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Investigation of the Performance of Ecological Cooling/Lubrication Methods in the Milling of AISI 316L Stainless Steel

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ABSTRACT

Ecological and eco-friendly cooling/lubrication methods have an important place in the sustainable manufacturing process. The hazards of the conventional cooling can be minimized, and it can be contributed the manufacturing performance, thanks to these ecological systems. In this study, the machinability of AISI 316L stainless steel under ecological cooling/lubrication methods was investigated. The face milling operation was applied to AISI 316L stainless steel for machinability examination under three different cooling cooling/lubricating conditions (minimum quantity lubrication-MQL, LN_2 and MQL+LN_2), three different cutting speeds (120, 150 and 180 m/min), constant feed rate (0.1 mm/rev) and a constant cutting depth (0.5 mm). The average surface roughness (Ra-µm), cutting temperature (T-°C), and tool wear (V_B - mm) were selected as machinability performance criteria. At the end of experiments, the lowest value of the cutting temperature (101.1 °C) was obtained at 120 m/min cutting speed under LN_2 cutting condition. The lowest value of surface roughness (0.237 µm) was obtained at 150 m/min cutting speed under MQL+LN_2 cutting condition. The lowest cutting tool flank wear (0.170 mm) was obtained under MQL+LN_2 hybrid cutting condition, at the end of 16 minutes machining time and at 180 m/min cutting speed. When the experimental results were evaluated in general, it was understood that the MQL+LN_2 hybrid cutting condition provided significant improvements in all cutting parameters compared to other cutting conditions.

AISI 316L Paslanmaz Çeliğinin Frezelenmesinde Ekolojik Soğutma/Yağlama Yöntemlerinin Performansının İncelenmesi

MAKALE BİLGİSİ

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ÖZET

Sürdürülebilir imalat sürecinde ekolojik, çevreyle dost soğutma/yağlama yöntemleri önemli bir yer tutmaktadır. Bu sistemler sayesinde konvansiyonel soğutmanın zararları minimize edilebilmekte ve üretim performansına katkılar sağlanabilmektedir. Bu çalışmada ekolojik soğutma/yağlama yöntemleri altında AISI 316L paslanmaz çeliğinin işlenebilirliği incelenmiştir. İşlenebilirlik incelemesi için AISI 316L paslanmaz çeliğine üç farklı soğutma soğutma/yağlama koşulunda (minimum miktarda yağlama-MQL, LN_2 ve MQL+LN_2), üç farklı kesme hızında (120, 150 ve 180 m/dak), sabit ilerlemede (0.1 mm/dev) ve sabit kesme derinliğinde (0,5 mm) yüzey frezeleme operasyonu uygulanmıştır. İşlenebilirlik performans kriteri olarak ortalama yüzey pürüzlülüğü (Ra-µm), kesme sıcaklığı (T-°C) ve maksimum yanak aşınması (V_B - mm) değişimleri izlenmiştir. Deneyler sonucunda elde edilen verilerle kesme sıcaklığının en düşük değeri (101.1 °C) 120 m/dak kesme hızında ve LN_2 kesme koşulunda elde edilmiştir. Yüzey pürüzlülüğünün en düşük değeri (0.237 µm) ise 150 m/dak kesme hızında ve MQL+LN_2 kesme koşulunda elde edilmiştir. En düşük kesici takım yanak aşınması (0,170 mm), MQL+LN_2 hibrit kesme koşulu altında, 16 dakikalık işleme süresinin sonunda ve 180 m/dak kesme hızında elde edilmiştir. Deney sonuçları genel olarak değerlendirildiğinde MQL+LN_2 hibrit kesme koşulunun diğer koşullara göre tüm kesme parametrelerinde önemli iyileşmeler sağladığı anlaşılmıştır.

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1. INTRODUCTION (GİRİŞ)

Austenitic stainless steels are widely used in the chemical, petrochemical, food and pharmaceutical industries, nuclear power plants, and stainless equipment. However, these materials are difficult to cut due to their high ductility, high strength, and low thermal conductivity [1-2]. Especially in difficult to cut conditions, high cutting force, difficulty in chip removal, chip adhesion to the cutting tool, poor surface quality, and rapid tool wear are observed during the machining of AISI 316 stainless steel. Therefore, it is important to select suitable cooling/lubrication methods during the machining of this materials. Although the conventional coolant provides significant improvements in efficiency of machining, it has some concerns on the environment and human health. In order to minimize the negative effects of conventional cutting fluids, the researchers started to be preferred the Minimum Quantity Lubrication (MQL) methods (also known as semi-dry machining) in the machining operations [3-4].

