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INVESTIGATION OF TOOL WEAR AND THRUST FORCE IN DRILLING AISI 316 AUSTENITIC STAINLESS STEEL USING ELECTROPHORESIS METHOD

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Abstract

Original scientific paper

Cutting tool costs are an important component of machining. For this reason, improving machining methods in machining affects the life of the cutting tool. Recently, various machining methods have been used to extend tool life by reducing cutting tool wear. One of these methods is electrophoresis-assisted processing. Electrophoresis-assisted machining is a non-traditional machining method created by the impact of abrasive nanoparticles on the machining area with the help of the generated electric field. Electrophoresis-assisted machining increases the machinability of difficult-to-machine materials with high strength and hardness properties compared to traditional machining methods. In this study, the impacts of various cutting parameters on the drilling performance of AISI 316 L stainless steel material were searched using electrophoresis-assisted drilling (EAD) and conventional drilling (CD) methods. In the study, SiC powder was used as nanoparticles in the solution obtained to create the electric field. Within the scope of the experiments, the effects of different machining methods, cutting speeds and feed rates on thrust forces and cutting tool wear values were experimentally examined. As a result of the investigations, the cutting tool wear and thrust cutting force obtained with EAD are better than CM. Increasing feed rate and cutting speed increased cutting tool wear in both machining methods. It has been determined that the thrust force decreases as the cutting speed increases, while it increases as the feed rate increases.

Keywords: *Electrophoresis, drilling, cutting force, tool wear, AISI 316.*

AISI 316 ÖSTENİTİK PASLANMAZ ÇELİĞİN ELEKTROFOREZ YÖNTEMİYLE DELİNMESİNDE TAKIM AŞINMASI VE İTME KUVVETİNİN İNCELENMESİ

Özet

Orijinal bilimsel makale

Kesici takım maliyetleri talaşlı imalat için önemli bir bileşendir. Bu nedenle talaşlı imalatta işleme yöntemlerinin iyileştirilmesi kesici takım ömrüne etki etmektedir. Kesici takım aşınmasını azaltarak takım ömrünün uzatılması için son zamanlarda farklı işleme yöntemleri kullanılmaktadır. Bu yöntemlerden biri de elektroforez destekli işlemedir. Elektroforez destekli işleme oluşturulan elektrik alan yardımıyla aşındırıcı nano partiküllerin işleme alanına etki etmesiyle oluşturulan geleneksel olmayan işleme yöntemidir. Elektroforez destekli işleme, geleneksel işleme yöntemlerine kıyasla yüksek mukavemet ve sertlik özelliklerine sahip, işlenmesi zor malzemelerin işlenebilirliğini artırır. Bu çalışmada AISI 304 paslanmaz çelik malzemesinin elektroforez destekli delme (EDD) ve geleneksel delme (GD) yöntemleri kullanılarak farklı kesme parametrelerinin delik delme performansı üzerine etkileri araştırılmıştır. Çalışmada elektrik alanını oluşturmak elde edilen çözeltide nano partikül olarak SiC toz kullanılmıştır. Deneyler kapsamında farklı işleme yöntemleri, kesme hızları ve ilerleme hızlarının itme kuvvetleri ve kesici takım aşınma değerleri üzerindeki etkileri deneysel olarak incelenmiştir. İncelemeler sonucunda kesici takım aşınması ve itme kuvveti için en iyi sonuçlar EDD ile elde edilmiştir. Kesme hızının ve ilerleme hızının artması her iki işleme yönteminde kesici takım aşınmasını artırmıştır. İtme kuvveti kesme hızı arttıkça azalırken ilerleme hızı arttıkça arttığı tespit edilmiştir.

Anahtar Kelimeler: *Elektroforez, delme, kesme kuvveti, takım aşınması, AISI 316.*

1 Introduction

Cutting force and cutting tool wear are important criteria in drilling. It is difficult to control and improve these two performance characteristics with traditional machining methods. Cooling methods are an effective method on machinability. However, the rotational movement of the cutting tool removes the fluid from the cutting area and results in an increased wear of the tool although it is also dependent on the material being cut. Stainless steels are preferred in the transportation via aerospace and also in marine due to their outstanding mechanical strength and corrosion resistance. Austenitic stainless steel alloys are in the group of materials that are

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difficult to cut. These steels contain high Cr and Ni. These properties make machinability difficult due to low thermal conductivity and hardening properties during machining [1], [2]. Therefore, it creates high cutting forces and cutting temperatures during machining [3]. This situation increases tool wear by increasing friction in the cutting area and causes chip accumulation on the tool tip [4], [5]. AISI 316 austenitic stainless steel is a challenging material to cut due to its distinctive machining characteristics. Its mechanical properties contribute to the difficulty of drilling this material. The workpiece undergoes hardening during the machining process, which results in increased wear on the cutting tool and a reduction in the quality of the machined surface. Furthermore, the material's inherent difficulty in undergoing deformation results in the generation of prolonged, elongated chips. These challenges have significantly constrained the utilization of AISI 316 steel, necessitating the urgent resolution of these issues within the industry. Extensive research has been conducted on the machinability of austenitic stainless steel alloys, with ongoing efforts to ascertain the optimal machining conditions. In this regard, it is crucial to investigate the most suitable machining conditions for the processing of these materials.

