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Araştırma Makalesi / Research Article

Improvement of Machining Vibrational Stabilization for a CNC Lathe in Turning of AISI 420 Stainless Steel by MQL and Cryogenic Methods

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ABSTRACT: It is common to find annealed and tempered stainless steels on the market for raw materials. The choice of proper heat treatment settings is one of the most influential aspects in determining the corrosion resistance of annealed materials. The degradation of materials as a result of wear and corrosion is a problem that leads to very considerable economic losses nowadays. By applying lubrication and cooling to the material's surface during operation, the destructive effects of wear and corrosion on the material may be reduced. This study investigates the influence that different machining and lubrication/cooling environments have on vibrational stabilization-based acceleration as well as power consumption during the turning of AISI 420 stainless steel under dry, minimum quantity lubrication (MQL), and cryogenic settings. In all of the turning trials, the cutting speed and the depth of cut were maintained at the same levels. When the data were analyzed, a change from the dry environment to the MQL condition resulted in a drop of 7.04% and 5.2% in power consumption and acceleration, respectively, while a change from the MQL test settings to cryogenic cooling conditions resulted in a decrease of 2.02% and 14.3% in power consumption and acceleration, respectively.

Keywords: AISI 420 stainless steel, Vibration, Power consumption, Minimum quantity lubrication (MQL), Cryogenic cooling, Turning

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1. INTRODUCTION

Surface treatments using different machining methods are directly or indirectly affected by machining parameters (Danish et al., 2021). Machining parameters that are not chosen well to cause economic losses such as breakage, rapid wear, and burning of cutting tools, as well as economic losses such as deterioration of the workpiece or low surface quality (Sharif et al., 2017). Machining has an important place among other manufacturing methods. In all manufacturing methods, besides the size and geometric tolerances of the product, a satisfactory surface roughness quality is also of great importance (Zhou et al., 2021). The surface structure of the machine parts is directly affected by the change of the workpiece, the tool, the machining conditions or any of the workbench, that is, the machining regime (Iyappan and Ghosh, 2018). The functioning of the manufactured parts as required, their mechanical life and resistance to external influences depend on the surface quality as well as other factors (Sarıkaya et al., 2021). Therefore, there is a need to determine or estimate how roughness occurs with numerical values. It is possible to use the contact vibration (chatter vibration) between the tool and the workpiece in the estimation of the actual value of the roughness, which affects the function and cost of the part (Türkeş and Neşeli, 2014; Takahashi et al., 2021). Because of this importance of surface quality, manufacturer’s attention has been focused on reducing the surface roughness of machined parts (Gupta et al., 2020). Chattering or machine tool vibrations, damage to the structure of the work material, tool wear or irregularities of chip formation contribute to surface deterioration during machining (Turkes et al., 2011). Estimating the surface roughness and evaluating the compatibility of machining parameters such as feed or cutting speed increases the product quality and sheds light on obtaining the desired surface roughness (Dubey et al., 2021). Mechanical vibrations should be well known in order to understand chatter vibrations in machine tools. The periodic movement of an object around its equilibrium position is called mechanical vibration (Pecat and Brinksmeier, 2014). In general, vibration is an unwanted and unnecessary energy state. It is a fact that it makes noise, breaks parts and transmits unwanted forces, especially in machine tools (Szaksz and Stepan, 2021). For these reasons, vibration reduction is necessary. In vibration problems, it is necessary to solve the equation of motion. The system is first simplified in terms of mass, spring and damping elements that express its existence, elasticity and friction (Mojahed et al., 2018). The equation of motion is expressed in terms of displacement as a function of time or to give the distance of the mass from the equilibrium position at any moment of motion (Chen et al., 2022). The natural frequency, which is the most important property of the systems, is obtained from the equation of motion. The main source of error in each machining operation is the relative dynamic movement between the tool and the workpiece (Wang et al., 2022). The relative motion between the tool and the workpiece is a natural frequency system and due to the unstable behavior, that occurs with large amplitude relative displacements, it can greatly damage the machined end surface and the cutting tool. If this movement develops beyond the acceptable limits, this phenomenon is called chatter, and the resulting chatter leads to poor surface results, poor dimensional accuracy, increased tool wear, frequent tool breakage and indirectly shortened machine life (Ni et al., 2020).

