Gazi University Journal of Science
GU J Sci
25(2):533-540 (2012)

ORIGINAL ARTICLE

The Effect of Cutting Paramaters on The Hole Quality and Tool Wear During The Drilling of Inconel 718

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Received: 31.07.2011 Accepted: 20.12.2011

ABSTRACT

In this study the effect of cutting parameters on the hole quality (circularity and hole diameter) and tool wear during the drilling of super alloy Inconel 718 with coated and uncoated carbide drills was investigated. Drilling tests were carried out with uncoated and TiN and TiAlN coated carbide drills of 5 mm diameter using a CNC vertical machining center under dry cutting conditions by drilling blind holes of 8 mm depth and employing four different cutting speeds (10, 12.5, 15, 17.5 m/min) and three different feed rates (0.05, 0.075, 0.1 mm/rev). Regarding hole diameters and the circularity measurements a comparison has been made in terms of the quality of the hole between cutting tools. It was observed that there was a decrease of tool performance and hole quality at high cutting speed and feed rate combinations. A serious increase in tool wear was observed when increasing cutting speed. The Utmost wear type was seen in the form of flank wear and chisel edge wear.

Key Words: *Drilling, Inconel 718, hole quality, tool wear.*

1. INTRODUCTION

Super alloys are resistant to high temperatures and retains their strength in elevated temperatures. These composite alloys have good corrosion and oxidation resistance, as well as high creep and yield strength at high temperatures [1-4]. These alloys contain iron-based alloys with chromium and nickel, iron-nickel-chromium-cobalt compounds, cobalt-based alloys with carbides, nickel-based alloys with solid solution and nickel-based alloys with precipitation and dissociation reinforcement [4,5].

In recent years several alloys with different working temperatures have been developed. Inconel 718 super alloy is one of the most important of these alloys. It has a polycrystalline and coaxial microstructure. Due to the excellent mechanical properties at low and medium temperatures (-250-700)^{o}C, there has been a wide field of application in the aerospace industry, petroleum and nuclear energy industries [6]. During the machining of Inconel 718 due to its well-known property of low thermal conductivity, tool temperature is easily increased. During machining, as a result of high hardness

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of the material, there are difficulties with chip formation [7-8]. Inconel 718 superalloy also has a high chemical affinity for many tool materials and as such forms an adhering layer leading to diffusion and attrition wear [7,9-10]. Due to high production cost of the material, the manufacturing errors during machining cause financial losses.

In the aerospace industry, hole drilling is one of the most important and well-known machining processes. However, machining research on Inconel 718 alloy up to now has mostly involved turning and milling operations and as a result the literature concerning drilling operations is very limited [7,11]. In the study of Subramamam and Cook [12] they determined that in aerospace industry hole drilling consisted of 40% of the whole chip removal operations.

Sved and Mannan [13] investigated the machinability of Inconel 718 under wet cutting conditions using different coatings with PM HSS (High Speed Steel) drills having identical tip geometry. The tests were carried-out on with PM HSS TiA1N coated drills of conventional geometry. In the study, peck drill (at the depth of 2 mm) and direct drilling methods were used. From the point of view of hole diameter measurement and circularity using the TiAlN coated drills with thinned tip geometry exhibited better performance than the TiAlN coated drills with conventional tip geometry. It was determined that from the point of view of hole quality, direct drilling method was more advantageous than peck drill method. It was observed that there was a tendency to increase in the circularity values when increasing the feed rate.

During machining obtaining the desired hole quality in the drilling operations is very important. In a directly drilled hole it is very difficult to provide the dimensioning within the desired tolerances. Hole enlargement and reaming are generally used for the purpose of obtaining desired dimensioning [14]. However, the need for a secondary operation increases doubtlessly the machining cost and effects the product cost adversely. For this reason the making of the hole at a time with the desired dimensioning is very important. When taking into consideration the importance of high precision expectations from manufacturing [15] in the aviation and aerospace industry, the importance of obtaining desired dimensioning in the drilling of widely used Inconel 718 alloy in this field is once more understood.

For this purpose, the effect of different combinations of cutting speed and feed rate on the hole quality during the drilling of Inconel 718 alloy with TiN, TiA1N coated and uncoated drills was examined. The optimum drilling conditions were specified and the effect of cutting parameters on the tool wear was investigated.