In machining, obtaining a quality surface, long tool life and increasing the metal removal rate are of great importance [6]. Drilling is a machining method that uses a cutting tool to remove materials from the drilling area to create a hole [7]. Tool wear, burr formation, surface quality, thrust forces and tool life are important parameters in drilling. In machining, the friction occurring in the cutting zone creates high cutting temperature and cutting pressure. Drilling becomes difficult because heat is concentrated in the cutting area [8]. Accelerated wear creates various mechanisms on the cutting tool. The various wear mechanisms depend on the cutting parameters and cooling methods in the cutting zone [9]. Tool wear influences surface quality and cutting performances [10], [11]. During the machining process, changes occur in the cutting tool geometry due to tool wear. Jawahir et al. [12] concluded in their study that the wear resistance and corrosion of the cutting tool have an effect on the surface quality. Kummel et al. [13] investigated the effect of cutting tool wear on machining quality and tool life. They found that increasing chip accumulation on the surface reduces wear and roughness. Considering the findings presented in the existing literature, the selection of appropriate additional techniques or process parameters during drilling and machining can enhance the machinability of the material. Consequently, the precision and efficiency of the machining process can be improved by employing alternative machining methods in conjunction with drilling.

The use of existing conventional machining methods in machining materials that are difficult to remove causes cutting tool wear and reduces machinability [14]. To increase the machining efficiency of austenitic stainless steel, researchers have proposed different cooling methods. In order to reduce wear in the cutting area, cutting temperature and cutting force must be reduced. For this reason, various cooling methods and cutting fluids are applied to the cutting area [15], [16]. Khan et al. [17] studied the cutting performance of AISI 9310 under dry and MQL conditions. They found that MQL increased tool life and surface finish by reducing the cutting temperature. However, the use of cooling methods has negative effects on the environment and human health due to their harmful chemical substance content [18], [19]. These negative effects have led to the use of alternative methods in machining. Due to the problems mentioned above, studies on harmless cooling methods that will decrease wear have become inevitable. With the electrophoresis-assisted processing method, which is one of these methods, negativities can be eliminated by creating an electric field in the processing area. This method is a non-traditional process used to cut metals that are generally hard or difficult to cut, where a conventional process is not suitable. Electrophoresis is the movement of charged nanoparticles in solution within the electric field created in the shear zone. In electrophoresis-assisted machining, abrasive particles penetrate the machining area thanks to an electric field, increasing machining efficiency [20]. He et al. [21] investigated the surface roughness of AL6061 workpiece with electrophoresis-assisted ultrasonic machining. As a result of the experiments, they found that electrophoresis-assisted ultrasonic machining increased the surface quality compared to other machining methods.

In this study, the positive/negative aspects of the performance characteristics were investigated in the machining of AISI 316 L austenitic stainless steel using the electrophoresis method, which is new and rare in machining, and the best solution methods that will create an alternative to traditional machining methods were determined. In the study, tool wear and thrust force were determined as performance characteristics. By applying the EAD method, it was aimed to increase the tool life as a result of minimizing the thrust force and cutting tool wear. It was seen in the obtained results that the EAD method was not used in drilling and this method increased the machinability compared to other machining methods. According to the results obtained, this study will make serious contributions to minimizing the current problems in the machining of engineering materials with similar mechanical properties to AISI 316 L austenitic stainless steel.

2 Materials and Methods

2.1 Experimental Setup

This study was established to investigate the impacts of different machining methods and different cutting parameters on cutting tool wear and thrust force in drilling experiments of AISI 316 L austenitic stainless steel. Workpieces with dimensions of 90x45x5 mm were used in the drilling experiments. The chemical composition and physical properties of AISI 316 L austenitic stainless steel are given in Table 1.

In the electrophoresis method, the voltage (V) applied between two electrodes using a direct current (DC) source and the distance (d) between the electrodes lead to the formation of an electric field (E=V/d). To create an electric field between two electrodes, charged abrasive particles are suspended in the working fluid tank and move towards the oppositely charged electrode [22]. Direct current (DC) is used as the electrical source. To create an electric field, the cutting tool is positively charged by being connected to the anode end, and the solution containing the working fluid is negatively charged by being connected to the cathode end. Thus, an electric field is created between the working fluid and cutting tool. Thanks to the electric field created, the nanoparticles move to the worn areas of the cutting tool and affect these areas.

