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# Finite Element Analysis to Predict Thrust Force and Torque in Drilling of Aged and Annealed Inconel 718

Mohammed B. HUSSEIN[1,*], Yavuz ZÜMRÜT[1]

[1] *Department of Mechanical Engineering, Faculty of Engineering, Gazi University, Ankara, Turkey*

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**Abstract**

In this study, drilling of two kinds of Inconel 718 superalloys (aged and annealed) were simulated with FEM based Deform 3D V.11 software, and the effects of feed rate and cutting speed on thrust force and drilling torque have been investigated. A 5 mm diameter uncoated carbide twist drill with a web thickness of 0.75 mm was modelled, and drilling operations were simulated for two feed rates (0.05 and 0.1 mm/rev) and two cutting speeds (10 and 20 m/min). The workpieces were modelled by using Johnson-Cook (J-C) material model whose parameters acquired from the published literature. Thrust forces and drilling torques of aged Inconel 718 were found to be considerably larger than that of annealed Inconel 718 under the same cutting conditions.

## 1. INTRODUCTION

Drilling process is one of the most significant machining processes that constitute about 22% of all machining processes in terms of the number of operations. It is often performed as one of the last operations in production of parts. On the other hand, drilling process is more complex than other machining operations, i.e. turning and milling, in terms of the kinematics and dynamics of the process, the process control, the chip removal and cutting heat dissipation. The drill tool properties and the process parameters should be properly determined by considering the specific drilling requirements and workpiece material. In this regard, drilling, and naturally other metal cutting operations, have been studied extensively in the published literature. Although experimental-empirical method for investigation of right parameters for metal cutting operations is often the main reference in the industry, it is valid for the ranges of the experiments conducted, and furthermore, it is costly and time consuming. Therefore, considerable progresses have been seen in the development of other industry-driven predictive models for machining operations in the last few decades. They may be categorized as analytical, numerical, Artificial intelligence (AI) based, and hybrid modelling techniques. Among them, numerical methods implemented to commercial codes, providing opportunities to connect to industry-relevant parameters, have been extensively used by the researchers [1-3].

Inconel 718 is a nickel-chromium based high strength superalloy. It is resistant to the variety of corrosive conditions, pitting and crevice corrosion. It provides outstanding mechanical properties like high tensile, fatigue and creep-rupture strength at elevated temperatures. It is used at cryogenic (-252 $^{0}$C) to high (704 $^{0}$C) temperatures. The alloy is preferred for use in aeronautics and land based gas turbines, marine engineering, nuclear power plants, etc. [4,5].

*Corresponding author, e-mail: mohammedbaqi.h@gmail.com

Inconel 718, like many other superalloys, is known as difficult-to-cut alloy. Work hardening, high temperature strength, poor thermal conductivity, abrasive and adhesive mechanism due to high amount of carbides in the alloy, adhesive tendency of the nickel, high heat generation are the prevalent reasons for the difficulty in machining Inconel 718 [6,7].

Although numerous research works have been carried out on turning and milling of Inconel 718, research on drilling of Inconel 718 is relatively limited in the published literature [7,8]. Likewise, less number of studies on drilling of different superalloys can be found in the literature.

Since cutting forces affect cutting temperatures, tool wear, surface integrity, power consumption, etc. considerably, they have been investigated substantially. As it is well known that the feed rate and the cutting speed are the primary machining parameters that determine the cutting forces. In the studies investigating the effects of cutting conditions on cutting forces, apart from dry cutting, various cooling methods have been also used to improve machinability. A few researches on the subject are given below.

Uçak et al. analysed experimentally and numerically the drilling operation on annealed Inconel 718 at dry cutting conditions, to investigate thrust force, torque and temperature [8]. They used Deform 2D and 3D to simulate the drilling operation and observed a good agreement between the numerical and experimental results.

Jian and Rongdi studied the drilling of Inconel 718 in terms of drilling deformation and drilling forces distribution. They obtained the drilling chip specimens by using self-made drilling quick-stop device. An empirical formula of shear angle was derived from the results of dry drilling tests. Thrust and torque values according to various cutting speeds and feed rates were recorded, and the ratio of thrust and torque on the lead cutting edge were determined. They compared all the results of Inconel 718 with that of AISI 1045 steel [9].

Rahim and Sasahara investigated experimentally the effect of high speed drilling under minimum quantity of lubrication conditions on drilling performance and surface integrity of Inconel 718. It was observed that, the thrust force and torque values decreased linearly with increasing cutting speed, and the values increased significantly with increasing feed rate. The cutting speed also influenced the distribution of the surface roughness significantly. Moreover, findings about tool wear, workpiece temperature, surface roughness and hardness variations beneath the machined surface were noted [7].