In the MQL method, a small amount of cutting oil is sent to the cutting zone in the form of aerosol with compressed air [5]. The MQL method provides significant improvements in machining efficiency, machining cost, and the environment, and human health [6-7]. However, the MQL system performs better in finish, and medium cutting conditions [8]. Due to the low quantity of oil used in heavy machining conditions, MQL cannot provide sufficient cooling/lubrication condition [9]. Recently, researchers started to study on the cryogenic cooling method (also called subzero cooling condition) as an alternative to the MQL method [10-11]. Liquid nitrogen (LN_2), and liquid carbon dioxide (LCO_2) are the most widely used refrigerants in cryogenic cooling conditions [12]. Nitrogen gas (melting point: -210.01 °C, boiling point: -198.79 °C), which is present in large amounts in the atmosphere (78.03%), is a lighter gas than air [13-14]. Therefore, immediately after liquid nitrogen is applied to the cutting zone, it evaporates and disperses into the atmosphere [9]. Due to these positive properties, LN_2 is one of the most preferred cryogens in the machining process [15]. Because of all these positive effects, the cryogenic cooling method is known as an environmentally friendly method compared to the conventional cooling methods [16]. LN_2 cutting condition gives positive results in terms of cutting temperature, cutting force, chip formation, surface quality and tool wear, besides its environmentally friendly, and harmless features [17]. However, when cooling applied for a long time in machining process, the temperature that helps plastic deformation reduce to low levels. In addition, since no lubricant agent used in LN_2 cutting condition, the friction coefficient can increase on the interface of cutting tool/workpiece. Nowadays, hybrid cooling/lubrication methods, which include two different methods, have been started to work. The lubrication properties of MQL, and cooling properties of cryogenic are combined in the hybrid cooling/lubrication methods. So machining efficiency can be increased, and machining costs can be decreased due to the hybrid cooling/lubrication methods.

There are not enough studies in the literature that use of MQL, and cryogenic cooling/lubrication methods in the milling of AISI 316L stainless steel. For this reason, some of the similar studies are listed below. Yıldırım examined the cutting temperature, and surface roughness values in the milling of AISI 316 material under MQL, and graphite (0.5, and 1 vol%) added nanofluid cutting conditions. As a result of the experimental study, the 1 vol% nano graphite added nanofluid cutting condition were better performance on surface roughness and cutting temperature than other condition [18]. Dhar and Ahmet examined dry, wet, and MQL cutting condition on surface roughness, and tool wear during the turning of AISI 4340 material. At the end of their study, they stated that the MQL cutting condition improved the surface roughness, and reduced tool wear [6]. Jerald and Kumar examined the cutting force, surface roughness, cutting temperature, and tool wear when turning of AISI 316 stainless steel under dry, wet, and cryogenic (CO_2) cutting conditions. The researchers claimed that the CO_2 cutting condition reduced the cutting temperature 32%, and improved the surface quality 52% compared to wet cutting condition [19]. Ravi and Gurusamy investigated the effects of machining performance of dry, wet, and LN_2 cutting conditions during the milling of AISI D2 material. They stated that the LN_2 cutting condition showed improvements in terms of machining performance [20]. Leadebal et al., examined the effects of dry, and LN_2 cutting condition during turning of AISI D6 material. According to the experimental results, the researchers claimed that the LN_2 cutting condition showed better machining performance compared to dry condition [21]. Dhananchezian et al., in the turning of AISI 304 stainless steel, investigated the performance of wet and LN_2 cutting condition. The researchers stated that the LN_2 cutting condition provided significant improvements in terms of cutting temperature, cutting force, surface roughness, and tool wear [22]. Yıldırım et al., examined the performance of MQL, LN_2, and hybrid MQL+LN_2 cutting condition when turning of Ni based Inconel 625 superalloy. As a result of the experimental study, it was emphasized that hybrid MQL+LN_2 cutting condition provides significant improvements in terms of machining performance [15].

When the studies in the literature are evaluated, it is understood that LN_2, and especially hybrid MQL+LN_2 cutting conditions provide significant improvements in terms of machining performance. In this study, it is aimed to milling of AISI 316L stainless steel, not enough study have been investigated sufficiently, under ecological cooling/lubrication methods. Surface roughness, cutting temperature, and tool wear were selected as criteria for machinability performance of MQL, LN_2 and hybrid MQL+LN_2 cutting conditions. Thus, it was aimed that investigating the machining performance of hybrid cutting conditions during milling of AISI 316L stainless steel.