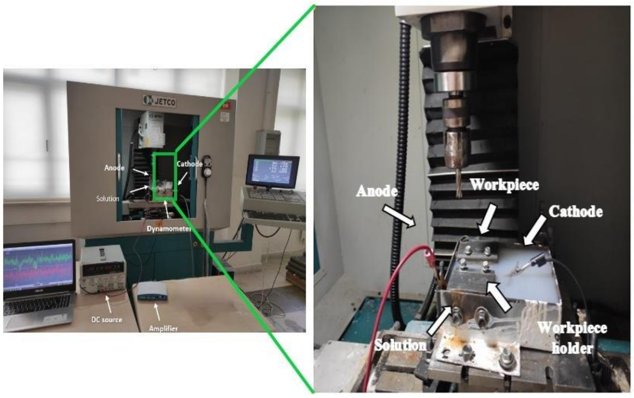
Table 1. Mechanical properties and chemical composition of AISI 316 austenic steel.

Parameter	Value
Density (lbs/cm^3)	0,29
Brinell hardness (HB)	149
Tensile stress (MPa)	205
Elastic modulus (GPa)	193
Chemical composition (%)	C: 0,035 Mn: 2,0 P: 0,040 S: 0,03 Si: 0,75 Cr: 16-18 Ni: 10-15

Within the scope of the experimental studies carried out, CD and EAD processes were carried out. Experimental parameters are given in Table 2. During the EAD process, the workpieces were placed in sample holders in electrophoresis solution. 10 mm diameter, 30o helix angle, 118o tip angle, N type DIN 345 uncoated HSS tools were used as cutting tools. The geometric parameters of the cutting tool are given in Figure 1. The cutting tool was renewed in each experiment to clearly observe the wear that occurred. In the EAD process, SiC powder with a size of 0.5 nm was used as nanoparticles in solution. The solution used was 1/100 SiC and 99/100 pure water by weight. To create the electric field, the solution was connected to the cathode to make it negatively charged, and the cutting tool was connected to the anode tip to make it positively charged. A direct current power supply with 0-3 A and 0-30 V characteristics was used to create the coating medium. The solution parameters for which EAD will be used are given in Table 3. During the experiments, a CNC milling machine (Jetco 3 axis CNC-Chinese) was used to perform the drilling and a dynamometer (ME-SYSTEME-K3D160; Germany) was used to measure the thrust force. The data acquisition frequency for thrust force measurement was 1 kHz. In tool wear studies, the amount of wear was measured with an optical microscope (NIKON-ECLIPSE MA100; Japan). In addition, the impacts of machining methods and parameters on wear were analyzed in scanning electron microscopy (SEM) and their effects were examined in detail. To investigate the change of tool wear during drilling process, tool wear was measured by looking at the amount of wear at the end of 25 holes to analyze the effect of cutting speed, feed rate and machining methods on tool wear. The number of holes was selected as 25 because it was the optimum value for wear in the preliminary experiments. Each drill was measured twice to obtain accurate results. The experimental setup is given in Figure 2.

Parameter	Value
Drill Diameter (d) (mm)	10
Helix angle (°)	30°
Tip angle (°)	118°

Figure 1. Geometric parameters of cutting tool.



(a) (b)

Figure 2. a) Experimental setup b) Cutting area.

Table 2. Experimental parameters.

Parameter	Conventional drilling	Electrophoresis assisted drilling
Spindle speed (m/min)	20-30-40	20-30-40
Feed rate (mm/dev)	0,09-0,12-0,15	0,09-0,12-0,15
Drilling diameter (mm)	10	10
Drilling cutting edge angle (degrees)	35	35

Table 3. Electrophoresis solution parameters.

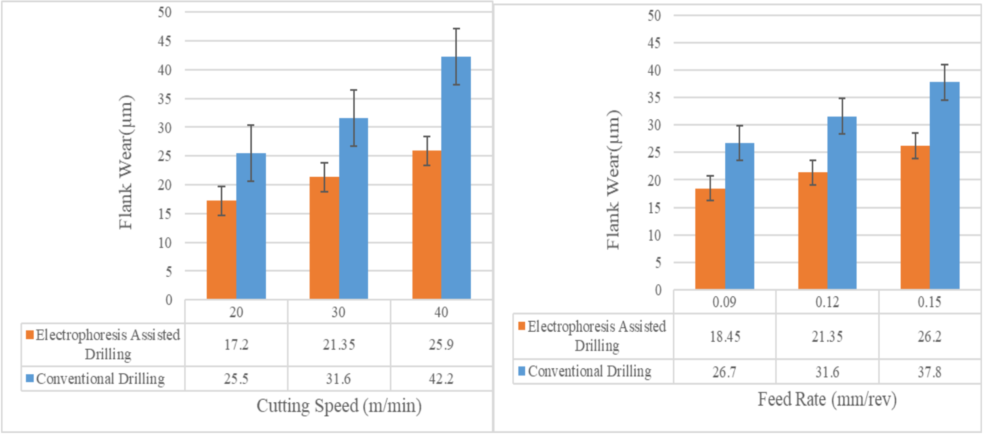
Parameter	Value
Particle size (nm)	0,5
Particle type	Silicon carbide (SiC)
Applied voltage (DC)(V)	10
Working fluid	Pure water

