

## Effect of Machining Parameters on Turning of Inconel X750 Using PVD Coated Carbide Inserts

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It is one of the few studies conducted on the machining of Ni-based Inconel X750 alloy, which has a wide range of applications in the main industries (gas turbines etc.) and aerospace (rotor blades etc.) industries. In this study, cutting tool wear, cutting forces and surface roughness were investigated in dry turning of Inconel X750 super alloy with coated carbide cutting tool. For the determining of the wear types and mechanisms electronic microscope and SEM were used. 4 different cutting speeds (40, 60, 80 and 100 m/min) and 3 different feed rate (0.1, 0.15 and 0.2 mm/rev) values were used in the experiments. The cutting depth was kept constant at 1 mm. According to the results; with increasing feed rate, the value of  $F_c$ ,  $F_f$  and  $F_p$  cutting force components increased. The feed rate was significantly influential on  $R_a$ . The cutting geometry and the cutting edge sharpness induced by the formation of stable BUE caused  $R_a$  to increase. The most suitable parameters for turning the Inconel X750 alloy in terms of all evaluation criteria were the cutting speed of 60 m/min and 0.1 mm/rev.

**Keywords:** Dry turning, Inconel X750, Cutting force, Tool wear, Surface roughness

### Introduction

Nickel-based super alloys are widely used for the production of mechanical parts such as plane engines, components of gas turbines, due to their high mechanical strength, excellent thermal fatigue resistance, and corrosion resistance<sup>1-4</sup>. Machining of the super alloys are difficult because of their high ductility, strain hardening, low thermal conductivity, high mechanical strength, the existence of abrasive carbide particles, and their chemical affinity to tool material<sup>1,3</sup>. Therefore, for optimum use of these alloys, solutions to workability problems must be found.

### Materials

Sharman *et al.* investigated the effect of tool nose radius on residual stress distribution when turning Inconel 718. It was shown that an increased tool nose radius results in an increase in the depth of microstructural deformation<sup>5</sup>. Petru *et al.* studied the selection of appropriate cutting parameters for machining the Inconel 625. The effect of three different cutting inserts and feed rates on durability and wear of the cutting tool and surface roughness was investigated<sup>6</sup>. Xavier *et al.* examined the

relationship between different tool materials and tool life when turning Inconel 718 under different cutting conditions. Results showed that tool wear was influenced by factors such as thermal softening, adhesion, diffusion, notching and thermal cracking<sup>7</sup>. Hao *et al.* used PVD coated carbide cutters for machining Inconel 718. Tool wear morphology and tool wear mechanisms were investigated. Wear characteristic were changed by the cutting speeds<sup>3</sup>. During the finish machining of Ni-based superalloys, CVD coated cutting tools can be an appropriate coating type<sup>8</sup>. Thakur *et al.* tested the effect of cutting speed on the surface roughness, the tool wear properties, the chip morphology and the chip rate by using CVD coated cutters in the dry machining of Inconel 825.

The results showed excellent resistance to coated tool crater and flank wear when CVD multilayer coated tools are compared to uncoated tools<sup>9</sup>. Sarıkaya *et al.* investigated the machinability of Haynes 25 under three cutting methods (dry, conventional cooling and lubrication, and minimum lubrication). As a result, when the MQL method was applied with high pressure, the amount of oil used was reduced while the machinability of the material was improved<sup>10</sup>. Ramkumar *et al.* discussed the effect of post-weld heat treatment on the fusion region microstructure and mechanical properties of Inconel

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Table 1 — Chemical composition and mechanical properties of Inconel X-750 (%)

Ni	Cr	Fe	Ti	Al	Nb	Mn	S	P	Cu	C	Co
70	14-17	5-9	2.25-2.75	0.4-1.00	0.7-1.2	1.00	0.50	0.01	0.50	0.08	1.00
Tensile Strength 1300 Mpa		Yield Strength 910 Mpa		Elongation % 27			Hardness (HRC) 35				

X750 activated tungsten inert gas (A-TIG) sources. Comparative studies were conducted on the microstructure and mechanical properties under both welded and post-weld heat-treated conditions<sup>11</sup>.

Stephenson *et al.* described the preliminary results of supercritical CO<sub>2</sub>-based minimum quantity lubrication (scCO<sub>2</sub> MQL) in an external turning operation on an Inconel 750 alloy. Results were improved by the use of scCO<sub>2</sub> MQL to improve lubrication, as well as improving predominant wear mechanisms, such as rapid notch wear and crater wear, compared to water-based flood coolant when turning Inconel 750 and similar nickel alloys<sup>12</sup>. Venkatesan *et al.* aimed to compare tool wear and cheek and nose wear of the cutting tool depending on the machining time when dry turning Inconel X750 and Waspaloy in their work. The wear rate ceases to increase beyond a stage when Inconel X-750 is turning at speeds of 75 m/min and 100 m/min.<sup>13</sup> Studies with Inconel X 750 show that cutting tool wear<sup>12-13</sup>, cooling conditions<sup>12</sup> and welded joints<sup>11</sup> have previously been evaluated. The original value of this study is to investigate the relationship of cutting forces and surface roughness to processing parameters in dry turning conditions. As a result of this, the aim is to contribute to the literature on Inconel X750. Furthermore, the scope of the study was expanded by examining cutting tool wear and chip formation.