2. MATERIAL AND METHOD

2.1. Experimental Procedure

For the experimental studies, test samples were prepared from Inconel 718 super alloy. The chemical composition of Inconel 718 super alloy is given in Table 1 and mechanical properties are given in Table 2. The test samples were cut in to plates of 100mm x 100mm x 10mm using a wire erosion machine. In each test group 10 holes were drilled and on each test sample 9 group test was carried on. Blind holes (8 mm deep) were drilled and the distance between two hole axes was 9 mm. Taking into consideration the hardness distribution around the drilled hole, the holes were placed at equal distances from each other as much as possible. This way, during the drilling operation it was aimed that the heat would be distributed as equally as possible. Each experiment was repeated two times to confirm the accuracy of the obtained data.

Table 1. Chemical composition of Inconel 718

C	Mn	Si	Cr	Ni	Co	Mo	Nb+Ta	Ti	Al	Fe
0.040	0.08	0.08	19.0	52.82	0.23	3.04	5.43	0.98	0.50	17.80

Table 2. Mechanical properties of samples

Hardness (HB)	Yield limits (Mpa)	Tensile stress (Mpa)	Elongation 5 %(do)
388	1375	1170	23.3

Drilling tests were carried out using a JOHNFORD VMC 550-7.5 kW CNC vertical machining center under dry cutting conditions. The experiment set-up was given in Figure 1. The drills used in the experiments were uncoated, TiN and TiAlN coated carbide (DIN 6539) twist drills of 5 mm diameter (Guhring). Technical specifications of cutting tools and coating materials are given in Table 3. Four cutting speeds (10, 12.5, 15, 17.5 m/min) and three feed rates (0.05, 0.075, 0.1 mm/rev) for two different coated and uncoated drills were used. To eliminate the twisting effect, distance to drill tip from the tool holder was determined as 30 mm. This value kept constant in all experiments to verify the obtained values.

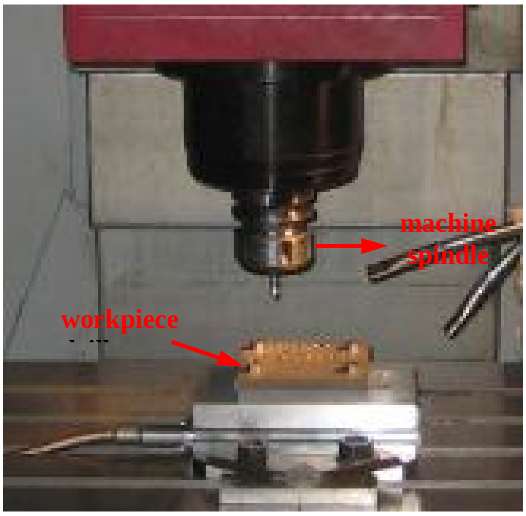
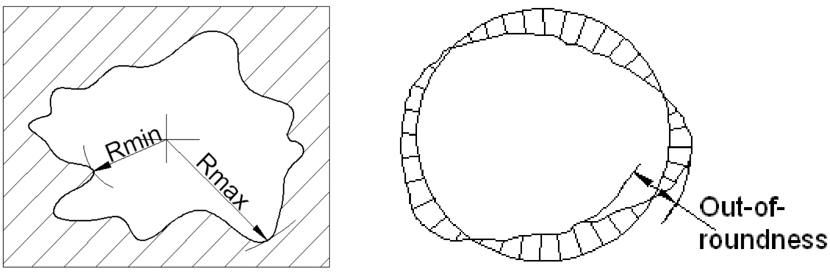


Figure 1. Details of experimental set-up.

Table 3. Technical specifications of cutting tools and coating details.

	Uncoated-carbide (WC)	Coated-carbide (TiN-PVD)	Coated-carbide (TiAlN-PVD)
Drill type	2 flute-twist drill	2 flute-twist drill	2 flute-twist drill
Drill diameter (mm)	5	5	5
Flute length (mm)	26	26	26
Total length (mm)	62	62	62
Point angle (degree)	135	135	135
Helix angle (degree)	35	35	35
Grain size (εm)	0.5	0.5	0.5
Coating thickness (εm)	-	1.8	3.2
Hardness (kg/mm^2)	1600	2000	3500

Deviation from circularity of the holes is generally the result of deflection, vibration, lack of lubrication and wear. Deviation from circularity means fluctuations on the surface. It is defined as the difference between the greatest and the smallest radius measured from a certain central point (Figure 2.a). However, there are commonly used methods to specify the center of a hole such as minimum radial seperation (MRS) method and least squares circle (LSC) method which accept the point of minimum obtainable radial deviation as the center. In this study, to determine the centers of the holes drilled on Inconel 718 blocks, LSC method was used. In LSC method, the central point is the center of a circle where the sum of the squares of the radial coordinates is the lowest. The out-of-roundness (Figure 2.b) value would be determined by the sum of the maximum inward and maximum outward ordinates divided by the proper chart amplification factor [16].



