Milling Inconel 718 Workpiece With Cryogenically Treated And Untreated Cutting Tools

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Abstract

Although Inconel 718 is an important material for modern aircraft and aerospace, it is a kind material, which is known to have low machinability. Especially, while these types of materials are machined, high cutting temperatures, BUE on cutting tool, high cutting forces and work hardening occur. Therefore, in recent years, instead of producing new cutting tools that can withstand these difficult conditions, cryogenic process, which is a heat treatment method to increase the wear resistance and hardness of the cutting tool, has been applied. In this experimental study, feed force, surface roughness, vibration, cutting tool wear, hardness and abrasive wear values that occurred as a result of milling of Inconel 718 material by means of cryogenically treated and untreated cutting tools were investigated. Three different cutting speeds (35-45-55 m/min) and three different feed rates (0.02-0.03-0.04 mm/tooth) at constant depth of cut (0.2 mm) were used as cutting parameters in the experiments. As a result of the experiments, lower feed forces, surface roughness, vibration and cutting tool wear were obtained with cryogenically treated cutting tools. As the feed rate and cutting speed were increased, it was seen that surface roughness, vibration and feed force values increased. At the end of the experiments, it was established that there was a significant relation between vibration and surface roughness. However, there appeared an inverse proportion between abrasive wear and hardness values. While BUE did not occur during cryogenically treated cutting tools, it was observed that BUE occurred in cutting tools which were not cryogenically treated.

Introduction

Inconel 718 is a nickel-based super alloy with high mechanical properties such as high temperature, corrosion resistance and oxidation even at very high temperatures [1-6]. The superior properties of this material make it be widely used in many fields. These fields can be counted as aerospace, space research, nickel hydrogen batteries, gas turbine engines, cryogenic tanks and power generation equipment [1-14]. Although Inconel 718 is used in many areas, it also has some disadvantages. Poor machinability and bad surface integrity come at the top of these disadvantages. However, these super alloys are classified as materials "difficult to machine" [1,3-7,9-11,13,14] due to their high mechanical characteristics and low thermal properties that lead to higher tool wear and lower surface integrity [4-6,9-11,14,15]. These materials, which are difficult to machine, have characteristics such as work hardening low, thermal conductivity, tendency to react to the cutting tool material, presence of abrasive carbide particles, hardness, forming high cutting force and high cutting temperature causing rapid wear of cutting tools [1,4,6,7,9,11,12,14,16]. Therefore, there are very few cutting tools that can withstand the difficult cutting conditions during machining of Inconel 718. In order to solve the problems encountered during the machining of these materials, the researchers have made several suggestions. Especially in recent years, cryogenic treatments applied to cutting tools have come to the forefront due to a number of advantages the application provides for cutting tools. In this experimental study, it was aimed to mill Inconel 718, which is difficult to machine, with cryogenic treatment applied cutting tools. The experimental studies that have been performed till today about Inconel 718 are given briefly below:

Sivalingam et al. investigated machining performance and tool wear with cryogenically treated (CT) and untreated (CU) cutting tools during milling Ti-6Al-4V. In the experimental study they carried out, they established that under the same machining conditions, CT cutting tools exhibited better machinability and longer tool life compared to CU cutting tools. Especially when experiments were performed with 48h CT cutting tools, they found that there was a significant decrease in cutting force values [17]. Çelik et al. compared the significant machinability criteria such as tool wear, friction coefficient, cutting force and chip morphology occurring during machining of Ti6Al4V titanium alloy with CT coated and uncoated end mills. As a result of the experiments, they found that as the CT time increased, the values of friction force and cutting force decreased. Also, they found that the best CT time in terms of tool wear was 36h [18]. Mukkoti et al. investigated the impact of the CT cutting tools on energy consumption and cutting forces in milling Inconel 718 alloy. In the study they carried out, they compared the CT and CU cutting tools. As a result, it was revealed that 36h CT cutting tools had a significant effect on power consumption and cutting forces [19]. Li and Wang studied the cutting forces in milling Inconel 718 workpiece under dry machining conditions, with coated cutting tools at high speeds. In their study, they found that the feed rate had a significant effect on cutting forces [20]. Li et al. investigated the microstructure and mechanical properties of deep CT carbide tools in hard milling. They attained optimal parameters with cryogenic temperature -190°C , soaking time 90 min, tempering temperatures 60°C , and cooling rate $8^{\circ}\text{C}/\text{min}$. The authors revealed that deep CT had a significant contribution to the increase of cutting tools life. They at the same time found that the wear resistance of the CT cutting tool increased in hard milling [21]. Thamizhmanii et al. studied surface roughness and tool wear in milling Inconel 718 with CT and CU PVD cutting tools. In their study, they obtained lower surface roughness on workpiece surfaces machined with CT PVD cutting tools at high cutting speeds and low feed rates. The authors found that flank wear occurring on CT PVD cutting tools was lower than those of CU ones [22]. Yong et al. examined the performance of CT tungsten carbide cutting tools in milling operations. They found that CT tungsten carbide cutting tools performed better than CU tungsten carbide cutting tools in terms of cutting tool wear. The authors emphasized that this performance was achieved by the CT contributing to the reduction of the heat on the chip/cutting tool interface [23].