**Methods**

The chemical composition and mechanical properties of work piece material<sup>14</sup> is shown in Table 1. The workpiece used in the experiments is Ø 40×180 mm. The turning tests were conducted in dry conditions on JOHNFORD T35 CNC lathe maximum power of 10 kW (FANUC control). The PVD TiAlN-TiN coated carbide inserts (SNMG 120404 FG TT5080 which fabricated by TaeguTec were used in turning tests. The inserts were clamped onto DSBNR-2525-M12 tool holder. A KISTLER 9257B piezoelectric dynamometer mounted on the CNC lathe was used to measure components of cutting forces. Values of surface roughness (R<sub>a</sub>) were measured with TIME TR-200 roughness meter with a

Table 2 — Turning parameters of Inconel X750

Machining Parameters	levels			
	1	2	3	4
Cutting Speed, V <sub>c</sub> (m/min)	40	60	80	100
Feed rate, f (mm/rev)	0.1	0.15	0.2	
Depth of Cut (mm)	1			

cut-off length of 0.8 mm. After each turning test, surface roughness was measured at intervals of 120° on outer diameter surface. The wear formed on cutting inserts were analysed by Insize digital microscope. Wear which occurring in constant chip removal volume was used in order to evaluating of the tool wear. Besides, tool wear and mechanism type were examined by using scanning electron microscope (SEM). Machining parameters and their levels used in the machining tests are given in Table 2.

**Results and Discussion**

**Cutting Forces**

Changes in cutting force components according to feed rate are given in Figure 1 for four different cutting speeds. It is seen that the cutting force components (Main cutting force (F<sub>c</sub>), feed force (F<sub>f</sub>) and passive force (F<sub>p</sub>) increase with an increase in the feed rate for all four cutting speeds. This situation is inevitable because of the increasing size of the chip section<sup>15-16</sup>. When the graphs are evaluated in terms of cutting speed values, it is seen that F<sub>p</sub> and F<sub>f</sub> cutting force components do not change significantly. Increasing cutting speed slightly reduces F<sub>c</sub>. Increased temperature at the cutting zone with increasing cutting speed will reduce the yield point, thus facilitating chip formation at the cutter<sup>15-19</sup>. The lowest value for the F<sub>c</sub> cutting force component was measured to be 343.65 N under an 80 m/min cutting speed and an 0.1 mm/rev feed rate. The highest F<sub>c</sub> was measured to be 635.93 N at a cutting speed of 40 m/min and at an 0.2 mm/rev feed rate. According to the results, it can be said that a combination of low cutting speed and high feed rate results in a high F<sub>c</sub> value<sup>15-16</sup>.

**Surface roughness**

Changes in the surface roughness value (Ra) according to the feed rate (a) and cutting speed (b) are