In dry conditions, researchers have proposed many ways for machining difficult-to-cut materials, including the use of surface texture on cutting inserts (Rao et al., 2021), coated tools (Erden et al., 2021), as well as the use of self-lubricating tools (Akhtar, 2021). All of these approaches, when compared to traditional machining, have shown a decrease in machining forces and friction coefficient. Tool wear and machined surface quality, on the other hand, continue to be a problem. The use of cutting fluids for the machining of difficult-to-cut materials is thus advised. Cutting fluids, on the other hand, provide a variety of health risks to operators as well as significant environmental consequences (Bertolini et al., 2021). The literature investigates alternative sustainable settings such as compressed air, cryogenic, and minimum quantity lubrication (MQL), among others, except for the assessment of vibrational stabilization. The effect of cutting parameters on natural frequency and surface roughness in turning aluminum alloy AA2024 was investigated by Rogov and Siamak (Rogov and Siamak, 2013) using a TiC-coated carbide insert and two different cutting tools made of AISI 5140 and the predicted optimal cutting parameters were obtained by Taguchi. Kusuma et al. (Kusuma et al., 2014) aimed to investigate the effects of cutting parameters such as depth of cut, feed rate, and spindle speed on tool vibration and surface quality by using microelectromechanical systems (MEMS) accelerometer on a high precision CNC milling machine. The results showed that in the milling machine, the depth of cut was more effective on surface roughness and vibration was more influenced by spindle speed. Zagórski and Kulisz (Zagórski and Kulisz, 2019) aimed to demonstrate the work on vibration and acceleration estimation in milling through artificial neural networks. It was also seen that the extent to which cutting speed, feed rate, and depth of cut affected the acceleration values ax, ay, and az during the milling process performed on the AZ91D magnesium alloy with a PCD cutting tool in this study. Ma et al. (Ma et al., 2020) aimed to demonstrate that vibration control is an important issue during both end-milling and micro-end-milling of complex surfaces to improve machining quality and extend tool life. The results showed that spindle speed had the greatest effect on cutting vibration when compared with the axial depth of cut and feed rate. They also revealed that among axial, feed, and transverse acceleration during micro end milling of the straight groove, the largest acceleration is the transverse acceleration, and the smallest acceleration is the axial acceleration. The machining of AISI 304 steel under minimum quantity cooling lubrication (MQCL) and flood-cutting conditions were experimentally examined by Liu et al. (Liu et al., 2021) to evaluate both tool vibration using the response surface methodology and surface roughness characteristics using the power spectral density. They found that both feed rate and MQCL conditions significantly affected not only surface roughness but also radial and axial vibration. Emami and Karimipour (Emami and Karimipour, 2021) analyzed the influence of cooling and lubrication on the dynamic stability of the turning process both theoretically and experimentally. It was obtained from the results that wet cooling and MQL during the machining process could change the chatter stability limit to a remarkable range. In addition, it was seen that the chatter stability in wet machining was higher than MQL machining in the spindle speed from 550 rpm to 1668 rpm but at spindle speeds above 1668 rpm, the stability in the MQL machining was higher than the stability in wet machining.

Numerous machining experiments using dry, MQL, and cryogenic cooling conditions and outputs of surface roughness, cutting forces, tool wear, etc. can be found in the literature. In addition, there are machining research on vibrational stabilization in dry circumstances exclusively. However, there are no or limited studies on vibrational stabilization with MQL or cryogenic cooling conditions. As the novelty, this study emphasized the effect of machining and lubrication/cooling environments on vibrational stabilization-based acceleration as well as power consumption in the turning of AISI 420 stainless steel on dry, MQL, and cryogenic conditions to fill this gap in the literature.

