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An Investigation on Surface Roughness and Tool Wear in Turning Operation of Inconel 718

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ABSTRACT: This paper investigates the influences of three different input parameters, such as feed rate, insert nose radius, and insert coating methods, in the turning operation of Inconel 718. The coating methods were selected as medium temperature chemical vapor deposition (MT-CVD) and physical vapor deposition (PVD) and in addition to coating methods, the role of various coating materials was discussed since the inserts were coated with multi-layers of TiCN/Al_2O_3/TiN and single-layer of TiAlN on carbide substrates. The results were discussed in terms of wear behavior of cutting tools and surface quality of the workpiece, which is indicated by surface roughness. A full factorial experimental design was employed in the present work and the results were evaluated using main effects plots. Furthermore, the analysis of variance (ANOVA) method was applied to specify both reactive and non-reactive effects of experimental parameter reactions. The results showed that surface roughness is reduced using low feed rates and large nosed inserts in the operations. Furthermore, TiAlN-coated inserts with PVD method provided better surface finish than with MT-CVD method. It was also found that surface roughness increases as the wear rate of inserts increases.

KEYWORDS: Turning operation, Surface roughness, Tool wear, Inconel 718.

INTRODUCTION

Applications in the aviation field have evolved notably due to increasing passenger capacity and flight range. Development in the science of materials for aeroengines has been one of the key factors in this evolution. In general, nickel-, titanium-, cobalt-, and iron-based alloys are employed for the components of aeroengine systems, depending on mechanical and thermal requirements. Nickel-based alloys are the most preferred materials for the aviation applications, especially Inconel 718, which is utilized approximately 75wt% in aerospace applications and 50wt% in modern jet engines. Inconel 718 has high strength-to-weight ratio and provides high strength at elevated temperatures, superior creep resistance, and good corrosion resistance. In aeroengines, this alloy is employed for turbine blades operating at crucial conditions, such as high temperature and pressure (Thakur *et al.* 2009; Çakır *et al.* 2015; Çakır *et al.* 2018). Although this advanced material contributes to improvement in the aviation industry, it exhibits poor manufacturing properties due to its superior mechanical and chemical properties, especially at elevated temperatures. In terms of machining properties, life of cutting tools deteriorates due to the work hardening and attrition properties of Inconel 718. Furthermore, very high cutting forces cause metallurgical damage to the workpiece, such as work hardening, surface tearing, and distortion (Madariaga *et al.* 2014; Sofuoğlu *et al.* 2018a; Sofuoğlu *et al.* 2018b).