Inconel 718 is classified as "materials difficult to machine" due to high cutting temperature and high cutting force created by its characteristic properties such as low thermal conductivity, hardness, tendency to react with the cutting tool material, presence of abrasive carbide particles and work hardening. For this reason, it is of great importance to control and select the suitable machining parameters and conditions such as cutting parameters, cutting tool geometry and coating material selection, coolant while these difficult-to-machine workpieces are machined. In machining of Inconel 718, there are very few cutting tool materials that can withstand the hard cutting conditions. In order to solve the problems encountered during the machining of these materials, the application comes to the forefront especially because of the features that the cryogenic process gives the cutting tool. Therefore, in this experimental study, the effects of especially CT and CU cutting tools on feed forces, surface roughness, vibration, cutting tool wear, hardness and abrasive wear that occur as a result of milling Inconel 718 workpiece were investigated.

Material Method

1.1. Workpiece material

Inconel 718, super alloy with 100×100×12.7 mm dimensions, was used as workpiece material in this experimental study. Chemical compound and mechanical properties of workpiece purchased from Harald Phil Company are shown in Table 1 and Table 2, respectively.

Table 1. Chemical Composition of Inconel 718

Content	C	Mn	Fe	S	Si	Cu	Ni	Cr	Al	Se
Composition (wt%)	0.03	0.09	17.64	0.001	0.065	0.22	53.45	18.55	0.56	<.000001
Content	Ti	Co	Mo	Nb	Ta	B	Bi	P	Pb	Nb+Ta
Composition (wt%)	0.98	0.23	2.92	5.17	0.004	0.002	<.000001	0.008	0.00002	5.18

Table 2. Mechanical properties of Inconel 718 (at room temperature)

Workpiece material	Tensile strength (MPa)	Yield strength (MPa)	Elongation (%)
Inconel 718	1378	1170	24

Cryogenic treatment and cutting tools

The cryogenic process applied to cutting tools was conducted in a heat treatment oven by keeping them at -148°C for 24 hours. Then, they were held up at 200°C for 2 hours and tempering was carried out. Tempering was realized in 2 cycles. The cutting tools used in the experiments were provided from SANDVIK cutting tool company. The properties of cutting tools are given in Table 3.

Table 3. The cutting tool geometry and properties

Tool Code	Cutting diameter	Coated Type	Grade	Axial rake angle	Radial rake angle	Cutting edge count	Depth of cut max.	Helix angle	Functional length
2P341-1000 MA	10 mm	PVD (TIALN)	1640	13.5°	15°	4	22 mm	41°	72 mm

1.2. Cutting parameters and CNC milling

Cutting parameters were determined by taking into account the value ranges suggested by the manufacturer of cutting tool for milling INCONEL 718 workpiece. In milling experiments, at constant depth of cut, three different cutting speeds and feed rates were used. The cutting parameter values utilized in the experiments are given in Table 4.

Table 4. Cutting parameters utilized in cutting experiments

Cutting Speed (m/min)	Feed rate (mm/tooth)	Depth of cutting (mm)
V= 35 - 45 - 55	f= 0.02- 0.03 - 0.04	a=0.2

1.3. Feed forces (Ff) and surface roughness (Ra)

The Ff values resulting from milling were measured using a quartz crystal based KISTLER 9257B type dynamometer capable of measuring three cutting force components (Fc, Ff and Fp). The Ra values on the surface of the workpiece occurring at the end of machining experiments were measured by means of TR 200 prototype measuring device. Ra values were calculated as an arithmetical mean taken from five different places with 5.6 mm measuring length from the surface of machined experimental sample.