(a) (b)

Figure 2. Roundness measurements a) Roundness error b) LSC (Least squares circle) [17].

In the drillability test works the measurement of hole diameter and circularity is highly important to specify the hole quality. The hole diameter and roundness error measurements were performed using a Mitutoyo CRT-A C544 three dimensional CMM (Coordinate Measuring Machine) device. Minimum 6 points were measured to obtain the hole diameter and roundness error measurements at a certain depth of the hole. Hole diameter and circularities of each hole which was drilled in an experiment were measured one by one. The graphics that were evaluated were formed by taking the average of these measured values. In the literature survey, it is stated that the diameter and out-of-roundness values at the hole entry is higher than the ones at the hole exit due to the dynamic instability of the cutting tool at the first entry to the hole. It is also said that these values decrease along the entry and the outlet of the hole due to the guidance of the hole to the drill up to the hole exit [18-19]. Taking this into consideration, hole diameter and out-of-roundness values were determined by the measurements taken from the hole entry.

In the study Chen and Liao [20] recommended the drill tip angle (in drilling of the super alloys) to be 135^o and higher and for the drilling of Inconel 718 they determined that the drills with 140 tip angle and space angle of 8^o exhibited better performance. From the aspect of literature it has been decided that the drill tip angle would be 135^o and the drill length would be short (3xD) in order to obtain the desired rigidity.

The determinations of cutting parameters were specified through the pilot experiments in regards of the values recommended in the cutting tool catalogue and also by referring to literature [11-13, 20-21]. During the pilot experiments, when the cutting speed exceeded 17.5 m/min and the feed rate exceeded 0.1 mm/rev, drills could only drill a few holes. So, some of the cutting tools were broken before completing 10 holes. Moreover, in the high cutting speed and feed rate combinations, outer corner wearing was observed causing disturbance of drill.

3. RESULTS AND DISCUSSION

3.1. Hole Circularity

The average hole diameter, which defines the size tolerance, was measured by the CMM at a given depth of an entire hole. A roundness (circularity) criterion specifies a tolerance zone bounded by two concentric circles within which each circular element of the surface must lie and applies independently at any plane [22]. The measurement of roundness has a critical importance for many applications. One of the most important fundamental forms for engineering components is the circular cross-section. Circular forms arise in many applications, particularly in bearing surfaces such as rotating shafts and ball bearings [23].

The comparison of the values of deviation from circularity of three different tools depending on the feed rates and at various cutting speeds is given in Figure 3. The Figure 3 show that there is an increase in the deviation from circularity values with the increase of feed rate. The increased feed rate increases the cutting forces during drilling causing the main shaft of the machine to scat and the holes to become circular [23]. Small diameter of the drill used in the tests and sufficient machine strength minimizes this scatting. However, even a low amount of scatting effects the cutting conditions adversely. Sved and Mannan [13] determined that circularity values had a tendency to increase depending on the increase of feed rate. The deviation from circularity values with the variation in the cutting speed did not show a variation as in the case of feed rate. The lowest deviation from circularity values were obtained at the 12.5 m/min cutting speed whereas the highest deviations from circularity values were obtained at the 17.5 m/min cutting speed. Especially at the 17.5 m/min cutting speed the increase in the feed rate was more effective with respect to the other cutting speeds. This can be explained as the spoilage of roundness of the hole due to the increased vibrations coming from the increased loads on the cutting tool at high cutting speed [17, 23]. The deviation from circularity values which were obtained with TiN coated tool exhibited a similar tendency at the 10, 12.5 and 15 m/min cutting speeds. When looking at the average of the deviation from circularity values it can be said that the lowest deviation values were obtained with the uncoated tools whereas the highest ones were obtained with the TiAlN coated tools. Inconel 718 alloy has a high ductility and this causes a build up edge (BUE) effect on the cutting tool during machining [6]. This build-up ruptures after reaching a certain size and takes also a piece away from the cutting tool causing tool wear and spoilage of hole quality. It can be said that this mechanism has an effective role on the removal of TiAlN coating which has a high coating thickness of 3.2 εm. Thus, in the study of Sved and Mannan [13] it was seen that mono-layer coating exhibited a better performance than the multi-layer coatings from the point of view of hole quality.

