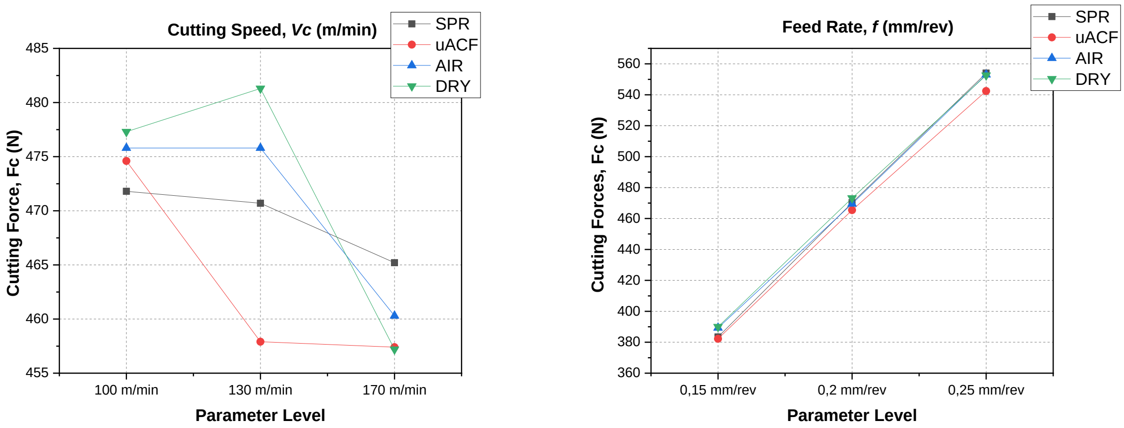
Cooling Condition Parameter	Experimental Parameter	Degrees of Freedom (DOF)	Sum of Squares (SS)	Mean squares (MS)	F-Rate	P-Value	Contribution Rate (%)
SPR	*Vc*	2	75.3	37.6	2.48	0.199549	0.17%
	f	2	43662	21831	1436.75	0.000002	99.69%
	Error	4	60.8	15.2			0.14%
	Total	8	43798.1				100.00%
uACF	*Vc*	2	574.6	287.3	9.65	0.029490	1.47%
	f	2	38504.4	19252.2	646.34	0.000010	98.23%
	Error	4	119.1	29.8			0.30%
	Total	8	39198.2				100.00%
AIR	*Vc*	2	479.6	239.8	5.61	0.069115	1.17%
	f	2	40207.9	20104	470.12	0.000018	98.41%
	Error	4	171.1	42.8			0.42%
	Total	8	40858.6				100.00%
DRY	*Vc*	2	998.1	499	4.15	0.105600	2.43%
	f	2	39675.6	19837.8	165.13	0.000100	96.41%
	Error	4	480.5	120.1			1.17%
	Total	8	41154.3				100.00%

In Figure 2a, the effect of cutting speed and feed rate combinations on the cutting force under different cooling conditions can be seen in the form of a bar graph. In order to compare the effect levels of the control parameters on the cutting force under different cooling conditions, ANOVA analysis was performed as shown in Table 6. Table 6 shows that as a result of the ANOVA analysis, the feed rate is the dominant parameter on the cutting force under all cooling conditions and has an effect of more than 96%. It is seen that cutting speed variation is significant on the cutting force parameter only for the uACF condition. When Figure 2a and Table 6 are analysed, it is seen that cutting speed and cooling condition have a much lower effect on cutting force than feed rate.

Table 7. Response table of cutting speed and feed rate levels on cutting forces (Kesme hızı ve ilerleme oranı seviyelerinin kesme kuvvetleri üzerindeki cevap tablosu)

Cooling Condition Parameter	Experimental Parameter	Level 1	Level 2	Level 3	Max-Min	Ranking
SPR	***Vc***	471.8	470.7	**465.2**	6.6	2
	f	**383.4**	470.2	554.0	170.6	1
uACF	***Vc***	474.6	457.9	**457.4**	17.2	2
	f	**382.2**	465.4	542.4	160.2	1
AIR	***Vc***	475.8	475.8	**460.3**	15.5	2
	f	**389.3**	469.5	553	163.7	1

DRY	***Vc***	477.3	481.3	**457.2**	24.1	2
	f	**390.0**	473.2	552.6	162.6	1



(a) (b)