Nagaraj et al. simulated drilling operation of Nimonic C-263 superalloy to investigate the thrust force, temperature generation, effective stress and strain by varying the spindle speed, feed rate and point angle. They compared the simulated thrust force and drill bit cutting edge temperature with the experimental results and observed 10% of error [10].

Using a 3D FEM, Parida studied drilling operation of Ti-6Al-4V, to simulate thrust force, torque, effective stress, effective strain, drill bit temperature, surface roughness and circularity by changing cutting speed and feed rates. Among the simulated results, Parida compared thrust, torque and circularity with the experimental results and observed a good agreement with few errors [11].

As known, heat treatment processes are applied to metals widely in order to change the physical and mechanical properties in a desirable way. Objectives of heat treatment process are; to increase strength, hardness, ductility, toughness, etc., and to improve formability, machinability, etc., for engineering applications of metals. Accordingly, differently heat treated, namely aged and annealed types of Nickel based superalloy Inconel 718 exhibit different physical and mechanical, especially strength and thermo-visco plastic, properties. Machinability properties of these materials naturally vary considerably. In this respect, the aim of this paper is to investigate numerically the effects of cutting conditions (feed rate and cutting speed) on the machining performance (thrust force and drilling torque), in drilling of aged and annealed types of Inconel 718.

## 2. METHODS

In this paper, drilling simulations were performed using SFTC DEFORM 3D V.11. In the simulations, a 5 mm diameter uncoated carbide twist drill with a web thickness of 0.75 mm was modelled to drill two different types of Inconel 718 (aged and annealed) superalloy. Drilling operations were simulated at two feed rates (0.05, 0.1 mm/rev) and two cutting speeds (10, 20 m/min). The limited material chemical composition for Inconel 718 is given in Table 1.

***Table 1.*** *Limiting chemical compositions of Inconel 718* [4]

| ***ELEMENTS*** | ***Min %*** | ***Max %*** |
|---|---|---|
| Nickel + Cobalt | 50.00 | 55.00 |
| Chromium | 17.00 | 21.0 |
| Iron | Balanced | |
| Niobium + Tantalum | 4.75 | 5.50 |
| Molybdenum | 2.80 | 3.30 |
| Titanium | 0.65 | 1.15 |
| Aluminum | 0.20 | 0.80 |
| Cobalt | .............. | 1.00 |
| Carbon | .............. | 0.08 |
| Manganese | .............. | 0.35 |
| Silicon | .............. | 0.35 |
| Phosphorus | .............. | 0.015 |
| Sulfur | .............. | 0.015 |
| Boron | .............. | 0.006 |
| Copper | .............. | 0.30 |

### 2.1. Twist Drill Model

For drilling of Inconel 718 at dry cutting conditions, using of uncoated carbide tools with lower feed rates was recommended for better hole quality [12]. A 3D twist drill model was created and meshed in the Deform 3D software and assumed to be rigid, shown in Figure 1. 15% Cobalt uncoated carbide was selected as tool material. Geometric parameters are as follows: drill diameter of 5 mm, web thickness of 0.75 mm, helix angle of $30^0$ and point angle of $140^0$.

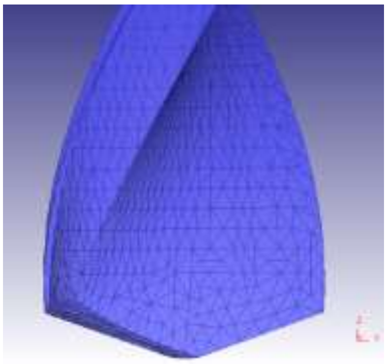

***Figure 1.*** *Meshed twist drill model*

Twist drill mesh properties and other related assumptions made in the FEM analysis are given in Table 2.

***Table 2.*** *Twist drill mesh properties*

| Assumptions | Values |
|---|---|
| Tool Material | Carbide %15 cobalt |
| Mesh Size ratio | 4 |
| Element type | Tetrahedral |
| Mesh type | Fine Mesh |
| Surface polygons | 4,296 |
| Nodes | 2,150 nodes |
| Relative mesh type | 32,000 |

## 2.2. Workpiece Model

The workpiece was modelled as a disc having a diameter of 7 mm and a height of 2.5 mm. To start the cutting process immediately at full load, a pre-machined conical hole was generated on the workpiece to a specific depth. As a function of the Deform 3D, the conical hole is created exactly from the imprint of drill bit as shown in Figure 2.