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Although there are several investigations into the machining of Inconel 718, it is still challenging to understand the nature and actual reasons behind the disadvantage of the machining of Inconel 718 to improve productivity and quality in manufacturing. In the most of early studies on Inconel 718, surface roughness was used as a key output and process parameters have been tuned to improve the surface quality of machined products (Zhuang *et al.* 2015; D'Addona *et al.* 2017; Mohsan *et al.* 2017; Cantero *et al.* 2018; Mehta *et al.* 2018). Guo *et al.* (2009) overviewed the machining characteristics of difficult-to-cut materials, including nickel-based alloys. The study focused on the residual stresses produced in workpieces. It was stated that residual stresses are induced by both mechanical and thermal effects in machining operations. Plastic deformation due to mechanical influences generates compressive stresses on the workpiece's surface as the surface layer is compacted. However, thermal load generates tensile stresses since the surface expands during cutting due to heat generation in the vicinity of the cutting zone while the workpiece's sub-surface is not heavily influenced by this heat generation. Upon cooling, the surface layer of the workpiece recovers against the resistance of the sub-surface, and therefore the machined surface is plastically strained by cutting and generating a work-hardened layer from the outer surface layer to a certain depth. Berruti *et al.* (2009) investigated the effects of cutting speed and feed rate in the machining of Inconel 718 turbine shaft. In their case study, uncoated carbide cutting tools were employed and the results showed that residual stresses are in tensile form at the workpiece's surface while in compressive form at its sub-surface. It was also noteworthy that higher cutting speed and feed rates produce higher residual stresses, but the trends change for different directions. Bushlya *et al.* (2012) studied the high speed turning of Inconel 718 with coated and uncoated cutting tools. It was stated that the protective function of coating on inserts is limited to low cutting speed range. The results also showed that the coated cutting tools, compared to the uncoated ones, are more prone to convert residual stresses from compressive to tensile surface stresses. Beside the influence of coatings on cutting tools, with respect to the uncoated ones, various types of coatings have been compared each other to observe individual effects of each coating in machining operations. Chemical vapor deposition (CVD) and physical vapor deposition (PVD) methods are extensively utilized for the coating of cutting tools and thereby have been attracting much attention from researchers in recent years. It was suggested, in early studies, that the PVD method is more beneficial than the CVD method for the machining operation of refractory materials in terms of wear resistance of cutting tools. It is well known that the wear behavior of a cutting tool is directly related to the surface roughness of the workpiece, which means that the PVD method comes to the forefront for high-quality surface finish (Çelik *et al.* 2016; Thakur and Gangopadhyay 2016). In fact, the coating method is not the only factor for surface quality since coating materials influence the friction and forces on cutting tool. In this light, coating materials with high hardness and low surface friction are important to relieve the crucial conditions in cutting zone. In addition, multi-layer coatings are selected to take the individual advantage of various coating materials. For example, a TiAlN/TiN multi-layer coated cutting tool improves machining operations utilizing the anti-sticking property of TiN and the low thermal conductivity of TiAlN (Hsieh *et al.* 1998; Thakur and Gangopadhyay 2016). Niu *et al.* (2013) investigated the cutting process of difficult-to-cut materials using carbide inserts with various coatings. The study discussed the cutting forces, chip morphology, tool wear, and surface roughness. According to this work, PVD-coated inserts were suggested for the cutting operations. Madariaga *et al.* (2014) and Liu *et al.* (2004) studied the effect of the cutting tool nose radius on the machining performance of hard materials. It was revealed that residual stress profiles and surface quality are heavily dependent on nose radius. An increase in the tool nose radius leads to a big difference between surface tensile stress and sub-surface compressive peak stress while improving the surface quality. Chou and Song (2004) investigated the effects of cutting tool nose radius and feed rate in hard turning operation. Based on this study, tools with large nose radius give fine surface finish and the feed rate strongly influences the surface roughness of the workpiece. In addition to stating the influences of input parameters, some studies have built analytical models to predict the operational outputs, depending on the collected data from experiments. Baek *et al.* (2001) proposed a surface roughness model to optimize feed rate in machining operations. The model was verified by a set of experiments using surface roughness and dimensional accuracy data in the operations. Basheer *et al.* (2008) offered a model to predict the surface roughness of machined surfaces based on the artificial neural network-based (ANN) method. The proposed model was found to be consistent with the experimental data set. Various statistical methods have been applied to machining operations to find the optimum process parameters and surface roughness, machining time, and tool cost were used as outputs for these operations (Abbas *et al.* 2017; Abbas *et al.* 2018a; Abbas *et al.*; 2018b).

Since superalloys are essential materials for aerospace applications, there should be various attempts to improve the surface quality of aerospace components without compromising the tool cost. Despite several researches on the machinability of metals, turning operations of superalloys such as Inconel 718 have not been investigated in detail using different tool nose radii and tool coatings. This work presents the role of these parameters on the surface roughness of products and tool wear. In the light of the present work, appropriate tool selection for the turning operation of Inconel 718 is aimed. The coating methods were selected as medium temperature chemical vapor deposition (MT-CVD) and PVD and in addition to coating methods, the role of various coating materials was discussed since the inserts were coated with multi-layers of $TiCN/Al_2O_3/TiN$ and single-layer of TiAlN on carbide inserts. The results were discussed in terms of wear behavior of cutting tools and surface quality of the workpiece, which is indicated by surface roughness. A full factorial experimental design was employed in the present work and the results were evaluated using main effects plots. Furthermore, the analysis of variance (ANOVA) method was applied to specify both reactive and non-reactive effects of experimental parameter reactions.