2. MATERIAL AND METHOD (MALZEME VE METOD)

2.1. Workpiece and Cutting Tool (İş Parçası ve Kesici Takım)

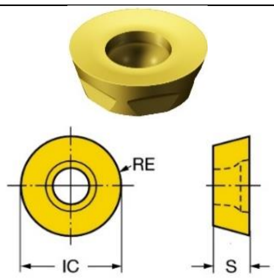
Commercial AISI 316L stainless steel was used in the milling experiments. The chemical composition of AISI 316L material is given in Table 1.

Table 1. Chemical composition of AISI 316L (wt %) (AISI 316L paslanmaz çeliği kimyasal bileşimi (% ağırlıkça))

C	Cr	Ni	Mn	Si	S	Mo	P	N	Cu	Fe
0.016	16.71	10.28	1.66	0.48	0.0006	2.07	0.02	0.067	0.12	Balance

R300-1032E-MM 2040 CVD coated cutting tool, and R300-025A20-10M coded tool holder (25 mm diameter) were used (manufactured by Sandvik company), in this study. Specifications, and sizes of the cutting tool are given in Table 2.

Table 2. Cutting tool specifications and sizes (Kesici takım özellikleri ve boyutları)



Radius (RE)	5 mm
Inner Circle (IC)	10 mm
Thickness (S)	3.175 mm
Coating	CVD TiCRN+Al_2O_3+TiN

2.2. Experimental Setup and Devices (Deney Düzeneği ve Cihazlar)

Milling experiments were carried out in DELTA SEIKI CNC-1050 A CNC vertical machining center that maximum spindle speed is 10000 rev/min. SKF brand Vario model MQL device and Özen brand compressor were used in the MQL system (Figure 1-c). Mineral based oil (density; 0.93 gr/mL at 20 °C, and kinematic viscosity; 14 cSt) produced by SKF company was used in the MQL system. The oil mixed in the system was applied to the cutting area at 8 bar pressure, 50 mL/hour flow rate, and 2 mm nozzle diameter.

XL 45 HP liquid cylinder produced by Taylor Wharton company was used in the cryogenic cooling experiments (Figure 1-d). LN_2, which is filled with pressure into the cylinder, was applied to the cutting area with a constant pressure of 15 bar, and a nozzle with a diameter of 3 mm.

Mahr brand Marsurf PS 10 model mobile surface roughness device was used to measure the surface roughness values. The mobile surface roughness device has probe positioning speed of 0,5 mm/sec, and cut off length of 0.08 mm, and traversing length is selected as 4 mm according to the ISO 12085 standard. ISO 4287 standard [23] was taken as reference in the surface roughness evaluation, and the arithmetic mean of the roughness deviation Ra values was taken for the machined surfaces. Three measurements were made from the beginning, middle, and end of each milled surface. Surface roughness Ra values were calculated by taking the arithmetic mean of the three values obtained. Before the experiments, the surface roughness measurement device was calibrated with a calibration block and the accuracy of the measurements performed was ensured.

Optris brand PI 450 model infrared thermal camera was used to measure the cutting temperature at the cutting zone (Figure 1-b). The thermal camera was calibrated by the manufacturer. The emissivity value is taken as 0.6 that recommended by manufacturer catalogue for stainless steel. The cutting temperature values in the cutting zone were measured and recorded with the Optris Connect software.