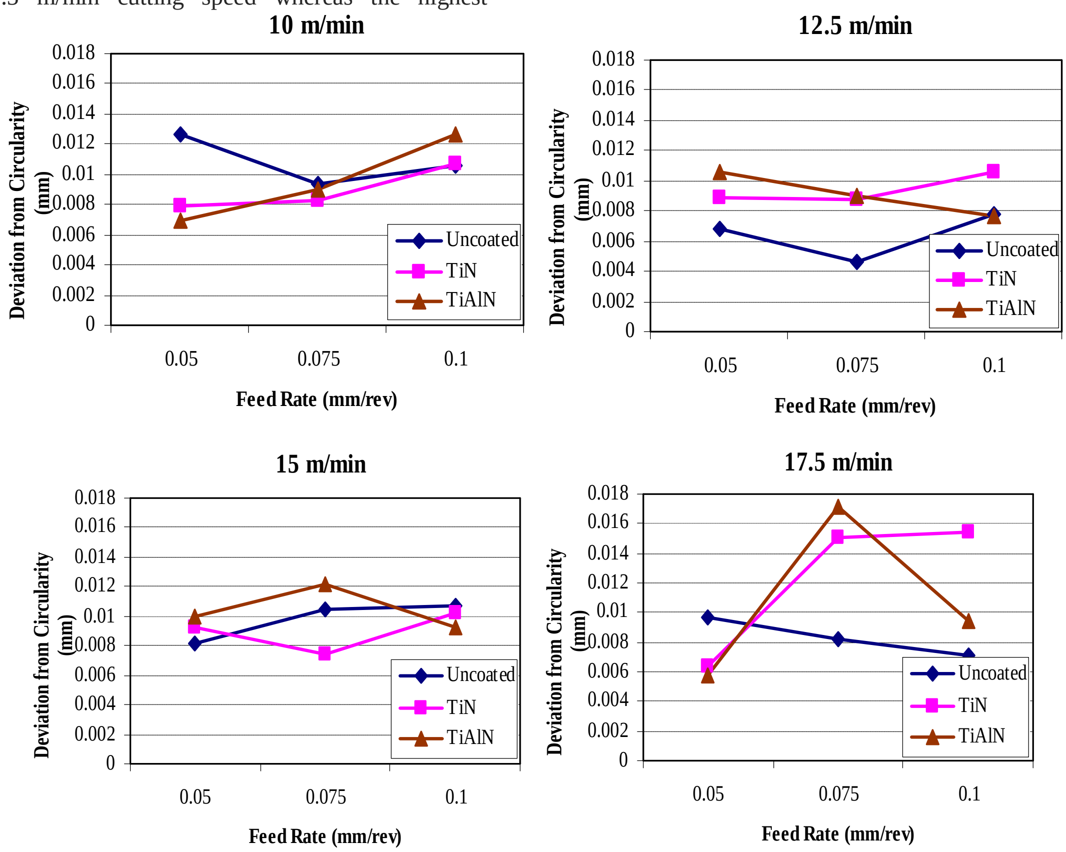


Figure 3. Variation in the average deviation from circularity values with the increase in the feed rate depending on the coating material and cutting speed.

3.2. Hole Diameter

The variation in the average diameter values which was obtained with three different tools at different cutting speeds depending on the feed rate is shown in Figure 4. At the same cutting speed and with the increase in feed rate, average diameter values exhibited an increase as was the case in the deviation from circularity values. It is thought that feed rate and increased cutting forces increase axial loads on the cutting tool causing the enlargement of hole diameter [24]. This increase was very effective at the 17.5 m/min cutting speed. At this cutting speed when the feed rate increased from 0.05 mm/rev to 0.1 mm/rev the increase in the average diameter values was approximately 6% despite the 100%

increase in feed rate. The diameter values closest to the nominal diameter (5mm) were obtained at the 0.05 mm/rev feed rate and at the 15 m/min cutting speed. Among the three tools the average diameter values were closest to each other at the 15 m/min cutting speed. When the hole quality were taken into consideration it can be said that the ideal cutting conditions were at this cutting speed. The most effective feed rate was at the 17.5 m/min cutting speed.