1.4. Abrasive wear experiments

For the abrasive wear tests of the CT and CU cutting tools, the cutting tools were cut in 30 mm length on the wire electro discharge machine. The abrasive wear of the cutting tools was realized on “pin-on-disk wear” device shown in Figure 1. Sandpaper, 80 grid SiC, was used as the abrasive wear. As seen in Figure 1, abrasive sandpaper is attached to the rotating disc of the pin-on-disk device. The sample was connected to the device arm. The parameters used in abrasive wear tests on cutting tools are given in Table 2. The speeds determined in the abrasion device were adjusted with the tachometer. At the end of the experiment, 0.1 mg precision weighing (Radwag) was used to measure the mass losses. At the end of each test, the used sandpaper was renewed and the next test was started.

Table 5. Experimental parameters and grades for abrasive wear

Parameters	Values
Loads (N)	10
Sliding speeds (m/s)	0.5
Sliding distances (m)	500
Time (s)	497
Frequency (Hz)	5

1.5. Cutting tool wear

The wears on the cutting tool, which occurred at the highest cutting parameters, were examined by means of SEM device. The schematic view of experimental set up is given in Figure 2.

1.6. Vibration and hardness measurements

Vibrations in the workpieces that occurred during the milling experiments were measured with NI-9230 3D vibration measuring device depending on the acceleration. In measuring the hardness of cutting tools, Ernst brand hardness measurement device was used. Hardness measurements were carried out in Rockwell under constant load of 150 kgf. The hardness of cutting tools was calculated taking the averages of measured hardness values from five different points of the cutting tool.

Experimental Results And Discussion

The graphs of the feed forces measured during the milling of the Inconel 718 super alloy with CT and CU cutting tools are given in Fig. 3 and Fig. 4. When the graphs in Fig. 3 are examined, it is seen that feed forces increased in all machining conditions as feed rate increased. In the literature, feed rate that affect feed forces was discussed by many authors [9, 20, 24]. The feed forces and the feed rate increased in direct proportion. The reason for the increasing feed forces owing to the increasing feed rate is that the chip load per tooth increases as the feed rate increases [9, 20, 24]. When the graphs in Fig. 4 are examined to see the impact of cutting speed on the feed forces, it is seen that the feed forces increase as the cutting speed increases. In the literature, it was stated by the authors that the increase in the temperature in the cutting zone owing to the increase in the cutting speed causes the feed forces to increase [9, 14, 25]. Based on the increase in cutting speed, the change of cutting tool geometry, chip welding and BUE formation on the cutting tool cutting edge damage the machined surface, which at the same time contributes to the formation of heat in the cutting zone were investigated. In this case, it causes an increase in feed forces depending on the increase in cutting speed [9, 14, 25]. As a result of the experimental studies, BUE is seen on the rake face of the cutting tool illustrated in Fig. 10. At the same time, Inconel 718 increases the hardness of the machined surface by causing the heat occurred during machining to be trapped on the surface of the workpiece owing to their low thermal conductivity. This situation increases the temperatures in the cutting zone as the cutting speed increases. Therefore, as the cutting speed increases, the feed forces increase as well.

When the graphs in Fig. 3 - Fig. 4 showing the effect of the cryogenically treated tools on the feed forces are examined, it is determined that the feed forces obtained with the CT tools are lower than the CU tools. This situation is parallel to the studies in the literature [17]. When milling Inconel 718 workpiece with CT tools, the achievement of lower feed forces was attributed to the effect of the cryogenic treatment. The hardness provided by the cryogenic treatment for the cutting tools plays a crucial role in maintaining the sharpness of the cutting tool. At the same time, due to the good rigidity and high hardness that the CT brings to the cutting tool, it causes lower feed forces than the CU cutting tool [17].

3.1. Evaluation of Ff values

The graphs of the feed forces measured during the milling of the Inconel 718 super alloy with CT and CU cutting tools are given in Figure 3 and Figure 4. When the graphs in Figure 3 are examined, it is seen that feed forces increased in all machining conditions as feed rate increased. In the literature, feed rate that affect feed forces was discussed by many authors [9, 20, 24]. The feed forces and the feed rate increased in direct proportion. The reason for the increasing feed forces owing to the increasing feed rate is that the chip load per tooth increases as the feed rate increases [9, 20, 24]. When the graphs in Figure 4 are

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3.2. Evaluation of Ra values

The graphs of the Ra values resulting from the milling of the Inconel 718 workpiece with the CT and CU cutting tools at three different cutting speeds and three feed values are given in Figure 5- Figure 6. When the Ra graphs based on the change of the feed values in Figure 5 are examined, it is determined that the Ra values increase in direct proportion as the feed rate increases. This result is an expected state. It is known in the literature that feed rate on Ra is the most effective parameter and it is affected by it directly proportionally [9, 24].