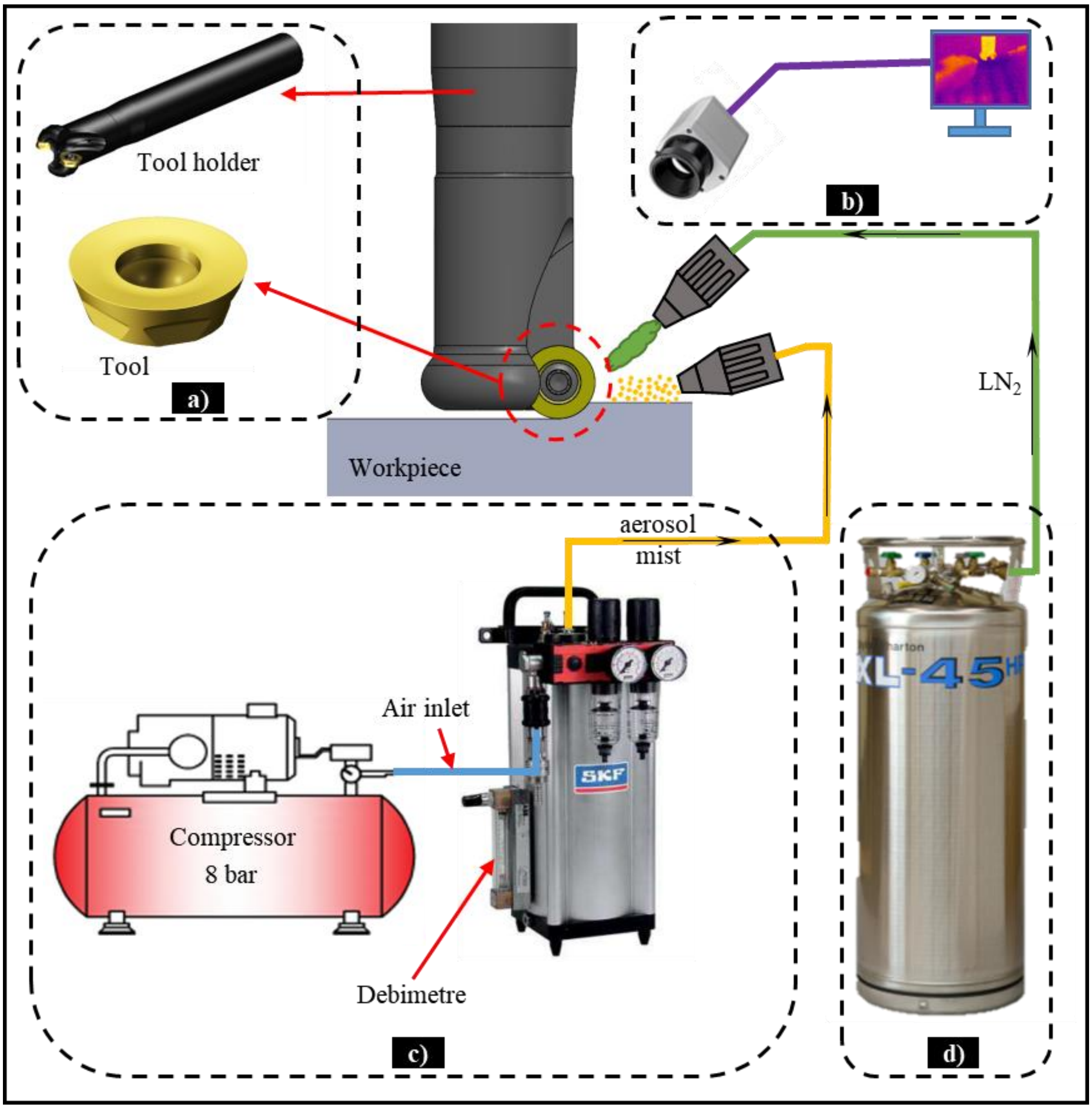


Figure 1. Experimental setup, a) Cutting tool and tool holder, b) Thermal imager, c) MQL system, d) Cryogenic cylinder (Deney düzeneği, a) Kesici takım ve takım tutucu, b) Termal kamera, c) MQL sistemi, d) Kriyojenik silindir)

DinoLite brand AM 4113 ZT model polarized digital microscope was used to measure the maximum value of cutting tool flank wear (V_B). Flank wear values were determined for each cutting condition at a cutting speed of 180 m/min, and at the end of the milling process for 16 minutes. Machining parameters, and variables used in milling experiments are given in Table 3.

Table 3. Machining parameters, and experimental variables (İşleme parametreleri ve deneysel değişkenleri)

Cutting condition	MQL, LN_2, and MQL+LN_2
Cutting speed (m/min)	120, 150 and 180
Feed rate (mm/rev)	0.1
Cutting depth (mm)	0.5
Radial cutting depth (mm)	15
Cutting tool	CVD coating, R300-1032E-MM 2040
Tool holder	R300-025A20-10M
MQL oil	Mineral based
MQL pressure (bar)	8
MQL flow (mL/h)	50
Cryogenic cooling pressure (bar)	15

3. EXPERIMENTAL RESULTS (DENEY SONUÇLARI)

3.1. Surface Roughness Results (Yüzey Pürüzlülüğü Sonuçları)

Surface roughness is a very important machining performance criteria, and it can also be defined as the quality characteristic of workpieces. Friction is inevitable in machine parts that work in contact with each other. Measuring, and controlling of surface roughness is very important because it reduce the friction and give visuality to the machined surfaces. Roughness average Ra is the most commonly used in the measuring of surface roughness. In this study, the Ra results of the machined surfaces at 120, 150 and 180 m/min cutting speed under MQL, LN_2, and MQL+LN_2 cutting conditions were evaluated. The arithmetic average of Ra values for all cutting conditions measured from the beginning, middle, and at the end of the 150 mm machined surfaces are given in Figure 2.