2. MATERIALS AND METHODS

For the purpose of carrying out the turning tests on the AISI 420 stainless steel, a Taksan TTC-550 CNC lathe was used. As can be seen in Figure 1, the length of the bar is 250 mm, and it has an outer diameter of 50 mm. The chemical composition is 0.15%~C, 1.0%~Si, 1.0%~Mn, 13%~Cr, 0.04%~P, 0.03%~S and the balance is Fe. After heat treatment, the material hardness and tensile strength increased to 50 HRC, 1570 MPa, respectively. CNMG 120404 ML cutting inserts produced by Korloy was used in the study. In addition, the cutting speed was kept constant at 180 m/min. throughout all of the tests, and the depth of cut was maintained at 0.5 mm. The feed rate was varied between 0.1, 0.15, and 0.2 mm/rev. depending on whether the environment was dry, MQL, or cryogenic. Experiments which are repeated 2 times were carried out in a variety of environments, including dry, MQL, and cryogenic settings. The Werte StN 15 MQL system, which was built by the Werte Mist Company, was deployed for MQL testing. The biodegradable vegetable-based essential oil WerteLubri was used as the cutting fluid, and it was applied with a nozzle having a diameter of 2 mm, which was positioned at a fixed distance of 45 mm from the cutting zone and at 45°. The flow rate was 100 mm/h, and the pressure was 5 bar (Çamlı et al., 2022). The YDS-10 liquid nitrogen tank that was manufactured by Low-Temp Company was utilized in the research involving cryogenic cooling (Figure 1). The cutting region was sprayed with liquid nitrogen (LN2) having the flow rate of 0.71 cm^3/s using a vacuum hose that had been custom-made for the purpose, with a nozzle that had a diameter of 3 mm and a pressure of 0.5 bar throughout (Korkmaz et al., 2022). Cryogenic machining requires the use of a nozzle that is positioned at a constant distance of 45 mm at 45°, just as the MQL nozzle. The experimental setup is shown in Figure 1, which may be found here.

The sample measurement length used for this evaluation was 5 mm. Before beginning each measurement, the validation block was navigated to in order to calibrate the instrument. Measurements of acceleration based on vibration were carried out with the help of the PCE-VD 3-Axis Vibration Datalogger that measures 3-axis shock/vibration via a built-in accelerometer sensor. The power consumption (total consumption over the turning process) measurements have been performed by KAEL Network Analyzer (Turkey) which is logged to CNC system by parallel connection. The values have been directly read from the analyzer.