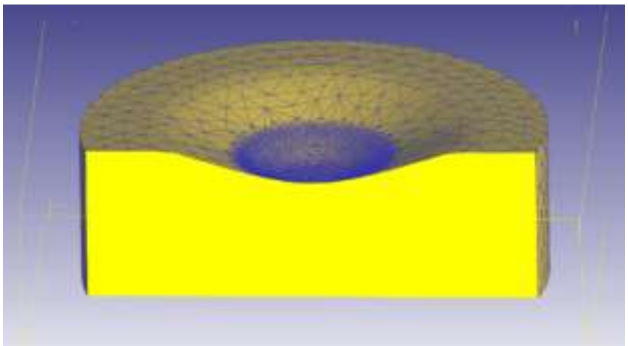

***Figure 2.*** *Meshed workpiece model with pre-machined conical hole*

By following this method, the simulation time is dramatically reduced, because the space between the cutting edges of the twist drill and the workpiece is minimized so that the machining process starts immediately at full load [13]. For achieving accepted results of thrust force and torque, the conical part of the twist drill must be completely entered into the workpiece. So that preparing a pre-machined hole decreases the computation time considerably to reach at this point. In each case, the depth of the pre-machined conical hole measured on the axis is adjusted to be a bit smaller than the height of the conical end of the drill bit, so that after a specific number of rotation which is related to the feed rate, drill's conical end completely enters into the workpiece.

The workpiece has been modelled as a plastic deformable with a mesh size of 80,000. For the simulations, different mesh sizes were tried from 35 thousand to 135 thousand. Although no significant differences were observed in thrust force and torque results, the lower mesh sizes led to bad chip geometry, the higher mesh sizes increased the computation time and caused extremely large amount of result files in hard disc. So 80 thousand mesh size was used as the optimum mesh size for the simulations in terms of good chip geometry and reasonable computation time. Workpiece mesh properties and other related assumptions made in the FEM analysis are given in Table 3.

***Table 3.*** *Workpiece mesh properties and other related assumptions in the FEM analysis*

| Assumptions | Values |
|---|---|
| Mesh size | 80,000 |
| Mesh Size ratio | 10 |
| Number of nodes | 22,500 |
| Work material type | Plastic |
| Surface polygons | 19,800 |
| Shear friction factor | 0.6 |
| Heat transfer coefficient | 45 N/Sec/mm/C |
| Coolant | not used (Air assumed) |
| Environment Temperature | 20ºC |
| Convection Coefficient | 0.02 (Air) |
| Number of Simulation steps | 1000 |
| Step increment to save | 10 |

The thermal properties of the Inconel 718 were taken from the Deform's material database.

A realistic material model describing the material flow curves adequately should be used for an accurate finite element analysis of a machining operation. Semi-empirical Johnson-Cook constitutive model is widely used material model due to its simplicity and availability of the parameters for significant materials. Thus, in this study, J-C model given below was employed [14, 15].

$$\bar{\sigma} = [A + B\bar{\varepsilon}^n]\left[1 + C\ln\left(\frac{\dot{\bar{\varepsilon}}}{\dot{\bar{\varepsilon}}_0}\right)\right]\left[1 - \left(\frac{T-T_{room}}{T_m-T_{room}}\right)^m\right]$$

where $\bar{\sigma}$ is the equivalent stress (MPa), $\bar{\varepsilon}$ is the equivalent plastic strain, $\dot{\bar{\varepsilon}}$ is the equivalent plastic strain rate ($s^{-1}$), $\dot{\bar{\varepsilon}}_0$ is the reference equivalent plastic strain rate ($s^{-1}$), $T$ is the temperature (°C), $T_m$ is the material melting temperature (1500°C - Deform value) and $T_{room}$ is the room temperature (20°C - Deform value). J-C model constants are *A*, the initial yield strength of the material at room temperature, *B*, the strain hardening coefficient, *C*, the strain rate hardening coefficient, *n*, the strain hardening exponent, and *m*, the thermal softening exponent. J-C model constants are determined by fitting the data acquired from material tests carried out at several strain rates and temperatures. In the J-C model, the expression in the first set of brackets is the strain hardening effect. The expressions in the second and third set of brackets are strain rate hardening and thermal softening effects, relatively.