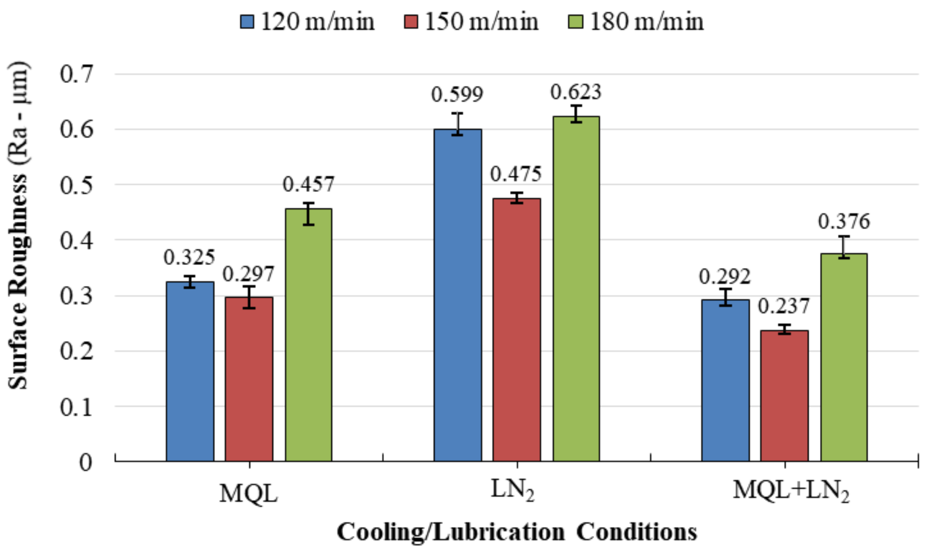


Figure 2. Measurement results of surface roughness under ecological cooling/lubrication cutting conditions, after the 150 mm machined surface (Ekolojik soğutma/yağlama kesme koşulları altında elde edilen yüzey pürüzlülük ölçüm sonuçları, 150 mm işleme sonrasında)

When Figure 2 is examined, it is understood that the lowest Ra value (0.237 µm) was obtained in MQL+LN_2 hybrid cutting condition, and at 150 m/min cutting speed. The lowest Ra of the MQL, and LN_2 cutting condition was obtained at a cutting speed of 150 m/min. MQL+LN_2 hybrid cutting condition improved the Ra 20.20% compared to the MQL cutting condition, and 50.11% improvement compared to LN_2 cutting condition. On the other hand, the MQL cutting condition were provided 37.47% improvement compared to the LN_2 cutting condition. MQL is a cutting condition where a very small amount of oil sending with pressure to the cutting zone via the nozzles. In this lubrication method, the compressed air/oil mixture is sent to the cutting zone from the tip of the nozzle to create an aerosol mist. Thanks to the lubrication tribofilm layer formed in the cutting tool/workpiece/chip interface areas, friction is minimized, vibration is reduced to reasonable levels, and chips are removed from the cutting zone [24]. In the LN_2 cooling method, the cutting temperature values occurring during the machining can be reduced to low levels with the -196 °C coolant gas sent to the cutting zone (Figure 4). However, the chips tend to be plastered to the machined surfaces on the workpiece (Figure 3). This is because of the LN_2 reduces the cutting temperature which is facilitating plastic deformation [15]. It can be said that the Ra roughness values were measured high due to the chips plastered on the workpiece surface in the LN_2 cutting condition. In the MQL+LN_2 hybrid cutting condition, where the lubricating effect of the MQL system and the cooling effect of the cryogenic system are together, better machined surfaces quality were obtained in all parameters compared to other cutting conditions. Similarly, it has been stated that hybrid cooling/lubrication cutting conditions improve the surface quality relatively compared to other conditions, in the literature [15], [25], [26].

When the cutting speed values was increased in all cutting conditions, it was observed that the surface roughness values improved. As the cutting speed increases, the temperature in the cutting zone increases. Increased temperatures which were facilitating plastic deformation, it has enabled chips to be separated from the workpiece more easily. Thus, it has been achieved improvements in the surface roughness Ra values. When the highest value of the cutting speed, 180 m/min, was reached, the worst roughness values were measured in all cutting conditions. When the surface roughness were measured the flank wear values, under LN_2, MQL, and MQL+LN_2 cutting condition, reached 0,141 mm, 0,102 mm, and 0,091 mm at 180 m/min cutting speed, respectively (Figure 6). It can be said that with the further increase of the cutting speed, the roughness values worsened because of the plastered of the chips on the cutting tool, and workpiece surfaces.