3 Results and Discussion

3.1 Tool Wear Results

Predicting tool wear is a difficult process because it is a parameter that changes over time in every manufacturing process. Workpieces produced with worn tools cause negative effects such as dimensional differences and poor surface quality [23]. Therefore, reducing tool wear has an important place in machining. Figure 3a shows the impacts of machining methods on wear and their changes depending on cutting speed. With increasing cutting speeds at fixed feed rate (0.12 mm/rev), cutting tool wear increased rapidly in both CD and EAD. As the number of revolutions increases, it causes more friction. As a result, it increases the temperature, creates corrosion mechanisms and increases wear [24]. When the cutting speed in CD increased from 20 m/min to 40 m/min, tool wear increased by 65%. Similarly, this rate was found to be 50% in EAD. Figure 3b shows the impacts of machining methods on wear and their changes depending on the feed rate. At fixed cutting speed (30 m/min), cutting tool wear increased in both machining methods as the feed rate increased from

0.09 mm/rev to 0.15 mm/rev. Tool wear increased as the amount of chip removed increased as the feed rate increased [23]. When the feed rate in CD increased from 0.09 mm/rev to 0.15 mm/min, tool wear increased by 41%. Similarly, in EAD this rate is 42%.



(a) (b)

Figure 3. Flank wear values a) According to cutting speed, b) According to feed rate.

During the machining process, nanoparticles are attracted to the cutting tool due to the electromagnetic field generated by the chemical interactions of the nanoparticles in pure water. This phenomenon enables the coating of the cutting tool with SiC nanoparticles. Wear is reduced by attracting nanoparticles to the wear areas on the cutting tool while drilling and penetrating the worn areas. Additionally, the temperature decreased because the drilling process took place in the electrophoretic solution. The decrease in temperature minimized thermal softening and reduced wear compared to CD.

Figure 4a and 4b show SEM analysis images showing tool wear types at a cutting speed of 30 m/min and a feed rate of 0.15 mm/rev. Side wear was observed as a result of abrasive wear during processing with CD. In addition, notch wear and occasional tip fractures were observed in CD due to the adhesive wear mechanism caused by high pressure and temperature. Reduced side wear was observed due to EAD reducing the cutting temperature compared to CD. In addition, nanoparticles prevent wear mechanisms by penetrating the wear zones in the cutting tool.

The types of wear and tool damage that occurred on the cutting tools used in the experiments carried out at 40 m/min (max) cutting speed and 0.12 mm/rev feed rate by applying CD are shown in Figure 4c. Small fractures and flank wear occurred on the cutting tool at maximum cutting speed. Due to the increasing speed values, the effect of friction increases and an increase in flank wear occurs [25]. The types of cutting tool damage that occurred in the cutting tools used in the experiments carried out with CD at 30 m/min cutting speed and 0.15 mm/rev (max) feed rate are seen in Figure 4d. Flank wear, notch wear and fracture occurred at the maximum feed rates. The high cutting forces formed by the increase in feed rate create thermal and mechanical stresses in the cutting zone and thus fracture and flank wear occur [26].

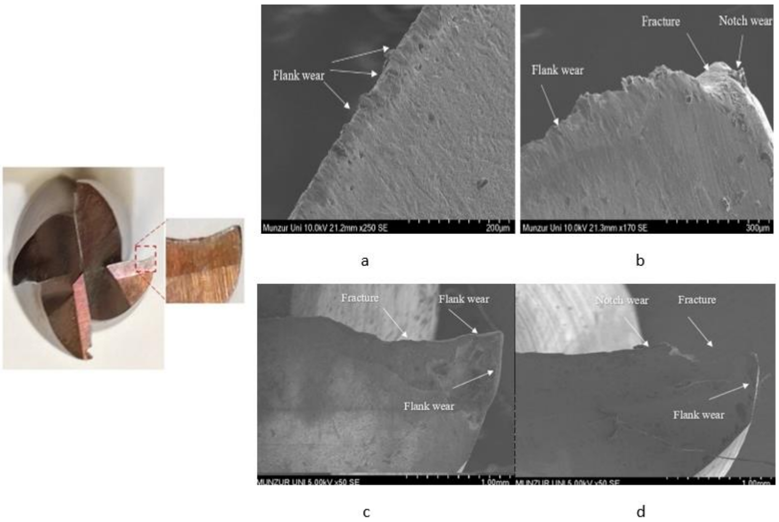


Figure 4. Wear on cutting tools a) Electrophoresis assisted drilling b) Conventional drilling c) Maximum cutting speed d) Maximum feed rate.