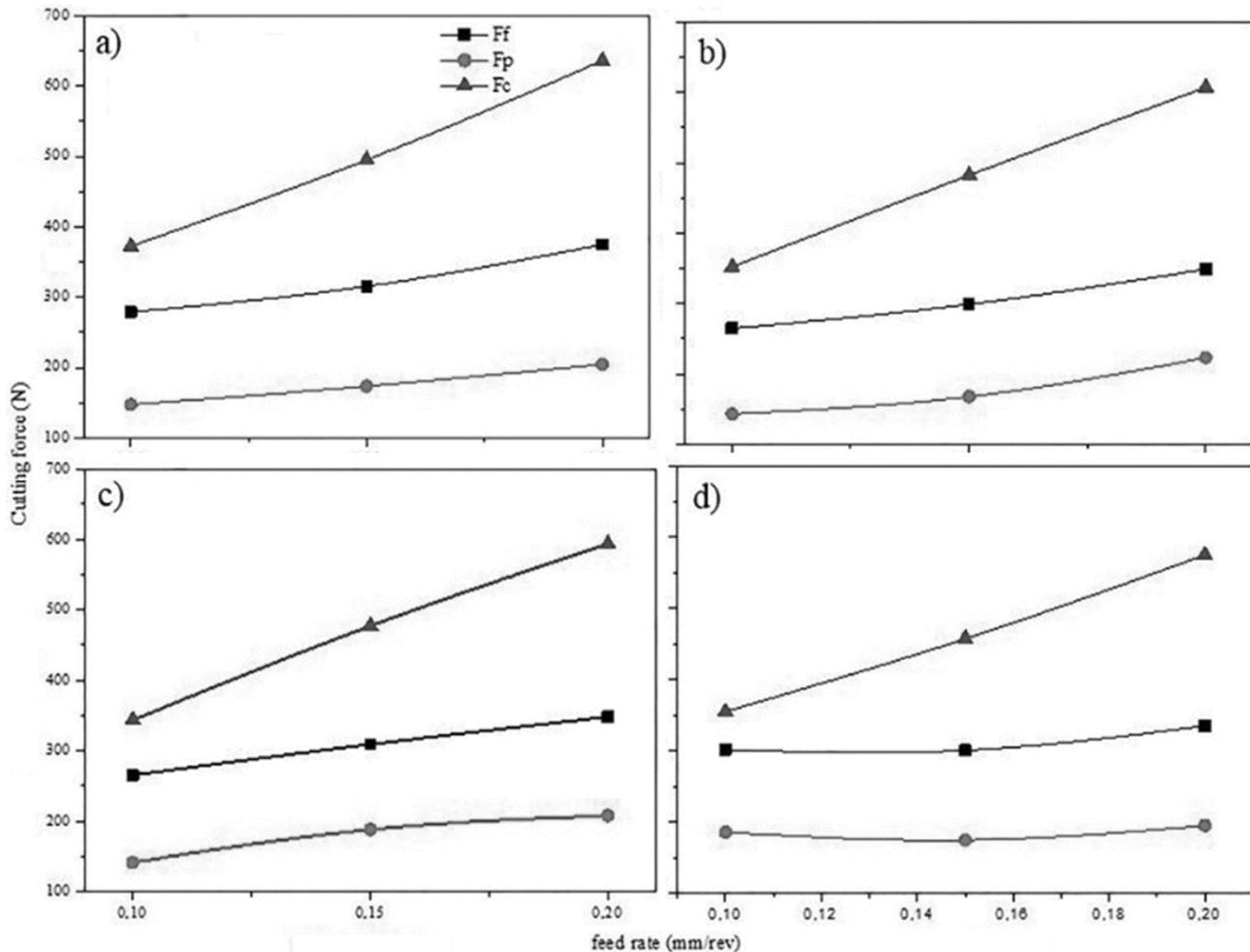


Fig. 1 — Changing of the cutting force components versus feed rate Vc=40m/min, b) Vc=60m/min, c) Vc=80m/min, d) Vc=100m/min

given in Figure 2. Increasing the value of the feed rate in both turning and milling operations increases the surface roughness value. With an increase in the feed rate, the increase in the chip section and volume of chips to be deformed has a disruptive effect on the surface<sup>20-22</sup>. In Figure 2a, Ra values increased with an increase in the feed rate value at all cutting speed values. It is clear from the curves in Figure 2 that the feed rate value has a significant effect on Ra. The effect of cutting speed on Ra was not like the effect of the feed rate. An increase in cutting speed is expected to improve Ra to some degree. This is attributed to a rise in the cutting area temperature with increasing cutting speed that reduces the yield limit of the work piece material<sup>20-21</sup>. However, when turning workpiece materials that are difficult to process, the effect of cutting speed on Ra becomes complicated. Different wear mechanisms are activated and have a negative effect on the cutting tool and the cutting geometry.

These negative changes in cutting geometry cannot be considered to have an effect on the roughness of the machined surface. In addition, some investigators specified that increases in temperature due to increased cutting speed during machining with carbide cutting tools may increase roughness<sup>23</sup>. Referring to the curves in Figure 2b, Ra was reduced by increasing the cutting speed from 40 m/min to 60 m/min at a 0.1 and 0.2 mm/rev feed rate. The Ra value was increased as the feed rate increased from 60 m/min to 100 m/min at 0.2 mm/rev. Here, abrasion mechanisms occurring on the cutting tool may have played a role at increasing cutting speeds. It is important to understand that a stable built-up-edge (BUE) formation will change the cutting geometry. Increased friction with BUE formation could adversely affect the quality of the treated face<sup>24</sup>. The situation can be thought of as the cutting effect at a particular cutting speed becomes greater. The lowest