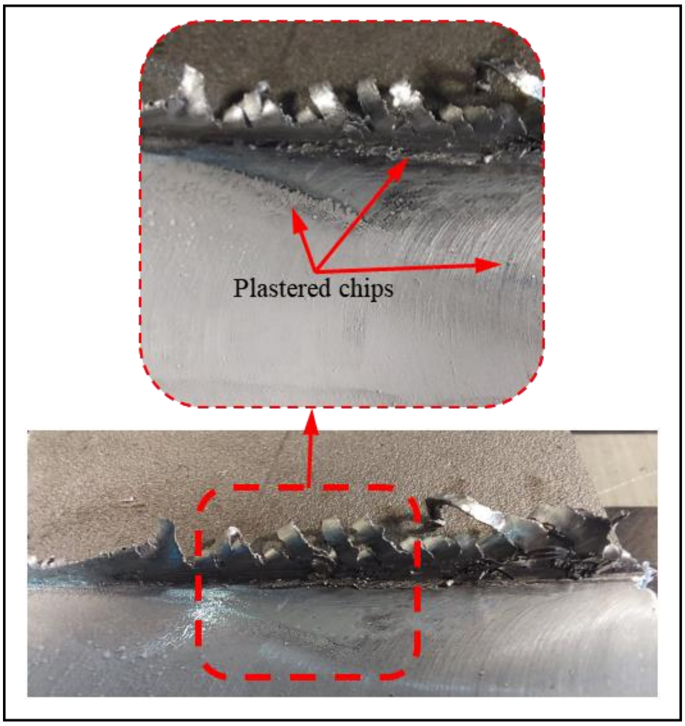


Figure 3. Plastered chips under LN_2 cutting condition (LN_2 kesme koşulunda talaş sıvanması)

3.2. Cutting Temperature Results (Kesme Sıcaklığı Sonuçları)

In metal cutting processes, when the temperature values increase, it can cause sudden abrasions of the cutting tool and deteriorations in workpiece surface quality [27]. Therefore, it is extremely important to control the temperature in the metal cutting processes. In this study, the cutting temperature value reached in the cutting zone was recorded by the Infrared Thermal Camera, which measures online and thermographic. The maximum value of cutting temperature was measured for all cutting conditions during the 4 minutes of machining time. The cutting temperature values obtained are given in Figure 4. The highest cutting temperature value (241.3 °C) was measured in

MQL cutting condition, and at 180 m/min cutting speed (Figure 5-a). For all cutting conditions, the highest cutting temperature values were obtained at 180 m/min cutting speed. When the cutting temperatures were measured the flank wear values under LN_2, MQL, and MQL+LN_2 cutting condition reached 0.201 mm, 0.124 mm, and 0.103 mm, respectively (Figure 6) . The lowest cutting temperature value (101.1 °C) was obtained in LN_2 cutting condition, and 120 m/min cutting speed (Figure 5-b). The lowest cutting temperature values of the MQL+LN_2 (132.4 °C), and MQL (197.9 °C) cutting conditions, was obtained at 120 m/min cutting speed. In other words, the LN_2 cutting condition reduced the cutting temperature by 23.65%, and 48.91%, compared to the MQL+LN_2, and MQL cutting condition, respectively.

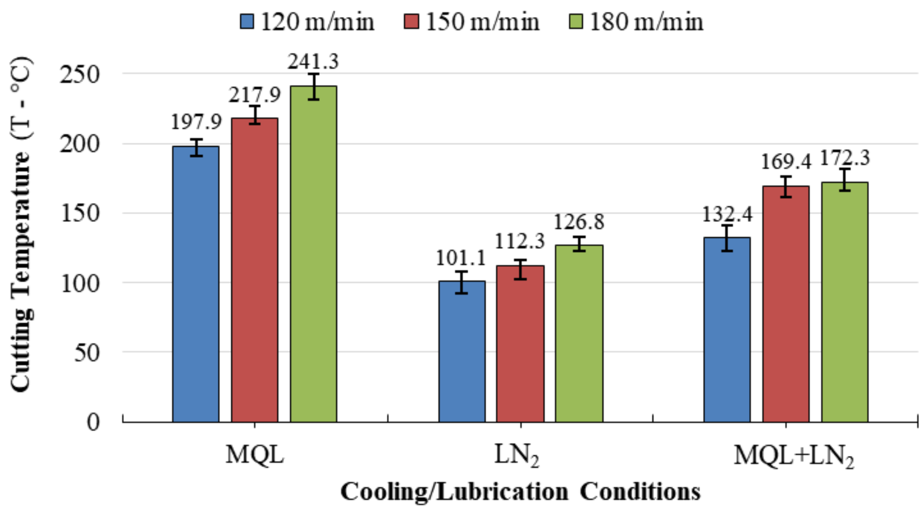


Figure 4. Measurement results of the cutting temperature under ecological cooling/lubrication cutting conditions, during 4 min machining time (Ekolojik soğutma/yağlama koşulları altında elde edilen kesme sıcaklığı ölçüm sonuçları, 4 dak işleme süresi boyunca)

When Figure 4 continues to be examined, it is seen that the increase in the cutting speed values increases the cutting temperature values. If the cutting speed is increased, the cutting tool workpiece contact rate also increases, as a result, it can be increase the coefficient of friction and coefficient of heat partition [28].