Figure 3. Main effect graph of cutting speed (a) and feed rate (b) levels on cutting forces

In Table 7, the response table for the effect of cutting speed, feed rate and cooling condition changes on the cutting force is presented. In Figure 3, the response table of the cutting force is graphised. In the light of the results obtained, it is seen that the use of the highest level of cutting speed decreases the cutting forces in all cooling conditions, although it does not have a linear and regular effect. On the other hand, it was found that the feed rate increase dramatically raised the cutting force in all cooling conditions and the feed rate-cutting force relationship was more stable. It is considered that the increase in cutting speed rises the cutting temperature, allowing thermal softening [18]. Additionally, increase in cutting speed reduces the tool-chip contact area, thus reducing cutting forces [19]. It can be said that the increase in feed rate increases the cutting forces by increasing the chip load and vibration [20].

In reducing cutting forces, uACF is generally superior to other cooling conditions. It is thought that the small-sized droplets formed by the uACF system successfully penetrate the cutting zone and form a thin film layer, regulate chip formation and friction distribution, and therefore reduce the cutting force. In the study, the lowest cutting force was obtained at the combination of 170 m/min cutting speed, 0.15 mm/rev feed rate and ‘uACF’ cooling condition. The highest cutting force was observed under 100 m/min cutting speed, 0.25 mm/rev feed rate and ‘DRY’ cutting condition.

3.2. Evaluation of Cutting Temperature (Kesme Sıcaklığının Değerlendirilmesi)

In all machining processes, it is known that high temperatures occur in the cutting zone with the contact of the workpiece and the cutting tool. Uncontrolled temperature increases the wear of the cutting tool and leads to undesirable results such as reduction in tool life, dimensional and geometrical mismatch, deformation of the workpiece.

Table 8 shows the result of ANOVA analysis to measure the effect of cutting speed and feed rate parameters on cutting temperature under different cooling conditions. With this analysis, it is seen that cutting speed and feed rate parameters are important parameters on the cutting temperature under all cooling conditions in general. Under spray cooling condition, the effectiveness of feed rate is more prominent, while cutting speed is more effective under other cooling conditions. The effectiveness of cutting speed on cutting temperature increased under uACF cooling condition. It is concluded that cutting speed, feed rate and cooling condition parameters are all effective and the right combination of cutting conditions should be made in order to minimise the cutting temperature.

While the response table of cutting speed and feed rate variations on cutting temperature under different cooling conditions is given in Table 9, Figure 4 shows the main effects of cutting speed and feed rate on cutting temperature graphically.

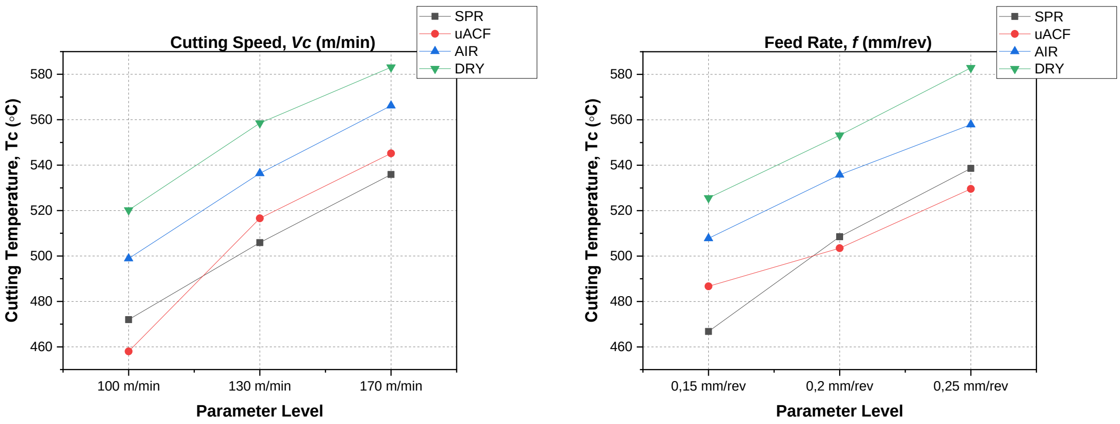
Table 8. ANOVA results table for cutting temperature, Tc (Kesme sıcaklığı, *Tc*, için ANOVA sonuç tablosu)