EXPERIMENTAL DETAILS

In the present study, a SAE AMS5662 specified forged Inconel 718 workpiece was selected, which is preferable for aerospace applications. The diameter of the workpiece was 945 mm and the machining was performed using a vertical CNC machine (You Ji, YV-1200ATC). In order to investigate the cutting tool-based effects, carbide inserts with different nose radii and coatings were utilized in the operations. The insert nose radius (n_r) was varied, using three levels, 0.4, 0.8, and 1.2 mm, which are preferable in the turning of Inconel 718. MT-CVD and PVD-coated inserts were selected to investigate the role of different coatings. Figure 1 shows the scanning electron microscopy (SEM) image of MT-CVD and PVD-coated inserts. In addition to these variables, two different feed rates (f_r), such as 0.15 and 0.20 mm/rev, were used in the experiments, considering the technical data sheets including the recommendations of tool manufacturers. The constant parameters in the experiments were the cutting speed (V_c) of 50 m/min and the cutting depth (d_c) of 0.25 mm. After completing the experiments, the workpiece surface roughness for each run was measured six times from different regions on the surface using a Taylor-Hobson Surtronic 3P surface profilometer. The failures on the inserts were visualized using a Mitutoyo Quick Scope microscope. Full factorial method was employed in the experimental design where the total number of experiments (N_{exp}) is calculated using Eq. 1. Table 1 gives the variable parameters and their levels in the experiments.

$$N_{exp} = a^k \tag{1}$$

where N_{exp} is the total number of experiments; k is the number of factors; and a is the different level number for each factor.

Table 1. Variable parameters and their levels.

Level	Feed rate, f_r (mm/rev)	Nose radius, n_r (mm)	Insert coating
1	0.15	0.4	Medium temperature chemical vapor deposition
2	0.20	0.8	Physical vapor deposition
3		1.2	

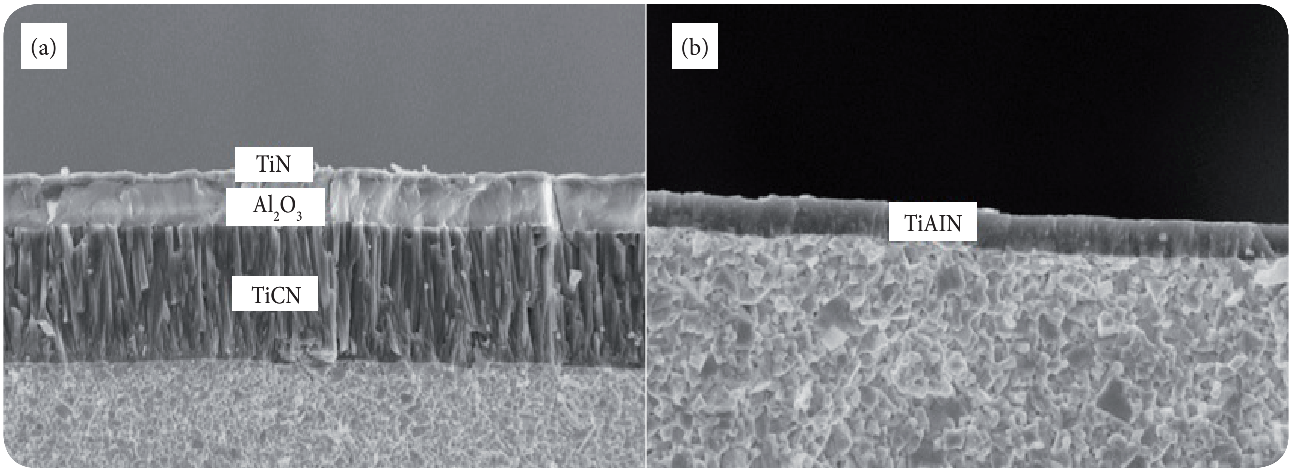

Figure 1. Scanning electron microscopy (SEM) image of (a) medium temperature chemical vapor deposition (MT-CVD) and (b) physical vapor deposition (PVD)-coated inserts (Hill 2012).