The J-C model parameters used in this study for both aged and annealed Inconel 718 were taken from the study of Ozel et al. [15], and are shown in Table 4. They have referred the J-C parameters for aged Inconel 718 to Lorentzon et al. (2009) [16], and referred the J-C parameters for annealed Inconel 718 to Uhlmann et al. (2007) [17]. The yield strength values of aged and annealed Inconel 718 are 1241 MPa and 450 Mpa respectively.

***Table 4.*** *Johnson-Cook model parameters for Inconel 718* [15]

| Heat Treatment | A (MPa) | B (MPa) | C (-) | n (-) | m (-) | $\dot{\bar{\varepsilon}}_0$ ($s^{-1}$) |
|---|---|---|---|---|---|---|
| Aged | 1241 | 622 | 0.0134 | 0.6522 | 1.3 | 1 |
| Annealed | 450 | 1700 | 0.017 | 0.65 | 1.3 | 0.001 |

## 2.3. Simulations

According to the simulation plan shown in Table 5, four drilling simulations were performed on Deform-3D software, for each of aged and annealed Inconel 718 superalloy.

***Table 5.*** *Simulation plan for drilling of aged and annealed Inconel 718*

| No. of operations | Cutting speed (m/min) | Feed rate (mm/rev) |
|---|---|---|
| 1 | 10 | 0.05 |
| 2 | 10 | 0.1 |
| 3 | 20 | 0.05 |
| 4 | 20 | 0.1 |

The simulations were performed on two different computers, one having Core i7 processor with an 8 GB of RAM and the other having Core i5 processor with a 6 GB of RAM. The computation time on each computer for each simulation was approximately 10 to 12 hours to complete one single revolution of the twist drill, which was sufficient in most cases to get the mean steady-state values of thrust forces and torques.

## 3. RESULTS AND DISCUSSION

In drilling operation, after entry phase, the steady-state phase is reached when the fluctuations and the variations of thrust forces/torques take place almost about an approximate value (typical entry and steady-state phases of torques with fluctuations when drilling Inconel 718 can indeed be identified from Figure 3). The mean steady-state value is determined by transferring the data in the steady-state interval to MS Excel and calculating the mean value. All drilling simulation results for aged and annealed Inconel 718 are given in Table 6.

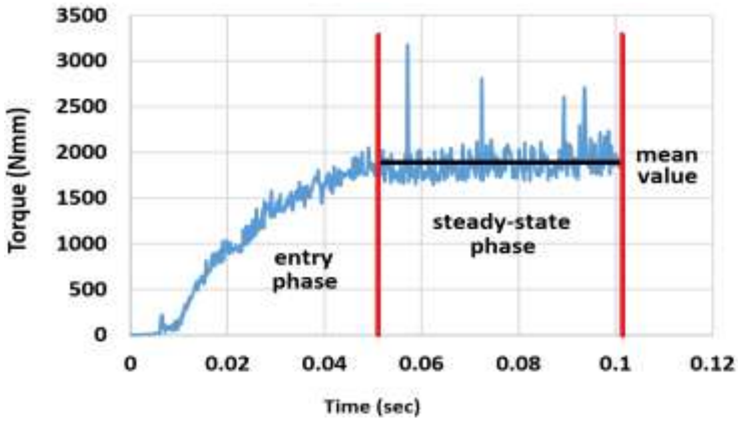


***Figure 3.*** *Typical entry and steady-state phase of torques*

***Table 6.*** *Drilling simulation results for aged and annealed Inconel 718*

| No. of operations | Cutting speed (m/min) | Feed rate (mm/rev) | Thrust force (N) | | Torque (Nmm) | |
|---|---|---|---|---|---|---|
| | | | Aged | Annealed | Aged | Annealed |
| 1 | 10 | 0.05 | 742.17 | 228.93 | 1888.21 | 660.61 |
| 2 | 10 | 0.1 | 816.49 | 294.01 | 3684.34 | 1395.78 |
| 3 | 20 | 0.05 | 599.78 | 219.75 | 1345.11 | 561.50 |
| 4 | 20 | 0.1 | 666.15 | 269.81 | 3280.43 | 1043.75 |

In drilling of both aged and annealed Inconel 718, the thrust force increases with increase in the feed rates, for both of the cutting speeds, see Figure 4. This result agrees with the experimental [7, 10, 11, 18, 19] and simulated results [10, 11, 18] found in the literature. When the cutting speed variation is considered, a decrease is observed in thrust force values of both aged and annealed Inconel 718 with increase in the cutting speeds, see Figure 5. This result agrees with the experimental [7, 11, 19, 20] and simulated results [11] found in the literature.