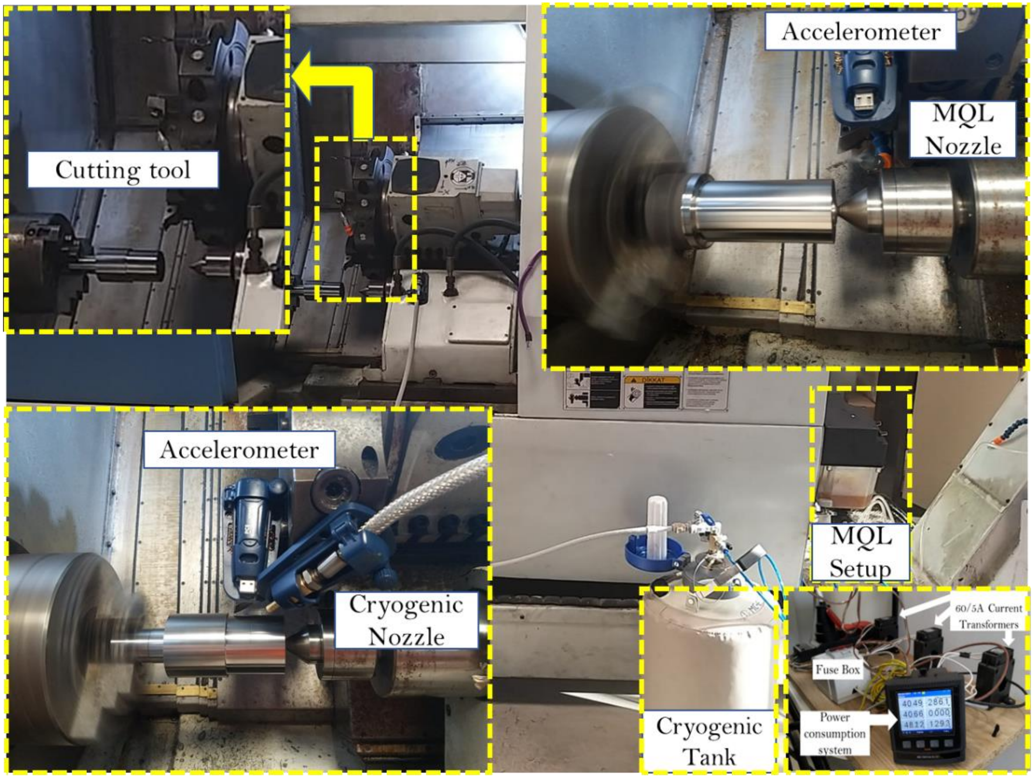

Figure 1. Experimental setup

3. RESULTS AND DISCUSSION

3.1 Evaluation of Acceleration (Vibrational Stabilization) Results

During the turning of AISI 420 stainless steel, the radial acceleration values a_z were observed. The observation results are depicted in Figure 2, regarding feed rates (f = 0.1 mm/rev, f = 0.15 mm/rev, f = 0.2 mm/rev), and cutting environments (dry, MQL and cryogenic). The maximum and minimum values of radial vibration acceleration were obtained using experimental results and then its root mean square (RMS) values were calculated. As shown in Figure 2, the radial vibrations gradually increased with an increase the feed rate from 0.1 mm/rev to 0.2 mm/rev at all cutting environments because vibration values increase as the feed rate increases.

The vibration values in the machining process can be divided into several different steps. As shown in Figure 2, it was seen that the fastest cutting speed in the dry testing condition resulted in the largest acceleration, which was 1.601 m/s^2 at its peak value. The largest acceleration values at low and medium feed rates were observed to be 1.110 m/s^2 and 1.490 m/s^2, respectively. An increase in feed rate from 0.1 to 0.15 mm/rev resulted in an increase in acceleration of about 34%. As the feed rate goes from 0.15 to 0.2 mm/rev, there was a corresponding increase in the acceleration about 7.4%. The acceleration for the cryogenic test condition came out to be 0.864 m/s^2 as the experiment was run with a low feed rate. In the cryogenic tests, the acceleration was found as 1.180 m/s^2 at medium feed rate, while the acceleration value was obtained as 1.280 m/s^2 at high feed rate. In the cryogenic test, whereas the feed rate is increased from 0.1 to 0.15 mm/rev or from 0.15 to 0.2 mm/rev, respectively, the measured acceleration values were increased by 36.6% and 8.5%, respectively. While the dry experiments were changed with the experiments conducted in a cryogenic state, the acceleration value for the low feed rate dropped by 20.2%. When the dry environment was changed with the MQL condition, there was a 5.2% drop at the low feed rate. During the parameters for the MQL test were moved to the cryogenic one with the low feed rate value, average acceleration values dropped by 14.3%. These values for decrease come in at 15.2% for medium feed rates and 18.1% for high feed rates, respectively.