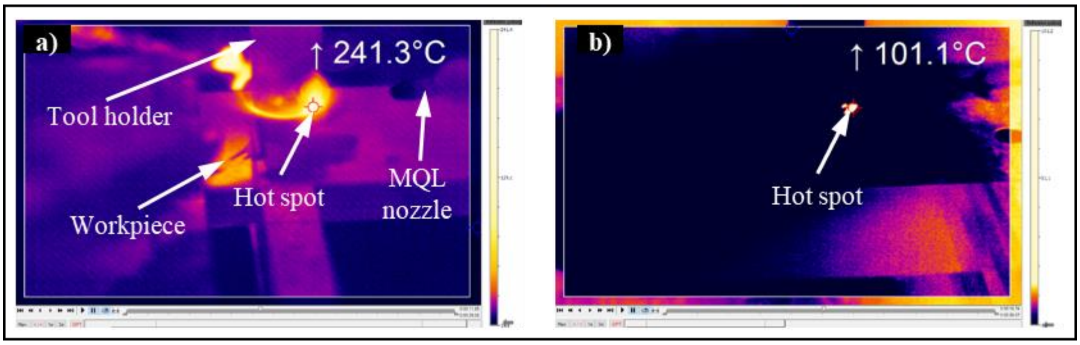


Figure 5. Cutting temperature results at the infrared thermal camera, a) MQL cutting condition, b) LN_2 cutting condition (Kızılötesi termal kamerada kesme sıcaklığı sonuçları, a) MQL kesme koşulu, b) LN_2 kesme koşulu)

When the cutting temperature values are evaluated in general, the lowest cutting temperature values were obtained under LN_2 cutting condition at all cutting speeds. This situation can be explained by sending N_2 with a temperature value of -196 °C in liquid form to the cutting zone. However, it is thought that the cutting tool is forced to separating the chips from the workpiece surface, as it reduces the temperature values in the cutting zone to undesirable levels. Surface roughness results (Figure 2), and plastered chips formation (Figure 3) support this situation.

3.3. Tool Wear Results (Takım Aşınma Sonuçları)

In this section, cutting tool maximum values of the flank wear (V_B) were measured at 180 m/min cutting speed under LN_2, MQL, and MQL+LN_2 hybrid cutting conditions, and at the end of 16 minutes of machining time. The flank wear values obtained are given in Figure 6. When Figure 6 is examined, the lowest V_B value (0.170 mm) was obtained at the MQL+LN_2 hybrid cutting condition. The MQL+LN_2 hybrid cutting condition was followed by MQL (0.306 mm) and LN_2 (0.780 mm) cutting conditions, respectively. In other words, the MQL+LN_2 cutting condition improved tool wear by 44.44%, and 78.21%, respectively, compared to the MQL, and LN_2 cutting conditions. This situation can be explained as the MQL+LN_2 hybrid cutting condition, which includes the lubrication capabilities of the MQL method and the cooling capabilities of the LN_2 method, provided significant improvements in cutting tool life. The highest cutting tool wear in the LN_2 cutting condition can be explained with the cutting temperature. Figure 4 cutting temperature results can be contributed to this situation. The lowest cutting temperature values were obtained in the LN_2 cutting condition. Cutting tools are exposed to variable thermal shocks in the milling operations. The thermal shock changes in the milling operations, the cutting tools can be cause rapidly wear, and it can be triggered development of wear mechanisms [29]. It can be stated that the cutting tool flank wear was measured to highest in the LN_2 cutting condition, because of the thermal shock changes on the cutting tool are greater.