RESULTS AND DISCUSSION

Surface roughness of machined parts is an important criterion for the quality of machine components. Products with low surface roughness improve the functional ability and reliability of machine systems (Yan 2009). Surface roughness influences the major properties of products such as fatigue strength, creep life, corrosion resistance, and wear resistance. In the engineering aspect, these properties should be improved through controlling the surface roughness of components in the manufacturing stage (Çelik *et al.* 2016). There is a direct relationship between surface roughness and parameters in machining operations. In order to observe this relationship, a series of experiments was performed and the influences of cutting parameters on the surface roughness of the workpiece were determined. Based on the experimental design, mean of surface roughness (*Ra*) and standard deviation (SD) for each measurement are given in Table 2. From the given values, each measurement yields a SD within a percentage of 5% from the mean of surface roughness. Therefore, it is possible to mention that each measurement is close to the average value, which means that the repeatability of the measurements is

Table 2. Results in the experimental design.

Run	Feed rate f_r	Insert nose radius n_r	Insert coating	Surface roughness *Ra*	Standard deviation (SD) (µm)	Percentage of SD (%)
1	1	1	1	1.16	0.04	3.3
2	1	1	2	1.11	0.03	2.4
3	1	2	1	0.83	0.02	2.0
4	1	2	2	0.72	0.02	2.6
5	1	3	1	0.44	0.02	4.7
6	1	3	2	0.38	0.02	4.8
7	2	1	1	1.69	0.06	3.7
8	2	1	2	1.41	0.06	4.4
9	2	2	1	1.06	0.04	3.9
10	2	2	2	0.86	0.04	4.7
11	2	3	1	0.83	0.04	4.9
12	2	3	2	0.67	0.03	4.6

quite good. ANOVA results are given to specify both reactive and non-reactive effects of experimental parameter reactions in Table 3. It is seen that the results satisfy the reliability interval of 95%, considering the probability (P) values where each of them is lower than the significance level of 0.05. In addition, the percentage contribution of each input (PC) on the total variation was calculated according to the sequential sums of squares (Seq SS). Considering the PC values, it is clear that the insert nose radius is predominant on the surface quality of the workpiece with the PC value of 77%. Even though the feed rate has a slight impact, as the PC value is 19%, insert coating is not effective on the formation of surface roughness since its PC value is only 4%. Therefore, it can be concluded that the insert nose radius is the most important parameter for the surface quality among the varied factors in the present study. This is also verified in an early work that shows that insert nose radius is a major factor on surface roughness as well as feed rate (Basheer *et al*. 2008).

Table 3. Analysis of variance (ANOVA) results for surface roughness.

Source	Degrees of freedom	Sequential sums of squares	Adjusted sum of squares	Adjusted mean of squares	Test statistic	Probability	Percentage contribution (%)
Feed rate	1	0.29203	0.29203	0.29203	44.18	0.000	19%
Insert nose radius	2	1.19165	1.19165	0.59583	90.15	0.000	77%
Insert coating	1	0.05964	0.05964	0.05964	9.02	0.020	4%
Error	7	0.04627	0.04627	0.00661			
Total	11	1.58960					

To indicate the importance of feed rate in machining operations, Baek *et al.* (2001) stated that surface roughness is mainly determined by feed rate. In the present work, in order to obtain the role of each input parameter on the surface roughness, main effects plots are presented in Fig. 2. It is clearly seen that feed rate has a negative response for the surface quality of the workpiece which means that surface roughness increases as feed rate is increased in the operation. Most of investigations into the machining of materials focus on the maximum material removal, and therefore feed rate is intended to be increased. However, the workpiece surface roughness acts as a constraint for the maximum material removal, and thus an optimization is required to achieve the best outputs in machining operations. The reason of poor surface finish stems from the enhanced cutting forces when feed rate increases. In particular, the increase in cutting forces becomes drastic in the machining of hard materials, such as Inconel 718. For this reason, the deterioration of surface quality is more prone to increase by using high feed rates in hard material cuttings. In fact, enhanced cutting forces at elevated feed rates accelerate the wear mechanism of cutting tools on the contacted regions, and therefore cutting edges