Cooling Condition Parameter	Experimental Parameter	Degrees of Freedom (DOF)	Sum of Squares (SS)	Mean squares (MS)	F-Rate	P-Value	Contribution Rate (%)
SPR	*Vc*	2	6125.8	3062.9	19.23	0.009	42.05%
	f	2	7805.1	3902.6	24.5	0.006	53.58%
	Error	4	637.3	159.3			4.37%
	Total	8	14568.2				100.00%
uACF	*Vc*	2	11868	5934.2	13.52	0.017	72.22%
	f	2	2809	1404.6	3.2	0.148	17.09%
	Error	4	1756	439			10.69%
	Total	8	16434				100.00%
AIR	*Vc*	2	6822.9	3411.46	35.28	0.003	62.08%
	f	2	3780.8	1890.4	19.55	0.009	34.40%
	Error	4	386.8	96.7			3.52%
	Total	8	10990.5				100.00%
DRY	*Vc*	2	6026.4	3013.2	24.25	0.006	52.61%
	f	2	4932.4	2466.2	19.85	0.008	43.06%
	Error	4	497	124.2			4.34%
	Total	8	11455.8				100.00%

As seen in Figure 4, it is observed that the cutting temperature rises with the increase of cutting speed and feed rate. It is thought that the energy released by increasing the cutting speed and feed rate values increases the chip load and friction, which causes an increase in the cutting temperature [16]. It has been evaluated that while the cutting tool-chip contact area increases with the increase in feed rate [21]. The deformation of the removed chip increases with the increase in cutting speed and feed rate [22]. In the light of the data obtained, it was observed that the cutting temperature was the highest under dry cutting condition at all cutting speed and feed rate levels, followed by compressed air cooling. It is thought that under dry cutting and compressed air cooling conditions, chip evacuation from the cutting zone is weak compared to other cutting conditions, so the cutting temperature reaches maximum levels.

Table 9. Response table of cutting speed and feed rate levels on cutting temperature

Cooling Condition Parameter	Experimental Parameter	Level			Max-Min	Ranking
		1	**2**	**3**		
SPR	***Vc***	**472**	505.9	535.9	63.9	2
	f	**466.8**	508.5	538.6	71.8	1
uACF	***Vc***	**458**	516.6	545.2	87.2	1
	f	**486.7**	503.5	529.6	42.9	2
AIR	***Vc***	**498.9**	536.4	566.2	67.3	1
	f	**507.8**	535.8	557.9	50.1	2
DRY	***Vc***	**520.2**	558.5	583.1	62.9	1
	f	**525.6**	553.2	582.9	57.3	2



(a) (b)

Figure 4. Main effect graph of cutting speed (a) and feed rate (b) levels on cutting temperature (Kesme hızı (a) ve ilerleme oranı (b) seviyelerinin kesme sıcaklığı üzerindeki ana etki grafiği)

The highest cutting temperature value was observed under the cutting speed of 170 m/min, feed rate of 0.25 mm/rev and "DRY" cutting condition. Under the cutting speed of 100 m/min, feed rate of 0.15 mm/rev and "SPR" cutting condition, the lowest cutting temperature value was obtained. It was observed that the cutting temperature was reduced much more effectively in spray cooling and ultrasonic atomization based minimal lubrication systems. It is evaluated that under these conditions, the chip is removed from the cutting area more effectively and the lubrication effect reduces friction. It can be said that the small droplets formed by the uACF cooling system accelerate and gain momentum with the carrier gas, form a thin film layer, reduce the cutting temperature by effectively cooling and lubricating, and are as effective as the SPR method with the advantage of less fluid consumption.

3.3. Evaluation of Average Surface Roughness (Ortalama Yüzey Pürüzlülüğünün Değerlendirilmesi)

Table 10 shows the results of ANOVA analysis to compare the effect of feed rate and cutting speed parameters on the average surface roughness under different cooling conditions.