Figure 5a and Figure 5b show the EDS analysis of the cutting edge where the wear is the most at 30 m/min cutting speed and 0.12 mm/rev feed rate under EAD and CD machining conditions. The presence of elements such as Ni and Cr shown on the cutting edge in CD confirms that these elements move from the workpiece to the cutting tool. Thus, the workpiece sticks to the cutting tool [27]. In EAD machining, the presence of elements belonging to the workpiece is seen in small amounts on the cutting tool. In EAD machining, the high amount of Si in the cutting area of the cutting tool proves that the abrasive particles move to the wear area of the cutting tool. During drilling, nano particles move to the worn areas with the help of the electric field and provide coverage of the area. This coating reduces wear on the cutting tool in EAD machining and causes flank wear.

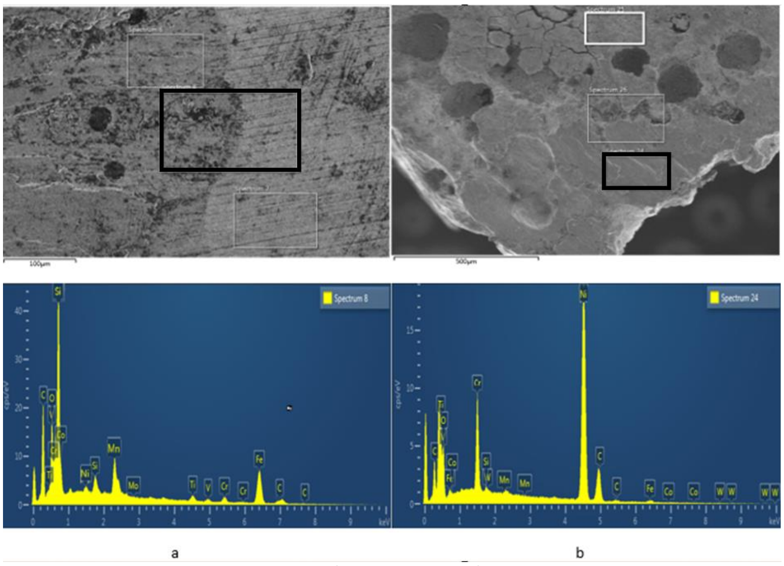
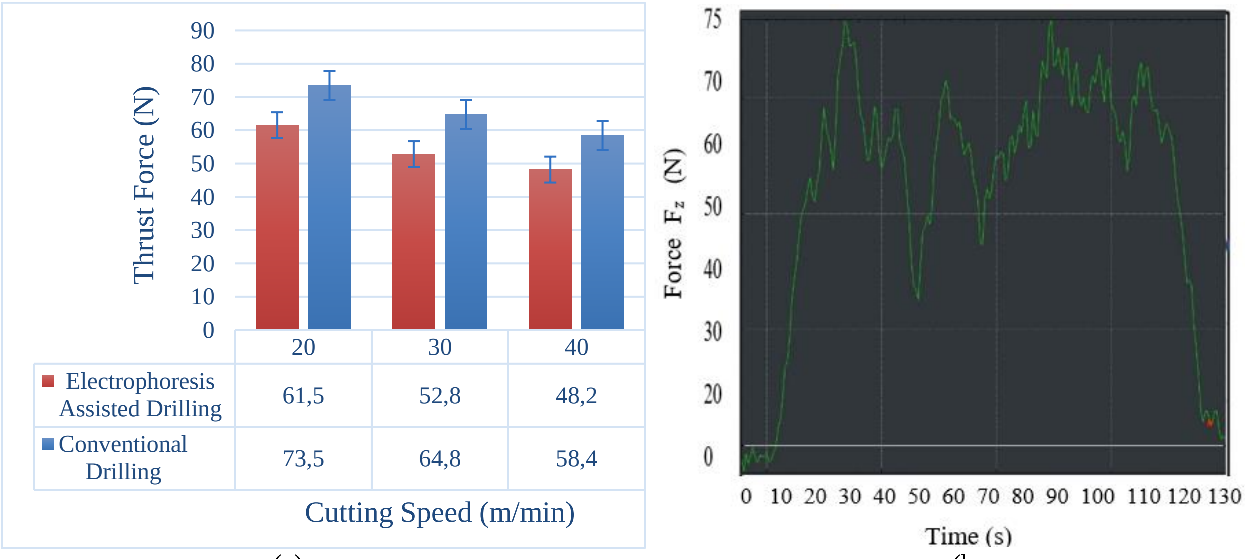


Figure 5. EDS results of cutting tool surface in a) EAD b)CD.