This situation was associated with the increase in material amount to be removed per unit time as the feed rate increased. It is thought that the increase in the vibration rate with the increase in the amount of material to be removed causes an increase in Ra values [9]. When the Ra graphs attained depending on the change of cutting speed in Figure 6 are examined, it is seen that the Ra values increases as the cutting speed increases. It is understood from the graphics in Figure 6 that the cutting speed has a crucial impact on the Ra. Cutting speed has a significant effect on the temperature in the cutting zone. The higher the cutting speed, the higher the temperature in the cutting zone [14]. The high temperature in the cutting zone causes chip welding to the cutting tool and built-up chip (BUE) formation, which is very common in Inconel 718 materials, causing the workpiece surface to deteriorate. At the same time, the low thermal conductivity of these materials causes heat trapped in the workpiece. Therefore, as the cutting speed increases, it is expected that the Ra values increase [14].

The Ra values measured from the machined surface of the workpiece as a result of milling Inconel 718 material with CT and CU cutting tools are illustrated in Figure 5 and Figure 6. When Ra graphs in Figure 5 and Figure 6 are examined, it is seen that the lowest Ra values were attained from CT cutting tools, while the highest Ra values were obtained from CU cutting tools. This situation is due to the properties that the CT brings to the cutting tool. CT cutting tools cause lower Ra values due to maintaining sharpness and rigidity of cutting tools compared to CU cutting tools, even at high cutting speed and feed rate.

3.3. Evaluation of vibrations

The graphs of vibration values measured during the machining of Inconel 718 workpiece with CT and CU cutting tools at constant depth of cut and three different feed rates and three cutting speeds are given in Figure 7 and Figure 8. When the graphs in Figure 7 showing the effect of the feed rate on vibration are examined, it is observed that the vibration values increase as the feed rate increases. Similar results are demonstrated by other authors [17]. The reason for the increase in vibration values owing to the increase in the feed rate is that the chip load for per tooth increases as the feed rate increases. The increase in the chip load for per tooth causes more strain on the cutting tool, which leads to an increase in vibration values.

When the graphs that give the effect of cutting speed on vibration in Figure 8 are examined, it is seen that vibration values increase as cutting speed increases. It is understood from the graphs in Figure 8 that the cutting speed has a crucial impact on the vibration values. Especially, when workpieces such as Inconel 718 are milled, chip welding to the sharp edge of the cutting tool and BUE formation increase due to the increase in cutting speed. In addition, as the chip removal process continues, work hardening occurs on the surface of Inconel 718 workpiece, which has a low thermal conductivity coefficient. At the same time, more vibrations occur owing to the increase of the cutting speed, for reasons such as more cutting tool wear and the inability to maintain the cutting-edge sharpness due to the BUE formation.

When the graphics in Figure 7 and Figure 8 are examined, it is observed that the cryogenic process has a significant effect on vibration. The lowest vibration values were determined when the workpieces were machined with CT cutting tools, while the highest vibration values were determined when the workpieces were machined with CU cutting tools. This situation is an expected one. The low tool wear, rigidity and strength, which the cryogenic process equips the cutting tool with, caused the lowest vibration values to be obtained when machining with CT cutting tools [17]. It was observed that the Ra values obtained from the surfaces machined with CT cutting tools were lower than the CU cutting tools (Figure 5- Figure 6). This situation reveals that there is an important relationship between vibration and surface roughness.

3.4. Evaluation of abrasive wear and cutting tool hardness

Abrasive wear and hardness measurements were conducted to see the properties that the CT brings to cutting tools. These measurements were made on new cutting tools never used in machining experiments before. Abrasive wear and hardness measurement values obtained from CT and CU cutting tools are given in Figure 9. When the graphs in Figure 6 are examined, it is determined that the hardness of the CT

cutting tool is higher than the CU cutting tool. It has been emphasized in the literature that the CT gives hardness to the material [17]. Looking at the abrasive wear results in Figure 9, the material mass loss in the CU cutting tool was higher than the CT cutting tool. In addition, the hardness results of these cutting tools support abrasive wear tests. The lower material mass loss in the CT cutting tool with high hardness value can be referred to the wear resistance provided by the CT to the cutting tool.

3.5. Evaluation of cutting tool wear

The wears occurring in CT and CU cutting tools were compared under the depth of cut $a=0.2$ mm cutting, feed rate $f=0.04$ mm/tooth and speed $V=55$ m/min, which are the highest cutting parameters. The wears that occur in cutting tools when Inconel 718 workpiece is machined are given in Figure 10. When the graph showing the cutting tool wear is examined in Figure 10, it is established that the least wear occurred on the cutting edges of the CT cutting tool, while the highest wear occurred on the cutting edges of the CU cutting tool. Similar results were obtained by other researchers in the literature [17, 26]. Due to the low thermal conductivity of Inconel 718, untreated cutting tools cause more heat between cutting tool and chip than CT cutting tools, and this leads to layer-by-layer chip formation on the cutting tool. Also, chip welding on the sharp edge of the cutting tool causes BUE formation [17].