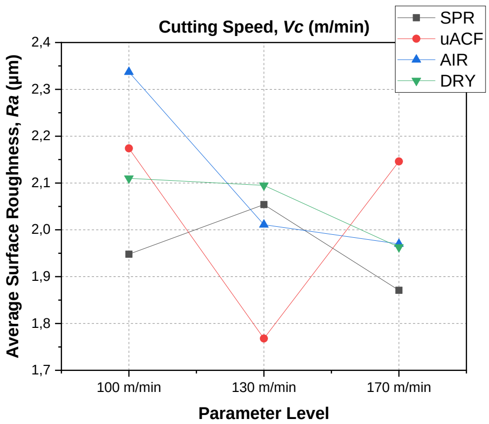
Table 10. ANOVA results table for average surface roughness, Ra

Cooling Condition Parameter	Experimental Parameter	Degrees of Freedom (DOF)	Sum of Squares (SS)	Mean squares (MS)	F-Rate	P-Value	Contribution Rate (%)
SPR	*Vc*	2	0.05046	0.02523	1.58	0.3125	1.68%
	f	2	2.88224	1.44112	90.11	0.0005	96.18%
	Error	4	0.06397	0.01599			2.13%
	Total	8	2.99667				100.00%
uACF	*Vc*	2	0.3077	0.15387	5.19	0.0773	7.54%
	f	2	3.6564	1.82818	61.71	0.001	89.56%
	Error	4	0.1185	0.02962			2.90%
	Total	8	4.0826				100.00%
AIR	*Vc*	2	0.242	0.121	1.42	0.342	5.50%
	f	2	3.8167	1.90835	22.37	0.007	86.74%
	Error	4	0.3413	0.08533			7.76%
	Total	8	4.4				100.00%
DRY	*Vc*	2	0.03915	0.01958	0.41	0.689	0.76%
	f	2	4.89177	2.44588	51.15	0.001	95.50%
	Error	4	0.19128	0.04782			3.73%
	Total	8	5.1222				100.00%

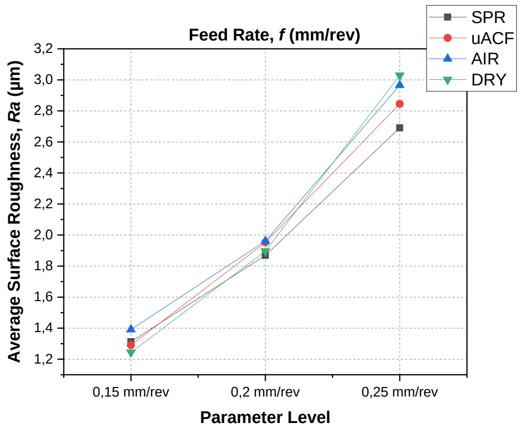
It was observed that feed rate was the most dominant parameter on surface roughness under all cooling conditions. Although the effect of feed rate on the average surface roughness parameter varied minimally under different cooling conditions, it showed parallel results. This effect level varies between 86.74% and 96.18%. It is evaluated that cutting speed variation has a low level of effect and significance on the average surface roughness. In addition, it was determined that the selection of different cutting parameter combinations under the correct cooling condition has an effect on the average surface roughness, but this effect level is very low compared to the feed rate change. Akgün [23] examined the effects of feed rate, cutting speed and insert radius on surface roughness and found that feed rate was the most effective parameter with 57.6%. Gan [24] showed that feed rate is much more effective than cutting speed on surface roughness. Yasir [25] found that cutting speed had no significant effect on the surface roughness parameter, while feed rate was quite dominant. Increasing feed rate significantly increases vibration and chip formation intensity, negatively affecting surface roughness.

Table 11. Response table of cutting speed and feed rate levels on average surface roughness

Cooling Condition Parameter	Experimental Parameter	Level 1	Level 2	Level 3	Max-Min	Ranking
SPR	*Vc*	1.948	2.054	**1.871**	0.183	2
	f	**1.313**	1.869	2.691	1.378	1
uACF	*Vc*	2.174	**1.768**	2.146	0.406	1
	f	**1.29**	1.953	2.845	1.555	2
AIR	*Vc*	2.337	2.011	**1.97**	0.367	1
	f	**1.391**	1.961	2.966	1.575	2
DRY	*Vc*	2.11	2.095	**1.963**	0.147	1
	f	**1.244**	1.896	3.029	1.785	2



(a)



(b)

Figure 5. Main effect graph of cutting speed (a) and feed rate (b) levels on average surface roughness (Kesme hızı (a) ve ilerleme oranı (b) seviyelerinin ortalama yüzey pürüzlülüğü üzerindeki ana etki grafiği)