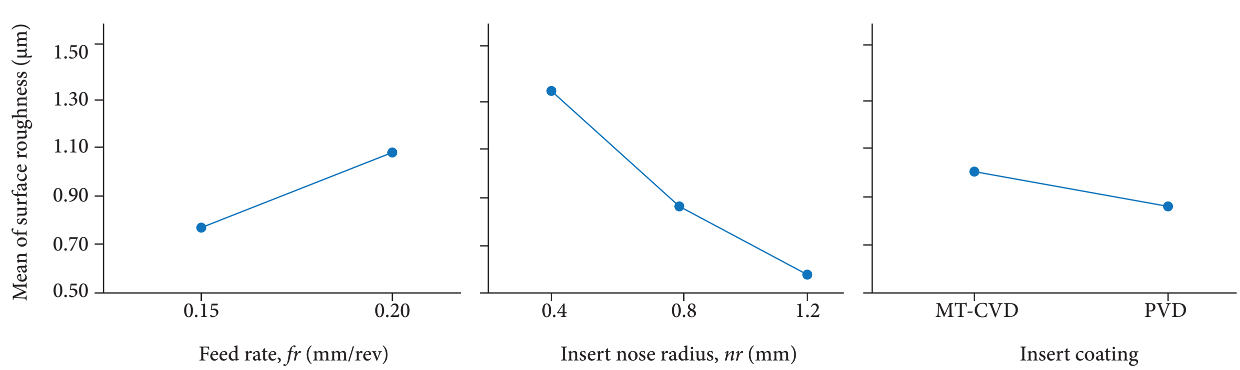

Figure 2. Main effects plot for surface roughness (*Ra*). MT-CVD = Medium temperature chemical vapor deposition; PVD = Physical vapor deposition.

on inserts become blunt and, consequently, the cutting process turns into tearing, which results in rough asperities on the workpiece's surface. More importantly, upon maintaining the operation with worn inserts, cutting forces reach excessive values due to the increasing rate of blunting in cutting edges, and thus disruption in the surface quality grows, but the fact remains that a sudden breakage of insert may be seen during the operation. In addition to poor surface finish, Thiele *et al.* (2000) noticed that residual stresses change from compressive to tensile, which are more destructive for components in their service conditions, in case of increased feed rates.

Considering the insert nose radius, it is seen that inserts with large nose radius are more beneficial in terms of surface quality of the workpiece. The surface roughness mechanism due to insert nose radius is completely different from that due to feed rate. As discussed before, increased cutting forces accelerate the wear mechanism on tool surface, and therefore surface quality is disrupted. However, insert nose radius influences the surface roughness in terms of the geometrical characteristics of the machining. As shown in Fig. 3, the simultaneous contribution of feed rate and tool nose radius determines the pitch and amplitude of the surface profile generated in the machining (Basheer *et al.* 2008). It can be also stated that the disadvantage of high feed rate can be eliminated using large nose radius inserts because the amplitude of the surface profile is decreased due to the extended contact zone in the operation. On the other hand, turning operations with small nose radius inserts cause high-pitched surface profile; however, the surface quality is improved lowering the feed rate in that case. In this light, it is possible to mention that the surface roughness of the workpiece is heavily dependent on the in-situ interaction of feed rate and insert nose radius, and therefore any drawback owing to one of these factors can be compensated altering the other one. In terms of plastic deformation on the workpiece's surface, inserts with small nose radius are recommended although they provide relatively poor surface finish. Large nose radius inserts enhance tensile residual stresses on the workpiece, especially at near surface regions. The influence of insert nose radius on residual stresses gradually diminishes as the distance from the workpiece's surface increases. Furthermore, it is indicated that large nosed inserts produce thick work-hardened layers in workpieces, which demonstrates that residual stresses and sub-surface plastic deformation are enhanced using inserts with large nose radius, based on early investigations (Thakur *et al.* 2012; Madariaga *et al.* 2014). In particular, critical components are suggested to be machined using small nose radius inserts and worn cutting tools are avoided to reduce both residual stresses and surface roughness on workpieces (Sharman *et al.* 2015). Increased residual stresses are attributed to increased cutting forces when using large nose radius inserts due to a large contact area in the cutting zone. In addition to these, it is stated that there is no strong difference in residual stress distribution among various insert nose radii as the wear on tool increases. In other words, the influence of insert nose radius on the plastic deformation of workpieces heavily decreases with an increase in the cutting tool wear (Liu *et al.* 2004). In terms of wear mechanism on cutting tools, Chou and Song (2004) suggested that there is not a significant difference between the wear behavior of large and small nose radius inserts, which means that the insert nose radius has not a remarkable influence on the wear mechanism of cutting tools.