Therefore, it is expected that CT cutting tools will wear more than CU cutting tools. This situation is seen in Figure 10.b. EDS analysis was performed to determine the BUE formed on the CU cutting tool. The aim of the EDS analysis in this study is to analyze the material transferred from the workpiece to the cutting tool during chip removal. The element spectral analysis of the materials adhered to the cutting edge surface of the cutting tool is given in Figure 11. When looking at the element spectral analysis of the materials adhered to the cutting tool in Figure 11, it is established that the highest values of the elements belonging to this part are Ni, Cr and Fe, respectively. When the element composition of INCONEL 718 in Table 1 is checked, it is seen that it is Ni (53.45%), Cr (18.55) and Fe (17.64). This proves the occurrence of build-up edge (BUE) on the cutting tool by element spectral analysis of the materials adhering to the cutting tool.

4. RESULTS

The results of feed forces, surface roughness, vibration, cutting tool wear, hardness and abrasive wear in milling INCONEL 718 with CT and CU cutting tools are briefly given below:

- It was determined that the F_f values obtained with CT cutting tools had lower values than CU cutting tools. It was found that the F_f values increased as the feed rate and cutting speed increased under all machining conditions.
- While the lowest R_a values were attained from the machined surfaces with CT cutting tools, the highest R_a values were attained from surfaces machined with CU cutting tools. As the feed rate and cutting speed increased, it was observed that R_a values increased in direct proportion.
- The lowest vibration values were measured when the workpieces were machined with CT cutting tools, while the highest vibration values were measured with CU cutting tools. As a result of the

experiments, it was revealed that there was a significant relation between vibration and surface roughness.

- It was determined that the hardness of the CT cutting tool was higher than CU cutting tools. It was established that the material mass loss in CU cutting tools was higher than CT cutting tools. It was found that there was an inverse proportion between abrasive wear and hardness values.
- In cutting tool wear, it was established that the least wear occurred on CT tool and the highest wear on CU cutting tool.
- BUE formation was observed in untreated cutting tools, while BUE formation was not formed in cryogenically treated cutting tools.

Declarations

Authors' contributions

Gürbüz and Baday both contributed to the conception of the study, manuscript writing and design. Data collection, preparation of material and method and analyzing the data were performed by Gürbüz and Baday.

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Data availability

The authors confirm that the data supporting the findings of this study are available within the article. The raw data are available from the corresponding author upon a request.

Declarations

Ethical approval

The work contains no libelous or unlawful statements, and does not infringe on the rights of others, and does not contain any materials or instructions that might cause harm or injury.

Consent to participate

The authors consent to participate.

Consent for publication

Informed consent was obtained from all individual participants involved in the study.

Conflict of interest

The authors declare that they have no conflict of interests.

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Figures

Figure 1

Pin-on-disk wear device

Figure 2

Schematic view of the experimental set up

Figure 3

The effect of feed rate on Ff

Figure 4

The effect of feed rate on Ff

Figure 5

The effect of feed rate on Ra

Figure 6

The effect of cutting speed on Ra

Figure 7

The effect of feed rate on vibrations

Figure 8

The effect of cutting speed on vibration

Figure 9

Hardness measurements and abrasive wear

Figure 10

Wear on cutting tools a) CT cutting tool b) CU cutting tool

EDAX TEAM EDS

Element	Wt %	Atomic %	Error %	Net Int.	Net Error %	K Ratio	Z	R	A	F
C K	33.07	56.46	9.33	185.70	1.61	0.1056	1.1043	0.9162	0.2891	1.0000
O K	21.34	27.35	10.57	216.74	1.62	0.0405	1.0681	0.9396	0.1777	1.0000
Nb L	2.77	0.61	7.53	118.46	6.10	0.0200	0.7926	1.1975	0.8918	1.0211
Cr K	10.36	4.08	2.67	806.65	1.36	0.1025	0.8584	1.0556	1.0093	1.1423
Fe K	8.86	3.25	3.23	555.31	1.44	0.0860	0.8576	1.0651	0.9776	1.1590
Ni K	23.60	8.24	2.16	1120.01	0.87	0.2091	0.8706	1.0735	0.9718	1.0471

Figure 11

Chemical composition of chip measured with the help of EDS