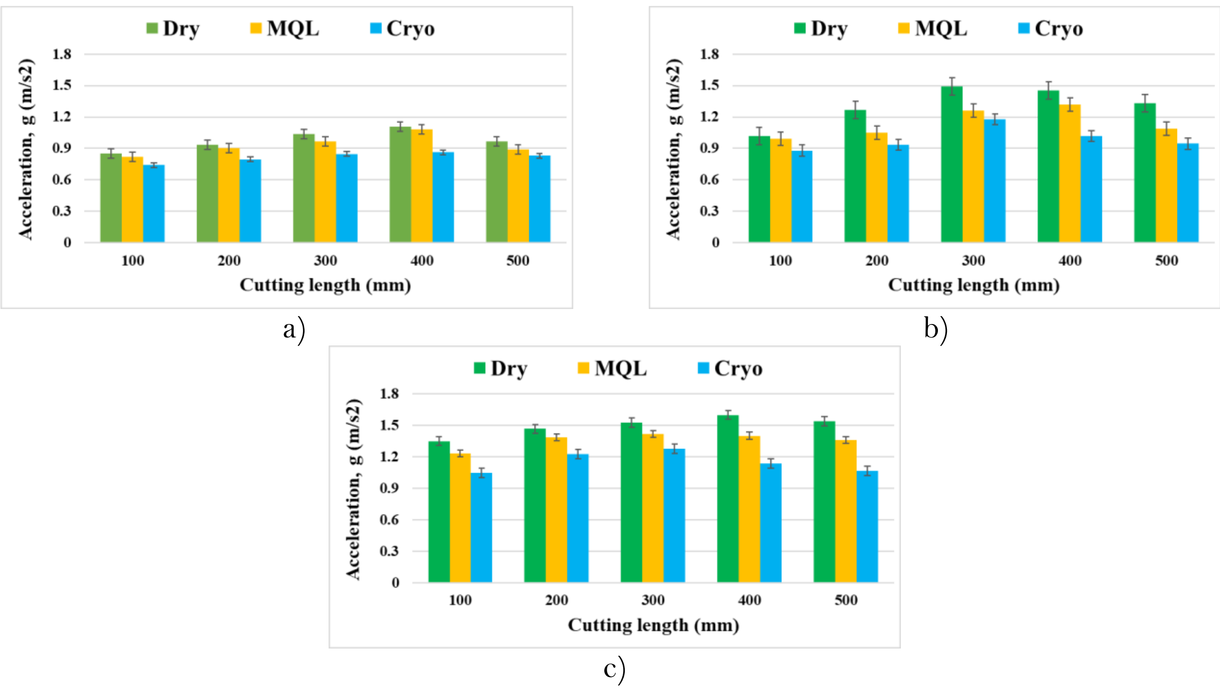

Figure 2. Vibrational evaluation based on acceleration for the different cutting environments, a) f=0.1 mm/rev, b) f=0.15 mm/rev, c) f=0.2 mm/rev

Due to the large contact area between the workpiece and the tool, material accumulation occurs in the same area, and this limits the heat dissipation. As the friction between the workpiece and the tool increased, the chips constantly sticking to the tool edge developed more accumulated edges. Because of this, the temperature has risen sharply. It also increased the cutting resistance, and so tool vibration increased significantly (Liu et al., 2021).

As seen in Figure 2, according to the test results, the vibration values under the cryogenic conditions were lower than the vibration values under both dry cutting and MQL technology. This difference was due to the effect of the cryogenic cooling in tool-workpiece interaction very high temperature occurs. The effect of heat dissipation was supplied at a low temperature, and this also reduced the cutting resistance of the removed material. When the vibration values in the machining performed under dry cutting and cryogenic cooling technology are compared, it was seen that the vibration values in the machining performed under cryogenic cooling technology were less than the under the effect of dry cutting as shown in Figure 2. This can be attributed to the fact that cryogenic machining conditions resulted in a better surface finish for the finished part. This is because cryogenic machining conditions resulted in better chip breakability and less accumulation of chips near the cutting zone. As a result, frictional contact between the chips and the finished workpiece was avoided (Jerold and Kumar, 2012). Moreover, MQL is also better than dry condition due to lubricant effect. It was delivered to the cutting zone to provide adequate lubrication and so it formed an interface with the help of oil droplets between the tool and the workpiece. As a result, vibration was reduced due to the reduction of friction force. The reason why this was so similar to the machining under MQL. Because it provided an extra interface between the tool and the workpiece, reducing the friction force in the region and allowing the heat dissipation. However, the interface formed for the reduction of the friction force did not reduce the friction force that much since it was not composed of oil as in the machining under MQL. Therefore, although it was understood that the vibration values in the machining performed under the MQL technology created more vibration than the cryogenic cooling technology, it had been observed that they finally created less vibration than dry cutting (Krolczyk et al., 2019).