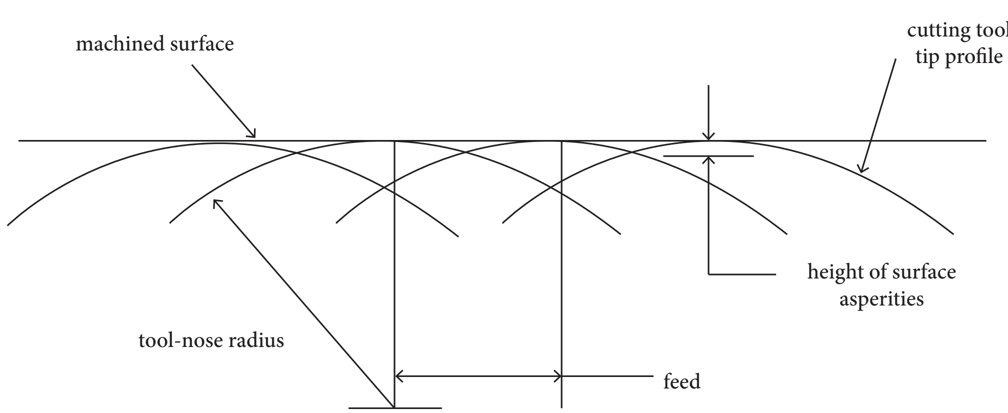

Figure 3. An illustration of the influence of insert nose radius (n_r) and feed rate (f_r) on surface roughness (*Ra*) (Basheer *et al.* 2008).

Coatings on cutting tools are significantly important since they directly influence the interaction between cutting tool and chip in cutting operations. Various types of coatings are applied onto cutting tools to improve wear resistance and prevent the sticking phenomenon at elevated cutting temperatures. Coatings also take part as thermal barriers, which leads to temperature reduction on cutting tools. Based on the experimental results, PVD coating provides smoother surface finish for the workpiece made of Inconel 718 than MT-CVD coating, although the relative weight of coating on surface roughness is poor among the other factors, taking into consideration the PC values in Table 3. In fact, both coating methods have beneficial outputs, such as reduced friction and cutting forces when compared to uncoated inserts. In addition to these, PVD coating exhibits better results than its CVD-coated counterpart in terms of friction according to ball-on-disc testing in early studies (Jiang and Ulbrich 2001; Atlati *et al.* 2015; Thakur and Gangopadhyay 2016). Furthermore, the ability to coat the sharp edges of inserts, which is improved owing to the relative thinness of PVD coating in comparison to CVD coating as in the present study, provides further reduction in cutting forces (Balasubramanyam *et al.* 2015; Thakur and Gangopadhyay 2016). In other words, the rounding of the cutting edge due to the presence of multi-layers on the CVD-coated tool is attributed to poor surface finish when compared to the thinner layer on the PVD-coated tool (Thakur *et al.* 2014). Supportively, early studies suggest that a high surface roughness of the workpiece is directly related to a large edge radius in coated tools, which makes the cutting edge blunted (Bushlya *et al.* 2012; Zhou *et al.* 2012). On the other side, coating materials determine the wear behavior of cutting tools and so the surface roughness of the workpiece. Alumina-based coatings provide excellent high temperature properties due to low thermal conductivity, preventing the generated heat to dissipate into cutting tool substrate and lowering the wear rate on insert. However, TiC and TiN coating layers, as in the MT-CVD-coated insert, lead to an increase in thermal conductivity, which accelerates the wear rate on cutting tool (Kumar *et al.* 2008). Beside thermal properties, the hardness of TiAlN coating is superior to other coating materials, and therefore the wear resistance of inserts is enhanced using this coating (dos Santos *et al.* 2007; Davim 2008). Considering all these facts, the PVD-coated inserts leave behind the MT-CVD-coated ones in terms of wear resistance. Figure 4 shows the wear tracks on different inserts used in cutting operations. It is clear that the wear tracks on the MT-CVD-coated inserts are more prominent in comparison to those on the PVD-coated ones for each cutting condition. It is also noteworthy that the wear formation on the tools is the crater type wear due to abrasive friction. Early studies suggest that an anti-friction property of TiAlN coating is responsible for the low friction behavior, which demonstrates that PVD-coated inserts exhibit high wear resistance in the turning operations (Liang *et al.* 2011; Niu *et al.* 2013). As a result, it can be concluded that TiAlN coating using PVD method provides improved wear resistance for the cutting tools and, in relation to that, the surface quality of Inconel 718 exhibits better results in the operations with PVD-coated inserts than in the MT-CVD ones.