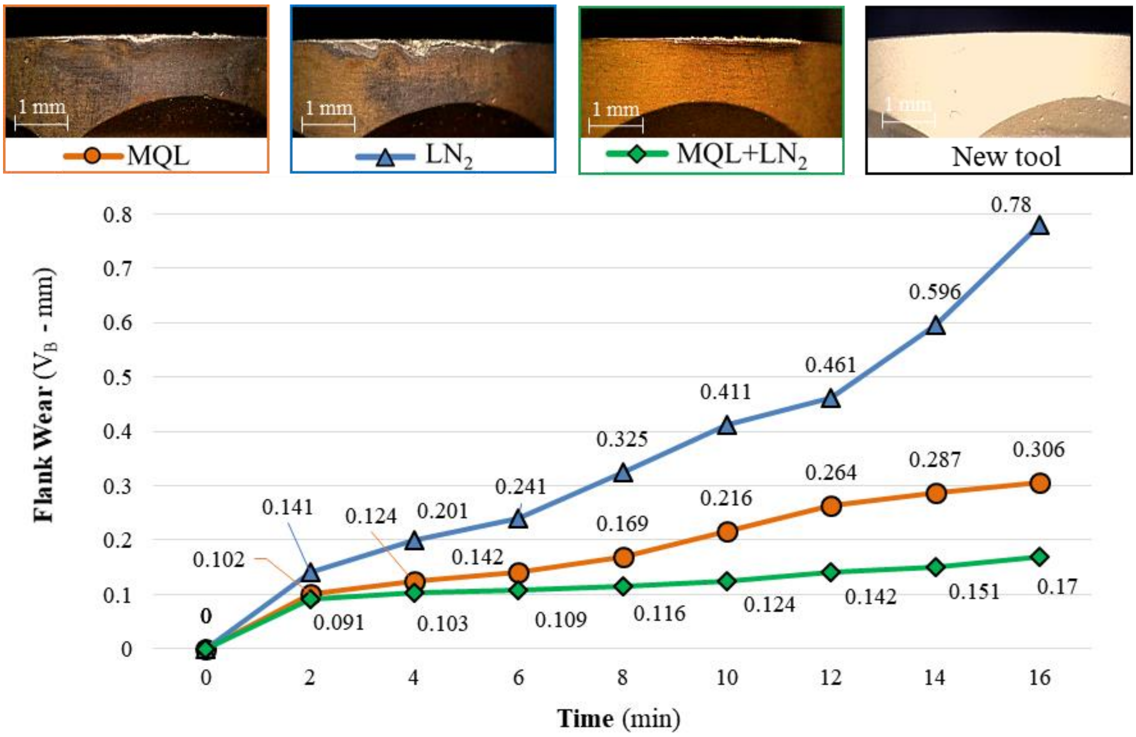


Figure 6. Flank wear results (at 180 m/min cutting speed, and 0.1 mm/rev feed rate) (Maksimum yanak aşınma sonuçları (180 m/dak kesme hızı ve 0.1 mm/dev ilerlemede))

4. CONCLUSIONS (SONUÇLAR)

In this study, the performances of ecological cooling/lubrication methods in the milling of AISI 316L stainless steel were investigated. Three different cutting conditions (MQL, LN_2, and MQL+LN_2), three different cutting speeds (120, 150, and 180 m/min), constant feed (0.1 mm / rev), and constant cutting depth (0.5 mm) were selected as machining parameters. Average surface roughness, cutting temperature, and tool wear were used as performance criteria. The results obtained from the experimental study are given below.

- According to the average surface roughness results, the lowest value was obtained with 0.237 µm under MQL+LN_2 hybrid cutting condition. The lowest Ra values of the MQL cutting condition with 0.297 µm, and LN_2 cutting condition with 0.475 µm was obtained at 150 m/min cutting speed. MQL+LN_2 cutting condition improved the surface roughness by 20.20%, and 50.11% compared to MQL, and LN_2 cutting condition, respectively.

- Surface roughness values decreased under all cutting conditions when cutting speed increased from 120 to 150 m/min. However, when the cutting speed increased to 180 m/min, the worst surface roughness value was obtained in all conditions.
- When the cutting temperature values at the cutting zone are examined, the lowest cutting temperature value was obtained with 101.1 °C under LN_2 cutting condition. The lowest cutting temperature of the MQL+LN_2 (132.4 °C), and MQL (197.9 °C) cutting conditions was observed at 120 m/min cutting speed. The LN_2 cutting condition provided a decrease in cutting temperature values at the rates of 23.65% and 48.91%, respectively, compared to MQL+LN_2, and MQL cutting conditions.
- When the cutting speed increased from 120 to 180 m/min, the cutting temperature values tended to increase.
- Flank wear V_B values were measured at a cutting speed of 180 m/min, under all cutting conditions, and end of the 16 min experimental time. The lowest V_B value (0.170 mm) occurred on the cutting tool was reached under the MQL+LN_2 hybrid cutting condition. The MQL+LN_2 hybrid cutting condition was followed by MQL (0.306 mm), and LN_2 (0.780 mm) cutting conditions, respectively. MQL+LN_2 cutting condition improved tool wear by 44.44%, and 78.21%, respectively, compared to MQL, and LN_2 cutting conditions.

When this study is evaluated in general, it is understood that hybrid cutting conditions, which combine the superior aspects of two different ecological cutting conditions, are promising for future studies. It is thought that especially MQL where tribological lubrication is provided and LN_2 cutting conditions where cooling is provided will provide important contributions to the sustainable manufacturing process.

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