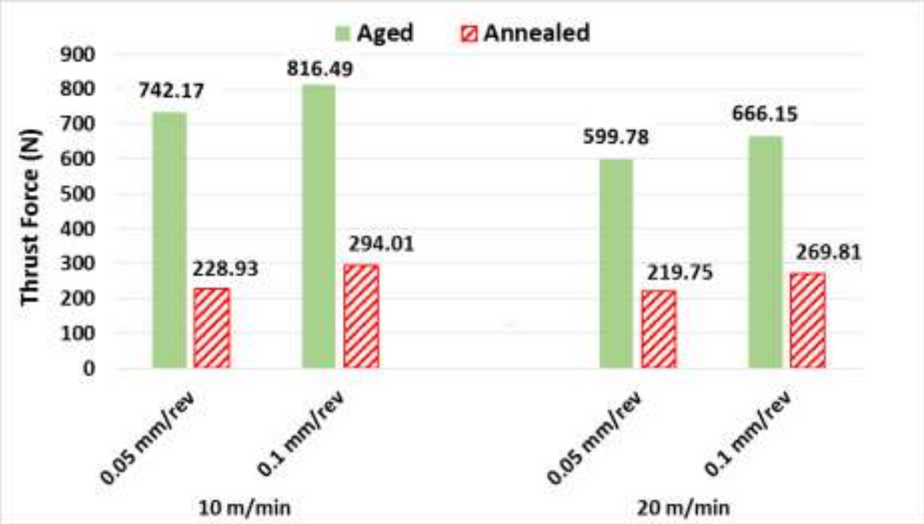


***Figure 4.*** *Thrust force results for drilling of aged and annealed Inconel 718 with varying feed rates at each cutting speed.*

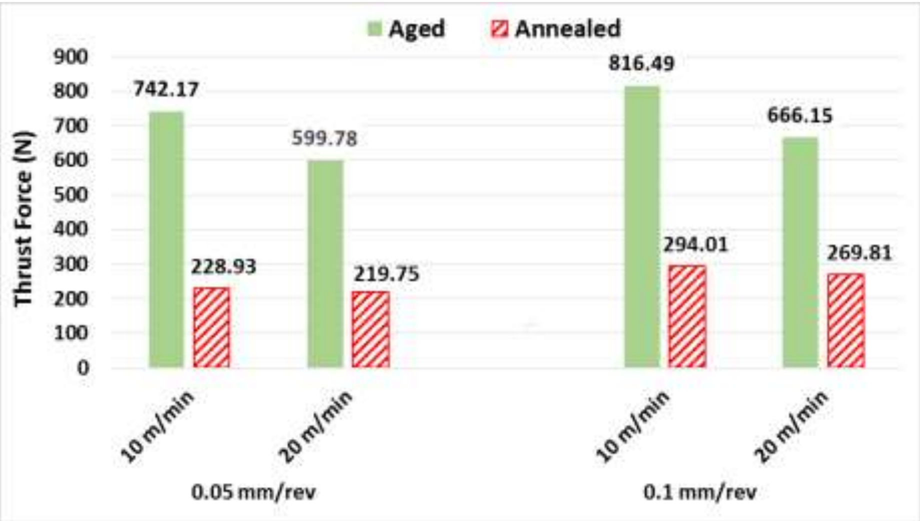


***Figure 5.*** *Thrust force results for drilling of aged and annealed Inconel 718 with varying cutting speeds at each feed rate.*

In drilling of both aged and annealed Inconel 718, the drilling torque increases with increase in the feed rates, for both of the cutting speeds, see Figure 6. This result agrees with the experimental [7, 11, 19] and simulated results [11] found in the literature. When the cutting speed variation is considered, there is a decrease in torque values of both aged and annealed Inconel 718 with increase in the cutting speeds, see Figure 7. This result agrees with the experimental [7, 11, 19, 20] and simulated results [11] found in the literature.

As pointed out above, in drilling of both aged and annealed Inconel 718, thrust force and torque values increase with increasing feed rates. This can be explained by cutting mechanics theory; as the feed rate increases, instantaneous cutting area increases leading to larger cutting forces, thereby thrust force, and torque [21]. On the other hand, thrust force and torque values of both aged and annealed Inconel 718 decrease with increasing cutting speeds. This behaviour can be attributed to reduction of strength due to thermal softening effect within the considered cutting speed range for dry cutting conditions [22].