3.2 Thrust Force Results

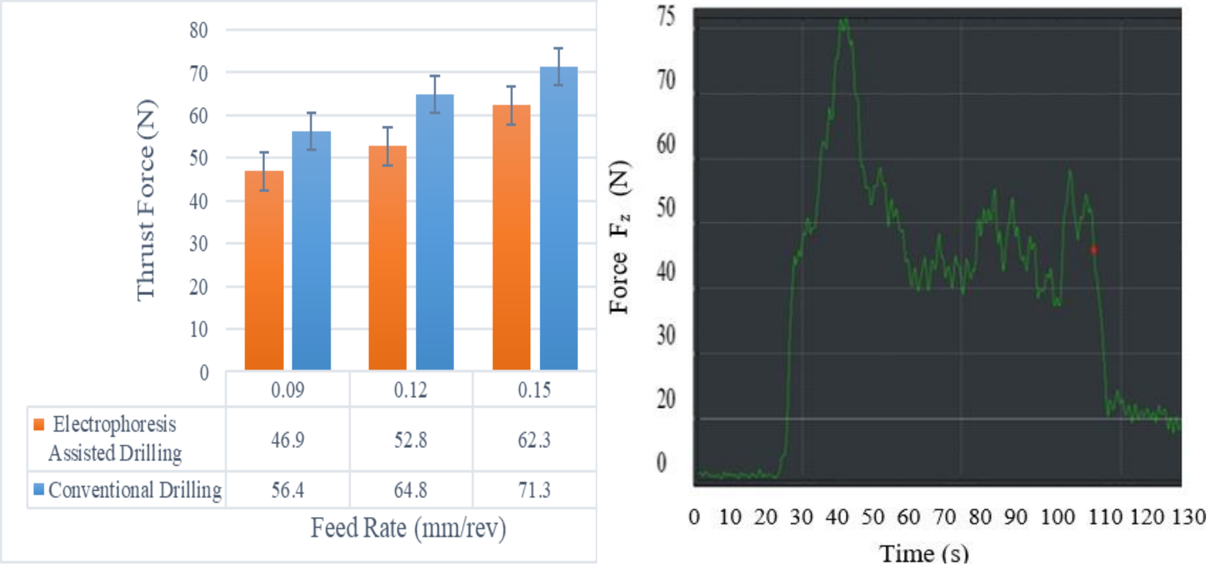
Determination of thrust force is important to determine the power to be used in machining. Thrust forces (Fz) measured with the help of a dynamometer were taken as cutting forces. In Figure 5 and Figure 7, thrust forces (Fz) measured with the help of a dynamometer were taken as cutting forces; force signals and the change of thrust force values depending on cutting speed and feed rate are given in the processing of AISI 316 austenitic stainless steel with EAD and CD. Figure 6 shows real-time thrust force signals and thrust force values according to the change of cutting speed at a fixed feed rate of 0.12 mm/rev. According to experimental studies, both CD and EAD thrust decreased with increasing speed. Increasing the cutting speed in the cutting zone provides thermal softening. This reduces unwanted friction. Additionally, increased thermal softening has the effect of reducing workpiece hardness. For these reasons, increasing the cutting speed reduces the thrust force. When the thrust forces are examined according to the processing methods, the thrust force values obtained with EAD at all cutting speeds are lower than those with CD. The rationale behind this phenomenon is that in the EAD method, nanoparticles are able to penetrate the cutting tool due to the electromagnetic field, thereby preventing wear. Reducing tool wear reduces the force exerted when removing material from the workpiece [28]. At 30 m/min, the thrust force values obtained with EAD decreased by 18.51% compared to CD. While the maximum thrust force measured at CD was 73.5 N at 20 m/min, it was measured as 61.5 N at EAD.



(a) (b

Figure 6. a) Effect of cutting speed on thrust force b) Thrust force signal.

In Figure 7, thrust force signals and thrust force values at variable feed rates at a fixed cutting speed of 30 m/min are given. In the two machining methods, the thrust force values are at their lowest at a feed rate of 0.09 mm/rev. As the feed rate increases, the amount of chip removed increases. Therefore, increasing the feed rate causes the thrust force to increase in both machining methods. Increasing the feed rate increases the amount of chip and increases the load on the tool. This causes more chip removal, thus increasing the thrust force [29]. When the thrust forces obtained at a feed rate of 0.15 mm/rev were examined, the thrust force measured by EAD decreased by approximately 12.62% compared to CD. While the maximum cutting force measured in CD was 71.3 N at a feed rate of 0.15 mm/rev, it was measured as 62.3 N at a feed rate of 0.15 mm/rev in EAD.