The response table for the changes in the average surface roughness due to the changes in the cutting level and feed rate is given in Table 11 and these data are shown as main effect graphs in Figure 5. When the graphs in Figure 5 are examined, it is seen that the effect of the cutting speed on the average surface roughness is irregular and unstable. While the medium level cutting speed under the uACF gives the lowest surface roughness result for this condition, the lowest average surface roughness value under other cooling conditions is seen at the highest level cutting speeds. The increase in cutting speed rises the temperature in the cutting zone, reduces the formation of built-up chips and reveals the softening of the material. For these reasons, while the appropriate amount of cutting speed has a positive effect on the surface roughness, excessive cutting speed increases the vibration and cutting tool lateral wear and increases the surface roughness. Very low cutting speeds can cause subsurface micro cracks [19]. The highest avarage surface roughness values were observed under the cutting speed of 100 m/min, feed rate of 0.25 mm/rev and "DRY" cutting condition. The lowest avarage surface roughness values were observed under the cutting speed of 170 m/min, feed rate of 0.15 mm/rev and "DRY" cutting condition.

It was observed that the effect of feed rate on the average surface roughness was much more stable than the cutting speed. With the increase in the feed rate parameter, tool marks, cutting loads and plastic deformation rises. For this reason, it was observed that the increase in feed rate had a high level of effect on the increase in average surface roughness under all cooling conditions and was the most effective parameter. It was observed that the uACF cooling condition was quite effective in reducing surface roughness under medium cutting speed and low feed rate conditions. It is thought that the increase in cutting speed triggered faster chip formation and caused the chips to accumulate at the cutting tool edge. For this reason, it was evaluated that the surface roughness increased by preventing the atomized cutting fluid generated by the uACF system from passing to the cutting zone [1]. It was determined that the ultrasonic atomization-based minimal lubrication system could compete with other cooling conditions under the correct combination of cutting parameters and produced successful average surface roughness results.

3.4. Evaluation of Effects on Chip Shrinkage Coefficient (Talaş Büzüşme Katsayısı Üzerine Etkilerin Değerlendirilmesi)

In chip removal operations, the progress of the cutting tool by sinking into the workpiece to a certain extent causes the phenomenon of plastic deformation and causes the formation of chips. The chip compressed by the effect of pressure expands compared to the uncut chip. The low coefficient of chip shrinkage is an important parameter in this context in terms of indicating the ease of plastic deformation.

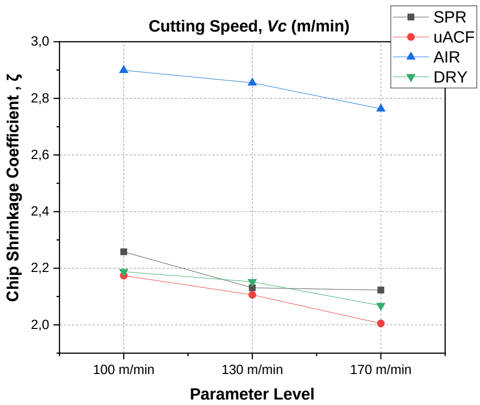
Table 12. ANOVA result table for chip shrinkage coefficient, ξ (Talaş büzüşme katsayısı, ξ, için ANOVA sonuç tablosu)

Cooling Condition Parameter	Experimental Parameter	Degrees of Freedom (DOF)	Sum of Squares (SS)	Mean squares (MS)	F-Rate	P-Value	Contribution Rate (%)
SPR	*Vc*	2	0.03437	0.017183	39.2	0.0024	43.49%
	f	2	0.04291	0.021454	48.94	0.0015	54.30%
	Hata	4	0.00175	0.000438			2.22%
	Toplam	8	0.07903				100.00%
uACF	*Vc*	2	0.04325	0.021624	4.76	0.087	35.88%
	f	2	0.05912	0.029559	6.51	0.055	49.05%
	Hata	4	0.01816	0.00454			15.07%
	Toplam	8	0.12052				100.00%
AIR	*Vc*	2	0.02871	0.014356	5.41	0.07282	1.44%
	f	2	1.96134	0.980669	369.65	0.00003	98.03%
	Hata	4	0.01061	0.002653			0.53%
	Toplam	8	2.00066				100.00%
DRY	*Vc*	2	0.02277	0.011383	12.6	0.019	21.27%
	f	2	0.08066	0.04033	44.64	0.002	75.35%
	Hata	4	0.00361	0.000903			3.38%
	Toplam	8	0.10704				100.00%