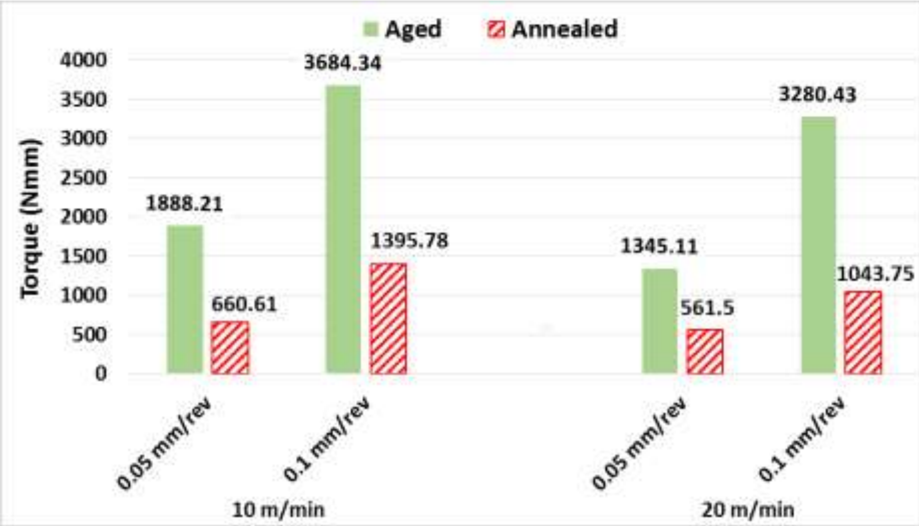


***Figure 6.*** *Torque results for drilling of aged and annealed Inconel 718 with varying feed rates at each cutting speed.*

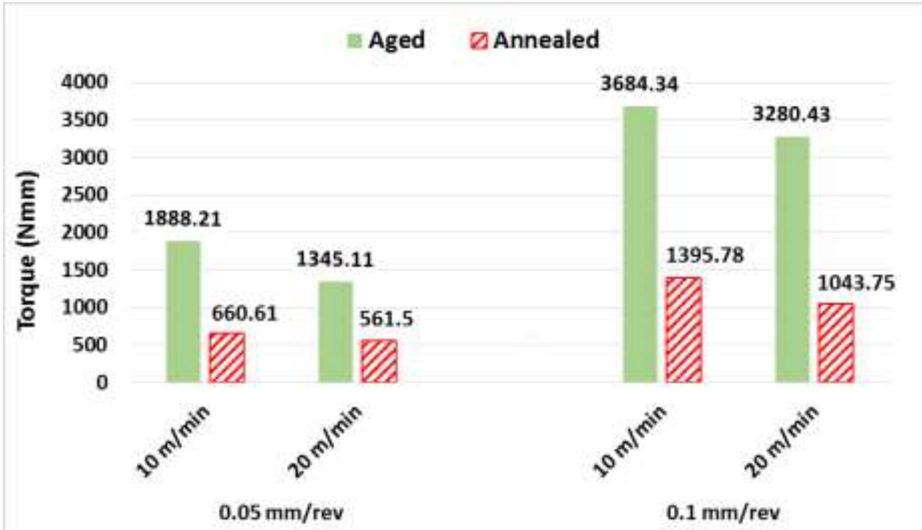


***Figure 7.*** *Torque results for drilling of aged and annealed Inconel 718 with varying cutting speeds at each feed rate.*

## 4. CONCLUSIONS

In this paper, the effects of feed rate and cutting speed were examined numerically in drilling of both aged and annealed Inconel 718 superalloys.

The following conclusions can be drawn from this study:

- Both materials have shown similar thrust force and drilling torque trends depending on feed rates and cutting speeds: the thrust forces and drilling torques for both materials increase with increasing feed rates and decrease with increasing cutting speeds.

- Thrust force and drilling torque values of aged Inconel 718 were remarkably larger than that of annealed Inconel 718, in all cases. This is already an expected trend because aged Inconel 718 has higher strength than does annealed Inconel 718 in plastic deformation.
- The smallest thrust forces and drilling torques for both materials were obtained at minimum feed rate (0.05 mm/rev) and at maximum cutting speed (20 m/min). On the other hand, the largest thrust forces and drilling torques for both materials were obtained at maximum feed rate (0.1 mm/rev) and at minimum cutting speed (10 m/min).
- Simulation results could be compared with experimental ones quantitatively for validation.

## CONFLICT OF INTEREST

The authors declares that, there is no conflict of interest regarding the publication of this paper.

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