(a) (b)

Figure 7. a) Effect of feed rate on thrust force b) Thrust force signal.

4 Conclusion

As a result of experimental studies on CD and EAD of AISI 316L austenitic stainless steel with HSS cutting tools, the following conclusions can be drawn:

- When the cutting tool wear values are examined, tool wear values increased for both machining methods with the increase of cutting speed and feed rate. Tool wear values obtained with EAD were lower than those with CD. While side edge wear and notch wear were observed as wear types in CD, only side edge wear was observed in EAD. Tip breakage occurred in some places in the CD.
- Thrust force decreased for both machining methods due to increasing cutting speed at constant feed rate. In experiments conducted at variable cutting speeds, the maximum thrust force was measured as 73.5 N at CD at a cutting speed of 20 m/min. The lowest thrust force was measured as 48.2 N in EAD at a cutting speed of 40 m/min. At a cutting speed of 30 m/min, EAD reduced the thrust force by 18.51% compared to CD.
- Thrust force increased for both machining methods due to increasing feed rate at fixed cutting speed. At a fixed cutting speed of 30 m/min and varying feed rates, the highest thrust force was measured as 71.3 N at CD at a feed rate of 0.15 mm/rev. The lowest thrust force was measured as 46.8 N in EAD at a feed rate of 0.09 mm/rev. At a feed rate of 0.15 mm/rev, EAD reduced the thrust force by 12.62% compared to CD.

Declaration

Ethics committee approval is not required.

References

[1] Ankalagi, S., Gaitonde, V. N., & Petkar, P. (2017). Experimental Studies on Hole Quality in Drilling of SA182 Steel. *Materials Today: Proceedings, 4*(10), 11201-11209.

[2] Naves, V. T. G., Da Silva, M. B., & Da Silva, F. J. (2013). Evaluation of the Effect of Application of Cutting Fluid at High Pressure on Tool Wear During Turning Operation of AISI 316 Austenitic Stainless Steel. *Wear, 302*(1), 1201-1208.

[3] Pilkington, A., Dowey, S. J., Toton, J. T., & Doyle, E. D. (2013). Machining With AlCr-Oxinitride PVD Coated Cutting Tools. *Tribology International, 65*, 303-313.

[4] Kumar, C. S., Urbikain, G., Fernandes, F., AL Rjoub, A., & De Lacalle, L. N. L. (2024). Influence of V Concentration in TiAlSiVN Coating on Self-Lubrication, Friction and Tool Wear During Two-Pass Dry Turning of Austenitic Steel 316 L. *Tribology International, 193*, 109355.

[5] Pang, X., Zhang, B., Li, S., Zeng, Y., Liu, X., Shen, P., ... & Deng, W. (2022). Machining performance evaluation and tool wear analysis of dry cutting austenitic stainless steel with variable-length restricted contact tools. *Wear, 504*, 204423.

[6] Ağar, S., & Tosun, N. (2021). Ultrasonic assisted turning of AISI 52100 steel using nanoparticle-MQL method. *Surface Topography: Metrology and Properties*, 9(1), 015024.

[7] Sujan Kumar, M., & Deivanathan, R. (2021). Effect of Process Parameters on Drilling—An Overview. *Materials Today: Proceedings, 46*, 1401-1406.

[8] Samy, G. S., & Kumaran, S. T. (2017). Measurement and Analysis of Temperature, Thrust Force and Surface Roughness in Drilling of AA (6351)-B4C Composite. *Measurement, 103,* 1-9.

[9] Munaro, R., Attanasio, A., Abeni, A., Cappellini, C., Tavormina, P., & Venturelli, F. (2024). A New Architecture Paradigm for Tool Wear Prediction During AISI 9840 Drilling Operation. *Procedia Computer Science, 232,* 1617-1625.

[10] Vasumathy, D., & Meena, A. (2017). Influence of Micro Scale Textured Tools on Tribological Properties at Tool-Chip Interface in Turning AISI 316 Austenitic Stainless Steel. *Wear, 376-377,* 1747-1758.

[11] Kümmel, J., Braun, D., Gibmeier, J., Schneider, J., Greiner, C., Schulze, V., & Wanner, A. (2015). Study on micro texturing of uncoated cemented carbide cutting tools for wear improvement and built-up edge stabilisation. *Journal of Materials Processing Technology, 215,* 62-70.

[12] Jawahir, I. S., Brinksmeier, E., M'saoubi, R., Aspinwall, D. K., Outeiro, J. C., Meyer, D., ... & Jayal, A. D. (2011). Surface integrity in material removal processes: Recent advances. *CIRP annals,* 60(2), 603-626.