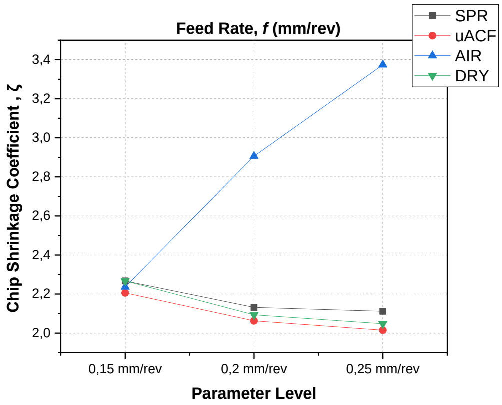
In order to determine the effect of cutting speed and feed rate values on the chip shrinkage coefficient under different cooling conditions, ANOVA analysis was performed as shown in Table 12. As a result of the analysis, it is seen that the feed rate is more effective on the chip shrinkage coefficient than the cutting speed under all cooling conditions. While this effect level is very high in compressed air cooling, it is at the lowest level in uACF system. Based on this result, it is inferred that the effect of feed rate on the chip shrinkage coefficient decreases with increasing cooling effect. It was observed that the significance and effect level of cutting speed variation on the chip shrinkage coefficient varied significantly for different cooling conditions. Cutting speed, feed rate and cooling condition parameters are all important for the chip shrinkage coefficient performance parameter and it is necessary to make the right combination of cutting conditions.

Table 13. Response table of cutting speed and feed rate levels on chip shrinkage coefficient (Kesme hızı ve ilerleme oranı seviyelerinin talaş büzüşme katsayısı üzerindeki cevap tablosu)

Cooling Condition Parameter	Experimental Parameter	Level 1	Level 2	Level 3	Max-Min	Ranking
SPR	*Vc*	2.258	2.131	**2.123**	0.135	1
	f	2.267	2.132	**2.112**	0.155	2
uACF	*Vc*	2.174	2.106	**2.005**	0.169	1
	f	2.206	2.063	**2.015**	0.191	2
AIR	*Vc*	2.899	2.855	**2.763**	0.136	1
	f	**2.237**	2.906	3.374	1.137	2
DRY	*Vc*	2.188	2.152	**2.068**	0.12	1
	f	2.267	2.094	**2.048**	0.219	2



(a)



(b)

Figure 6. Main effect graphs of cutting speed (a) and feed rate (b) levels on chip shrinkage coefficient

Table 13 and Figure 6 show the response table and main effect graphs for the effects of cutting speed and feed rate variations on the chip shrinkage coefficient under different cooling conditions, respectively. It is observed that the increase in cutting speed decreases the chip shrinkage coefficient under all cooling conditions. Increasing the feed rate decreased the chip shrinkage coefficient under all cooling conditions except the compressed air cooling condition. A low 'chip shrinkage coefficient' indicates a close interaction between the chip and the cutting tool [23]. The increase in feed rate and cutting speed values increases the temperature in the cutting zone and causes softening of the material [5]. It was found that the increase in cutting speed and feed rate reduces the chip shrinkage coefficient by facilitating plastic deformation [24-27]. It is seen that the uACF cooling system is superior to other cooling conditions in terms of chip shrinkage coefficient. The highest cutting speed (170 m/min), the highest feed rate (0.25 mm/rev) and the smallest chip shrinkage coefficient value were obtained under uACF cooling condition. The highest chip shrinkage coeffient values were observed under the cutting speed of 130 m/min, feed rate of 0.25 mm/rev and "AIR" cutting condition. It can be said that effective cooling and lubrication under uACF cooling condition facilitates plastic deformation by reducing the friction coefficient. It was observed that the chip shrinkage coefficient values observed at medium and high feed rates under compressed air cooling condition were significantly higher than the other conditions. It was observed that the chip shrinkage coefficient under AIR cooling condition was higher than the other cooling conditions. At this point, under the AIR condition, the chip-tool interface is deprived of the lubrication effect and there is a temperature drop compared to the dry cutting condition due to the effect of pressurised air. Under the AIR cooling condition, the temperature drop and the absence of lubrication make the chip deformation difficult and increase the chip shrinkage coefficient.