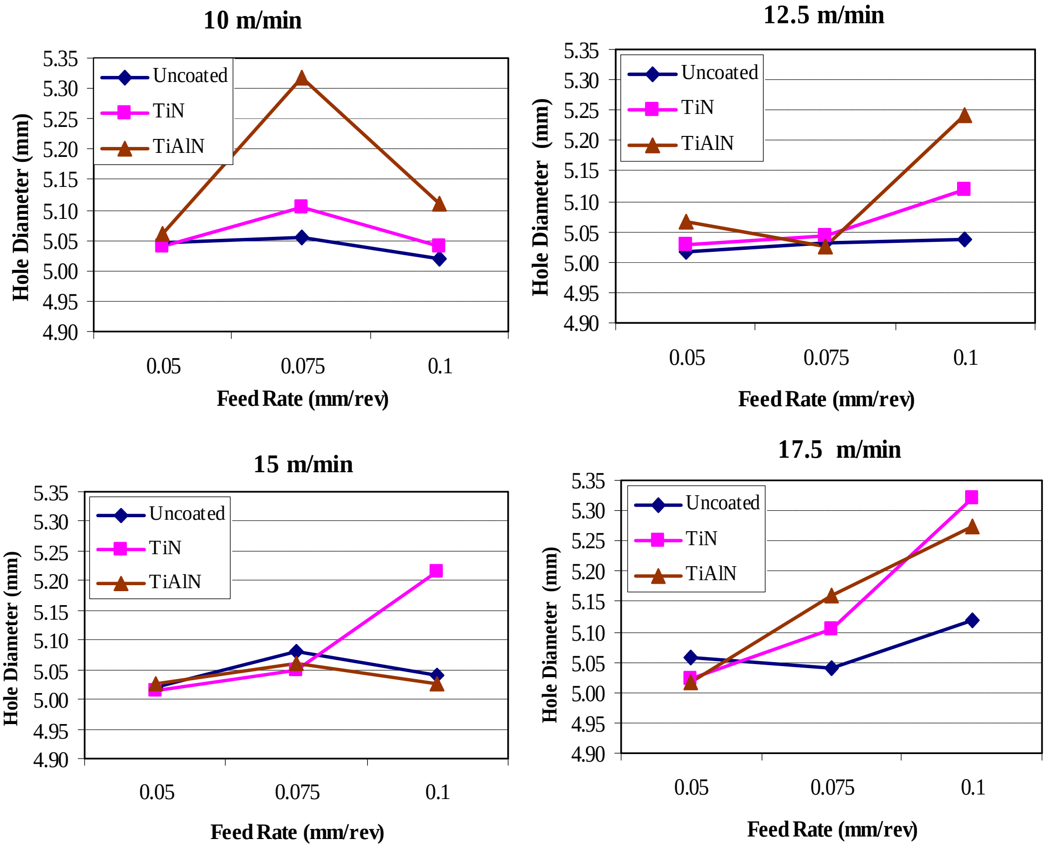


Figure 4. Variation in the average hole diameter values with the increase in the feed rate depending on the coating material and cutting speed.

During the tests at the 17.5 m/min cutting speed made with uncoated tool the increase in the hole diameters with respect to hole number is shown in Figure 5.

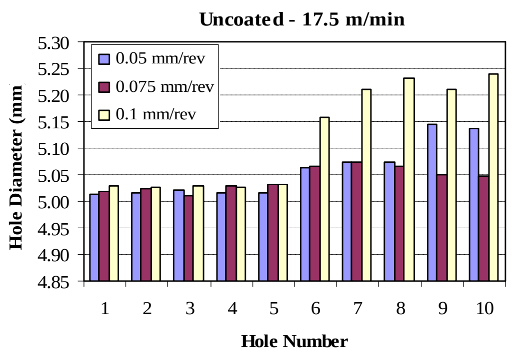


Figure 5. Variation of average diameter values with the increase of hole number and depending on the feed rate at the 17.5 m/min cutting speed with uncoated tool.