3.2 Power Consumption

The use of electrical power in the machining process may be broken down into a few distinct steps. As shown in Figure 3, it was discovered that the highest feed in the dry testing condition resulted in the largest power consumption, which was 2928 W at its peak value. In terms of the amount of electricity that is used, the low and medium feed rates utilize 2556 W and 2664 W, respectively. The increase in feed rate from 0.1 to 0.15 mm/rev resulted in an increase in power consumption that was 5%. As the feed rate value goes from 0.15 to 0.2 mm/rev, there is a corresponding increase of 9.4% in the power consumption value. The power consumption number for the cryogenic test condition came out to be 2328 W when the experiment was run with a low feed rate. In the cryogenic tests, cutting at a medium feed rate required 2544 W of power, while cutting at a high feed rate used 2664 W of power. When the feed rate in cryogenic testing is increased from 0.1 to 0.15 mm/rev or from 0.15 to 0.2 mm/rev, respectively, there is a 9.3% and 4.7% increase in the amount of power that is consumed. When the dry experiments were switched out for those conducted in a cryogenic state, the value for the low feed rate dropped by 8.9%. When the dry environment was switched out for the MQL condition, there was a 7.04% drop at the low feed rate. When the parameters for the MQL test were moved to the cryogenic one with the low feed rate value, the overall power consumption dropped by 2.02%. These values for decrease come in at 1.38% for medium feed rates and 4.38% for high feed rates, respectively. It is understood from the values that the cryogenic machining required considerably less power than dry environment. As claimed by Khanna et al. (Khanna et al., 2020), this is due to the cryogen ability to rapidly remove the heat created during dry machining.