3.5. Discussion on the uACF System (uACF Sistemi Üzerine Tartışma)

In the light of the study, it was observed that the uACF system provided superiority or achieved close success to the best result for the performance parameters examined in the turning of AISI 1050 material compared to traditional cooling methods. However, the uACF system must be used in the correct operation and material. The uACF system can effectively penetrate the cutting zone due to the small dimensions of the atomized cutting fluid, but it is anticipated that it will be insufficient in terms of cooling and lubrication in high-volume chip removal operations due to the low pressure and amount of cutting fluid it provides. In this context, the uACF system seems unlikely to compete with innovative cooling methods such as high-pressure cooling application (HPC) and cryogenic cooling methods in terms of removing high-volume chips from the cutting zone and meeting the high cooling need. Especially in exotic materials such as Ti-6Al-4V and inconel, high-volume cooling capacity is required to reduce the high temperature occurring in the cutting zone. In low and medium volume machining operations, the uACF system provides a significant advantage in terms of easy supply of components and low cutting fluid consumption, and emerges as an alternative to expensive cooling systems. The easy integration and small dimensions of the system enable it to be used in low and medium volume milling, drilling and grinding operations. In order to use the uACF system in different machining operations, it is sufficient to adjust the nozzle exit position to penetrate the cutting zone. In order to reveal the limits and potential of the uACF system; studies can be conducted on more complex geometries, different material types, different cutting fluids and different machining operations. Unlike the performance parameters considered in the study, the uACF system has the potential to be investigated on the effects of the cutting tool wear, cutting tool life and dimensional stability. The findings and observations obtained from this study can be used in further research on uACF and similar systems.

4. CONCLUSIONS (SONUÇLAR)

This study presents the comparison of ultrasonic atomisation based cutting fluid spray system (uACF) with spray cooling (SPR), compressed air cooling (AIR) and dry cutting (DRY) conditions under different cutting speed and feed rate combinations for turning AISI 1050 carbon steel. Cutting force (*Fc*), cutting temperature (*Tc*), average surface roughness (*Ra*) and chip shrinkage coefficient (ξ) were selected as performance characteristics. In order to determine the best parameter combinations, ANOVA analyses were performed in the experimental study based on the Taguchi experimental approach to determine the effect of cutting speed and feed rate values on the performance characteristics under different cooling conditions.

1. It has been observed that the small-sized liquid droplets formed by the uACF system successfully penetrate into the cutting zone and form a thin film layer, regulate chip formation and friction distribution, and therefore are generally successful in reducing the cutting force compared to other cooling conditions. It has been evaluated that the rise in feed rate goes up the cutting force dramatically by increasing the chip load and vibration, while the increase in cutting speed reveals the concept of softening in the material and reduces the cutting force.

2. It was observed that the cutting temperature was reduced much more effectively in SPR and uACF conditions compared to other cooling conditions. It is thought that under these conditions, the chip is more effectively removed from the cutting zone and the lubrication effect reduces friction. It is observed that the cutting temperature rises with the increase of cutting speed and feed rate. Energy released by increasing the cutting speed and feed rate values increases the chip load and friction, which causes an increase in the cutting temperature.

3. It was evaluated that the rise in cutting speed causes softening of the material by increasing the cutting temperature, but too high cutting speed increase causes vibration. Since cutting speeds selected at very low levels may cause sub-surface microcracks, it is necessary to select the ideal cutting speed under the appropriate cutting condition for the surface roughness parameter. Increasing the feed rate dramatically raises the average surface roughness by increasing tool marks and cutting forces. The uACF cooling condition was found to be very effective in reducing the

surface roughness under medium cutting speed and low feed rate conditions. It is believed that the increase in cutting speed increases the chip formation and causes the cutting tool to accumulate at the cutting edge, which prevents the atomised liquid from penetrating the cutting zone properly.

4. Increasing the feed rate decreased the chip shrinkage coefficient under all cooling conditions except the compressed air cooling condition. Under the AIR cooling condition, the temperature drop and the absence of lubrication make the chip deformation difficult and increase the chip shrinkage coefficient. The increase in cutting speed and feed rate decreases the chip shrinkage coefficient by facilitating plastic deformation. uACF cooling system was found to be superior to other cooling conditions in terms of chip shrinkage coefficient. Effective cooling and lubrication under uACF cooling condition facilitated plastic deformation by reducing the friction coefficient.

5. As a result of the study, uACF system was found to be competitive in all performance parameters with almost a thousand times less cutting fluid consumption compared to conventional cooling methods, and was evaluated to have high potential.

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