The results which were obtained with this tool, as with the other tools, exhibited a tendency to increase in the hole diameter after the fifth hole. At the three feed rates and at the first five holes the obtained diameters were close to the nominal diameter and after the fifth hole due to the serious tool wear increase in the diameter values were observed. At the specially chosen 0.1 mm/rev high feed rate, hole diameter increased up to 5.22 mm. This shows the effect of high feed rates (at the same cutting speed) on the tool wear.

3.3. Tool Wear

Drilling is a complex operation, at the centre of the drill the cutting speed is essentially zero and material removal around the chisel edge occurs primarily by extrusion with the transport of material radically away from the centre. On the cutting edges material removal occurs by shear in the same manner as for turning and milling tools with the cutting speed and rake angle varying with distance from the drill centre. These differing material removal mechanisms cause the wear mechanism on the drill to varying depending on its location [25].

In the uncoated cutting tools SEM pictures showing the wear due to the variation of the cutting speed is given in Figure 6. It is obvious from the pictures that tool wear increases with the increase in cutting speed. At low cutting speed (10 m/min) the outer corner wear came out to be an effective wearing type (Figure 6.a). Outer corner wear was also reported by Chen and Liao [20] in their study on drilling Inconel 718 although final failure of the drills was caused by high average flank wear along the cutting edge. With the increase of cutting speed (12.5 m/min) outer corner wear and flank wear started to be effective (Figure 6.b). At high cutting speeds (15-17.5

m/min), chipping which may have fractured the cutting tool and chisel edge wear that might have changed the radial mouth geometry occurred (Figure 6.c-d). Especially at high cutting speed and feed rate combinations chipping volume removed per unit time went up with machining and increased friction causing elevated temperatures which accelerated the tool wear. In the drilling of Inconel 718 with a lower thermal conductivity, the none usage of a cooling liquid also caused a considerable effect on wear. When outer corner wear started it grew with the increase of cutting speed and extends up to chisel edge. In constant feed rate, increase of cutting speed by 75% from 10m/min to 17.5 m/min led to a tool wear which was incomparably high.