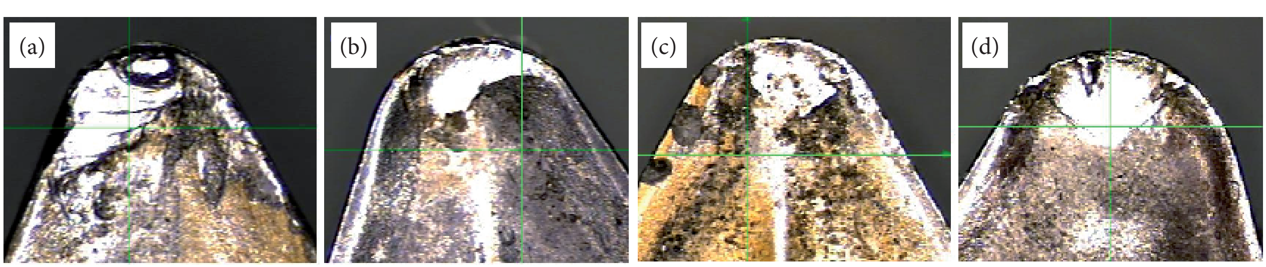

Figure 4. Wear on the inserts at the feed rate (f_r) of 0.20 mm/rev; (a) medium temperature chemical vapor deposition (MT-CVD)/ radius: 0.4 mm, (b) physical vapor deposition (PVD)/radius: 0.4 mm, (c) MT-CVD/radius: 0.8 mm, and (d) PVD/radius: 0.8 mm.

CONCLUSIONS

In the present work, the turning operation of Inconel 718 was investigated in terms of the surface quality of the workpiece and the wear behavior of cutting tools. The study reveals the relationship between these outputs and input parameters, such as feed rate, insert nose radii, and insert coating methods. The coating methods were selected as MT-CVD and PVD and, in addition to these, the role of various coating materials was discussed since the inserts were coated with multi-layers of TiCN/Al_2O_3/TiN and single-layer of TiAlN on carbide substrates. From the roughness results, repeated measurements on each specimen exhibited close values, which means that the repeatability of the measurements are quite good since the SD are within a percentage of 5% from the mean of surface roughness. Based on the ANOVA results, the percentage contributions of insert nose radius, feed rate, and insert coating were found as 77%, 19%, and 4%, respectively. In this light, the insert nose radius has the most powerful impact on the surface roughness of the workpiece. Feed rate has also considerable influence, whereas the weight of the insert coating is relatively low on the surface quality of the workpiece. The results show that surface roughness is reduced using low feed rates and large nosed inserts in the operations. Furthermore, TiAlN-coated inserts with PVD method provided better surface finish in comparison to the inserts coated with MT-CVD method. It was also found that surface quality is related to wear rate of cutting tools, which means that surface roughness increases as the wear rate of inserts increases. Due to the present work, the influences of tool-based parameters such as insert nose radius and insert coating were investigated in detail. Therefore, the study provided brief results for appropriate tool selection in the turning operation of Inconel 718.

AUTHOR'S CONTRIBUTION

Conceptualization, Tali D and Kuşhan MC; Methodology, Tali D; Investigation, Gürgen S and Tali D; Writing – Original Draft, Gürgen S; Writing – Review & Editing, Gürgen S and Kuşhan MC; Supervision, Kuşhan MC.

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