[13] Kümmel, J., Gibmeier, J., Müller, E., Schneider, R., Schulze, V., & Wanner, A. (2014). Detailed Analysis of Microstructure of Intentionally Formed Built-Up Edges for Improving Wear Behaviour in Dry Metal Cutting Process of Steel. *Wear, 311*(1), 21-30

[14] Axinte, D. A., Andrews, P., Li, W., Gindy, N., Withers, P. J., & Childs, T. H. C. (2006). Turning of Advanced Ni-Based Alloys Obtained Via Powder Metallurgy Route. *CIRP Annals, 55*(1), 117-120.

[15] Yıldırım, Ç. V., Kıvak, T., Sarıkaya, M., & Erzincanlı, F. (2017). Determination of MQL Parameters Contributing to Sustainable Machining in the Milling of Nickel-Base Superalloy Waspaloy. *Arab Journal of Science and Engineering, 42*(11), 4667-4681.

[16] Ali, M. A. M., Azmi, A. I., Murad, M. N., Zain, M. Z. M., Khalil, A. N. M., & Shuaib, N. A. (2020). Roles of New Bio-Based Nanolubricants Towards Eco-Friendly and Improved Machinability of Inconel 718 Alloys. *Tribology International, 144,* 106106.

[17] Khan, M. M. A., Mithu, M. A. H., & Dhar, N. R. (2009). Effects of minimum quantity lubrication on turning AISI 9310 alloy steel using vegetable oil-based cutting fluid. *Journal of materials processing Technology,* 209(15-16), 5573-5583.

[18] Shokoohi, Y., Khosrojerdi, E., & Rassolian Shiadhi, B. H. (2015). Machining and Ecological Effects of a New Developed Cutting Fluid in Combination With Different Cooling Techniques on Turning Operation. *Journal of Cleaner Production, 94,* 330-339.

[19] Jindal, H., Kumar, S., & Kumar, R. (2020). Environmental Pollution and Its Impact on Public Health: A Critical Review. *TARCE, 9*(1), 11-18

[20] Lian, H. S., Guo, Z. N., Liu, J. W., Huang, Z. G., & He, J. F. (2016). Experimental Study of Electrophoretically Assisted Micro-Ultrasonic Machining. *International Journal of Advanced Manufacturing Technology, 85*(9), 2115-2124.

[21] He, J., Guo, Z., Lian, H., Wang, J., Chen, X., & Liu, J. (2020). Improving the Machining Quality of Micro Structures by Using Electrophoresis-Assisted Ultrasonic Micromilling Machining. *International Journal of Precision Engineering and Manufacturing-Green Technology, 7*(1), 151-161.

[22] Besra, L., & Liu, M. (2007). A Review on Fundamentals and Applications of Electrophoretic Deposition (EPD). *Progress in Materials Science, 52*(1), 1-61.

[23] Colantonio, L., Equeter, L., Dehombreux, P., & Ducobu, F. (2021). A Systematic Literature Review of Cutting Tool Wear Monitoring in Turning by Using Artificial Intelligence Techniques. *Machines, 9*(12), Article 12.

[24] Huang, W., Cao, S., Li, H. N., Zhou, Q., Wu, C., Zhu, D., & Zhuang, K. (2021). Tool wear in ultrasonic vibration–assisted drilling of CFRP: a comparison with conventional drilling. *The International Journal of Advanced Manufacturing Technology, 115(5),* 1809-1820.

[25] Dadgari, A., Huo, D., & Swailes, D. (2018). Investigation on tool wear and tool life prediction in micro-milling of Ti-6Al-4V. *Nanotechnology and Precision Engineering* (NPE), 1(4), 218-225.

[26] Hou, Y., Zhang, D., Wu, B., & Luo, M. (2014). Milling force modeling of worn tool and tool flank wear recognition in end milling. *IEEE/ASME Transactions on Mechatronics,* 20(3), 1024-1035.

[27] An, Q., Chen, J., Tao, Z., Ming, W., & Chen, M. (2020). Experimental investigation on tool wear characteristics of PVD and CVD coatings during face milling of Ti6242S and Ti-555 titanium alloys. *International Journal of Refractory Metals and Hard Materials,* 86, 105091.

[28] Subhedar, D. G., Chauhan, K. V., & Patel, D. A. (2022). An Experimental Investigation of TiN Coating on Cutting Force and Surface Finish in Milling of Aluminium. *Materials Today: Proceedings, 59,* 161-165.

[29] Ercetin, A., Aslantaş, K., Özgün, Ö., Perçin, M., & Chandrashekarappa, M. P. G. (2023). Optimization of Machining Parameters to Minimize Cutting Forces and Surface Roughness in Micro-Milling of Mg13Sn Alloy. *Micromachines, 14*(8), Article 8.