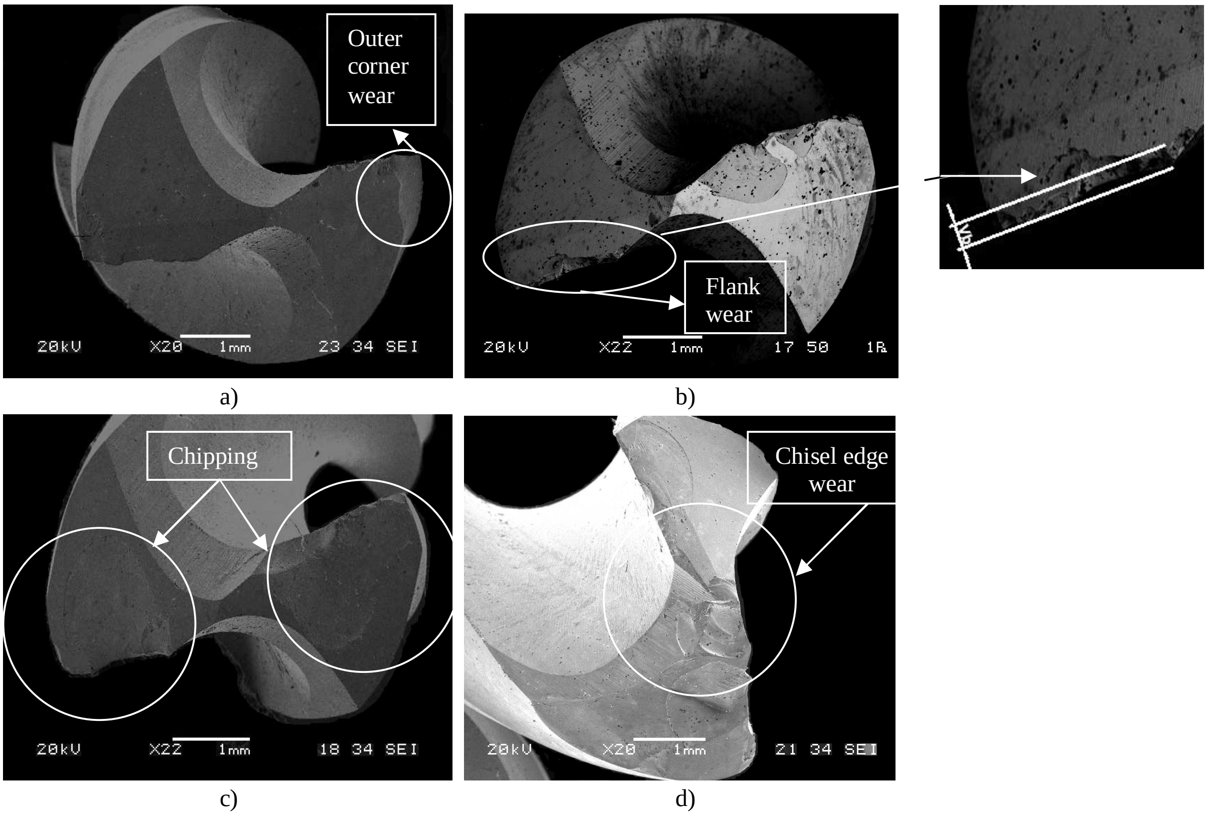


Figure 6. The variation in the tool wear on the uncoated tool at the end of 10 holes at the 0.1 mm/rev feed rate depending on the cutting speed a) 10 m/min b) 12.5 m/min c) 15 m/min d) 17.5 m/min.

In Figure 7 in TiN coated tool, the variation occurring in tool wearing with the increase of feed rate is illustrated. At low feed rate the wearing occurring on the surface led to chisel edge with increase of feed rate by 50%. It is thought that this is the result of pressure of the radial mouth of cutting tool coming from the increase in the feed rate.

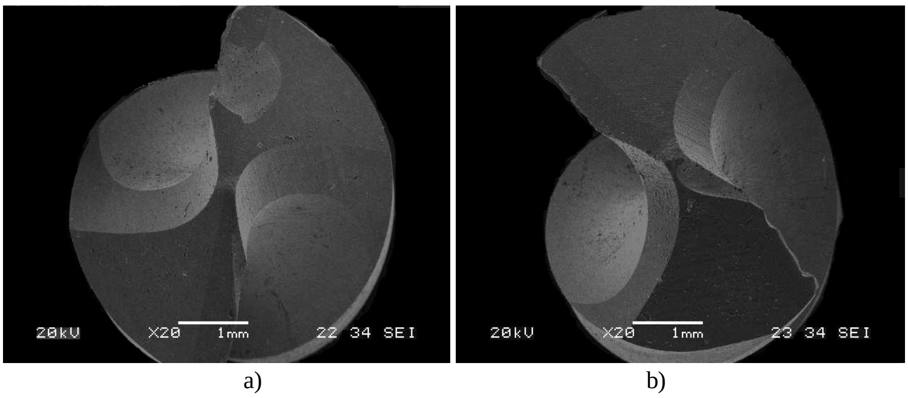


Figure 7. The variation in the tool wear on the TiN coated tool drill at the end of 10 holes with the increase of feed rate at the 15 m/min cutting speed. a) 0.05 mm/rev b) 0.075 mm/rev.

4. CONCLUSIONS

The results which were obtained at the end of the experimental studies are summarized below.

i- The lowest deviation from circularity values were obtained at the 12.5 m/min cutting speed whereas the highest deviation values were obtained at the 17.5 m/min cutting speed. At the 17.5 m/min cutting speed the feed rate played a great role in the variation of deviation from circularity values. As the feed rate increased, deviation from circularity values also increased. The lowest deviation from circularity values were obtained from the holes that were drilled with uncoated tool.

ii- At all cutting speeds and feed rate combinations, the best values for hole diameters were obtained with uncoated tools. In general, for all the three tools as the feed rate increased the hole diameters increased too. The feed rate for which the lowest hole diameters were obtained (at four cutting speeds) was 0.05 mm/rev. As for the cutting speeds the best result for the three feed rates was 15 m/min. The feed rate for which the greatest hole diameters were obtained came out to be 0.1 mm/rev.

iii- With the increase of cutting speed serious increases were observed in the tool wearing. Utmost wearing type was seen in the form of flank wear and chisel edge wear.

iv- From the point of view of the hole quality under dry cutting conditions, in the drilling of Inconel 718 uncoated cementite carbide tools are recommended. Furthermore, the hole quality can be increased by using lower feed rates.

v- High cutting speed and feed rate combinations were effective on the spreading of wearing from outer corner to chisel edge.

ACKNOWLEDGMENT

The authors thank Gazi University Scientific Research Projects Group supporting this study with 07/2007-41 project no.

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