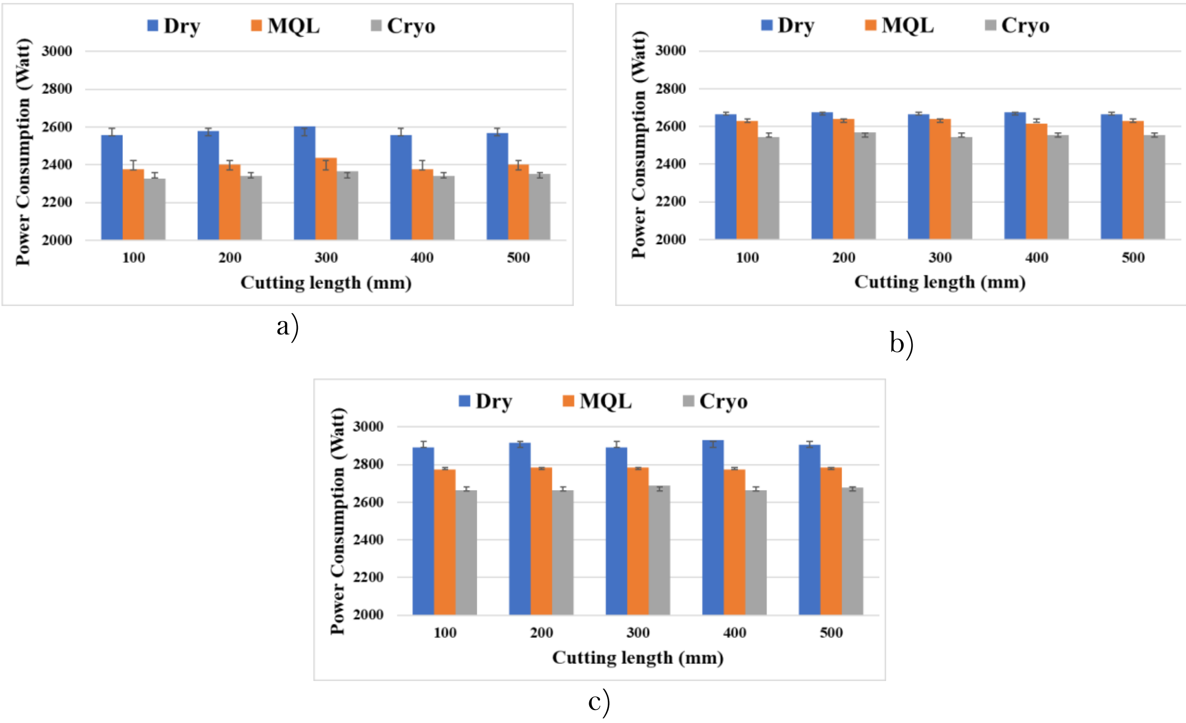

Figure 3. Power consumption based on the different cutting environments, a) f=0.1 mm/rev, b) f=0.15 mm/rev, c) f=0.2 mm/rev

The production of a lubricant-film between two moving surfaces, a reduction in the friction coefficient, and the prevention of wear on the moving surfaces are the goals of lubrication (Korkmaz et al., 2022). Lubricity is intended to make movement simpler by doing these things. The majority of coolants work to minimize friction, while cryogenic cooling works to lower the high temperature in the cutting zone. Together, these effects lessen the amount of power that must be used to machine a given material. This will not only cut down on the amount of energy that is consumed, but it will also lower the amount of heat that is produced (Gupta et al., 2019). When there is less heat produced, there is an increase in the tool life, and the surface integrity of the material being worked on is maintained (Hong and Ding, 2001).

4. CONCLUSION

This experimental investigation was carried out to investigate the machinability of AISI 420 stainless steel in order to determine the impact that employing dry, MQL, and cryogenic cooling had on the machining outputs, namely acceleration based on vibrational stabilization, as well as power consumption. The following are some of the conclusions that may be drawn from this study:

- The increase in feed rate from 0.1 to 0.15 mm/rev led to a rise in the measured acceleration was equal to 34% more. When the value of the feed rate is increased from 0.15 to 0.2 mm/rev, there is a corresponding rise in the value of the power consumption that is 7.4% higher.
- When the dry environment was switched out for the MQL condition, there was a 5.2% drop in acceleration. On the other hand, when the MQL test settings were transferred to cryogenic cooling conditions, there was a 14.3% decrease in acceleration.

- The increase in feed rate from 0.1 to 0.15 mm/rev led to a rise in the amount of consumed power was equal to 5% more. When the value of the feed rate is increased from 0.15 to 0.2 mm/rev, there was a corresponding rise in the value of acceleration that is 9.4% higher.
- When the dry environment was switched out for the MQL condition, there was a 7.04% drop in power consumption. On the other hand, when the MQL test settings were transferred to cryogenic cooling conditions, there was a 2.02% decrease in power consumption.
- It is anticipated that this study will be useful to research and development centers in the machining industries regarding stainless steels. In particular, it is anticipated that this study will be useful to research and development centers that are focused on improving cooling technologies in the machining of stainless-steel components.

5. ACKNOWLEDGEMENTS

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6. CONFLICT OF INTEREST

Authors approve that to the best of their knowledge, there is not any conflict of interest or common interest with an institution/organization or a person that may affect the review process of the paper.

7. AUTHOR CONTRIBUTION

Fatih PEHLİVAN contributed determining the concept of the research and research management, design process of the research and research management, data analysis and interpretation of the results, critical analysis of the intellectual content, preparation of the manuscript, and final approval and full responsibility.

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