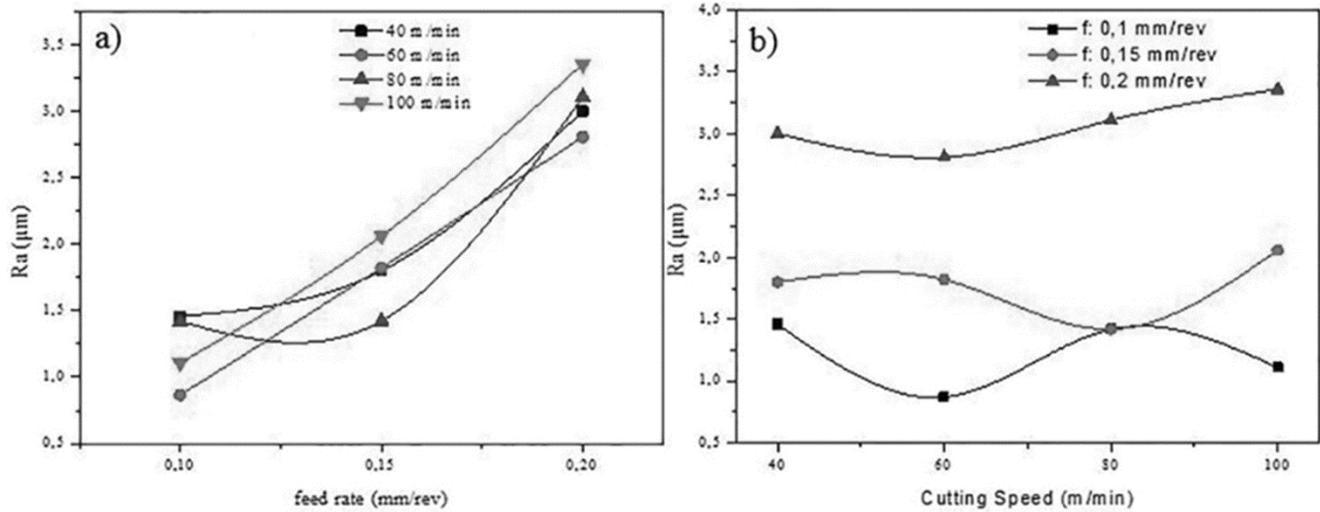


Fig. 2 — Changing of the Ra versus a) feed rate, b) cutting speed

Ra value was  $0.87 \mu\text{m}$  at a cutting speed of 60 m/min, and a feed rate of 0.1 mm/rev.

#### Tool Wear

In order to examine types of wear occurring in the cutting inserts, photographs of the cutting inserts were taken via an Insize electronic microscope. As a result of turning Inconel X750 alloy with PVD TiAlN-TiN coated carbide inserts, it can be seen that material adhesion and BUE occur for almost all test parameters when the cutting inserts are examined. Cutting speed, feed rate and depth of cut are important cutting parameters in terms of cutting tool wear and tool life<sup>25</sup>. Regarding wear at a constant depth of cut, the cutting speed is followed by the feed rate in order of importance. Scanning electron microscopy (SEM) images were taken to do a more detailed investigation of tool wear types and wear mechanisms. In the light of the experimental parameters and the information obtained from wear photograph, SEM images of cutter was taken used in the experiments where both cutting speed and feed rate are at their highest. It can be said that cutting conditions are challenging and the risk of abrasion is highest at these parameters. SEM images for the cutting insert used in the turning experiment for  $V_c = 100 \text{ m/min}$  and  $f = 0.2 \text{ mm/rev}$  are shown in Figure 3. Looking at the images in this figure, it is seen that chip adhesions are at the forefront. BUE formations are clearly seen in images *b* and *c*. It is caused by the effect of the BUE adhesive wear mechanism and cutting some materials at low speeds. In addition, BUE is often seen in the machining of

ductile materials<sup>10</sup>. From time to time during the cutting process, the BUE form breaks and particles break apart from the cutter while separating. Because of repeated continuous cutting process periods, chipping occurs as a result of the BUE coming away from the cutting tool surface. Chipping can normally also be caused by mechanical vibrations from the machine spindle or component fixtures, overloads, high feed rates and cutting speed<sup>7</sup>. Thin layer-shaped melt chip adhesion and galling marks on the chip surface are seen in Figure 3 image *b*. In order to identify these traces, EDX analyzes were performed at points A specified in image *b*. According to the graphical and weight percentages of the analysis results, it was determined that these traces consisted of alloy elements such as Ni and Cr from the workpiece material structure. According to these results, it would be appropriate to refer to these marks as melt chip adhering or galling. Similar findings were found in some studies<sup>3</sup>. Nickel-based superalloys show a high chemical affinity with many cutting tool materials. They form an adhesive layer leading to diffusion wear<sup>5</sup>. Low thermal conductivity of nickel-based superalloy workpiece material and the high temperature of the cutting zone accelerate the effect of this adhesive wear mechanism<sup>6,13</sup>. When images *c* and *d* were viewed, flank wear was observed. Flank wear is a result of the abrasive wear mechanism. This can be related to the presence of hard carbide and oxide particles which may be present in the workpiece material<sup>5,13</sup>. The amount of flank wear present is far from the threshold limit with regard to the tool life criterion. Small particle breaks

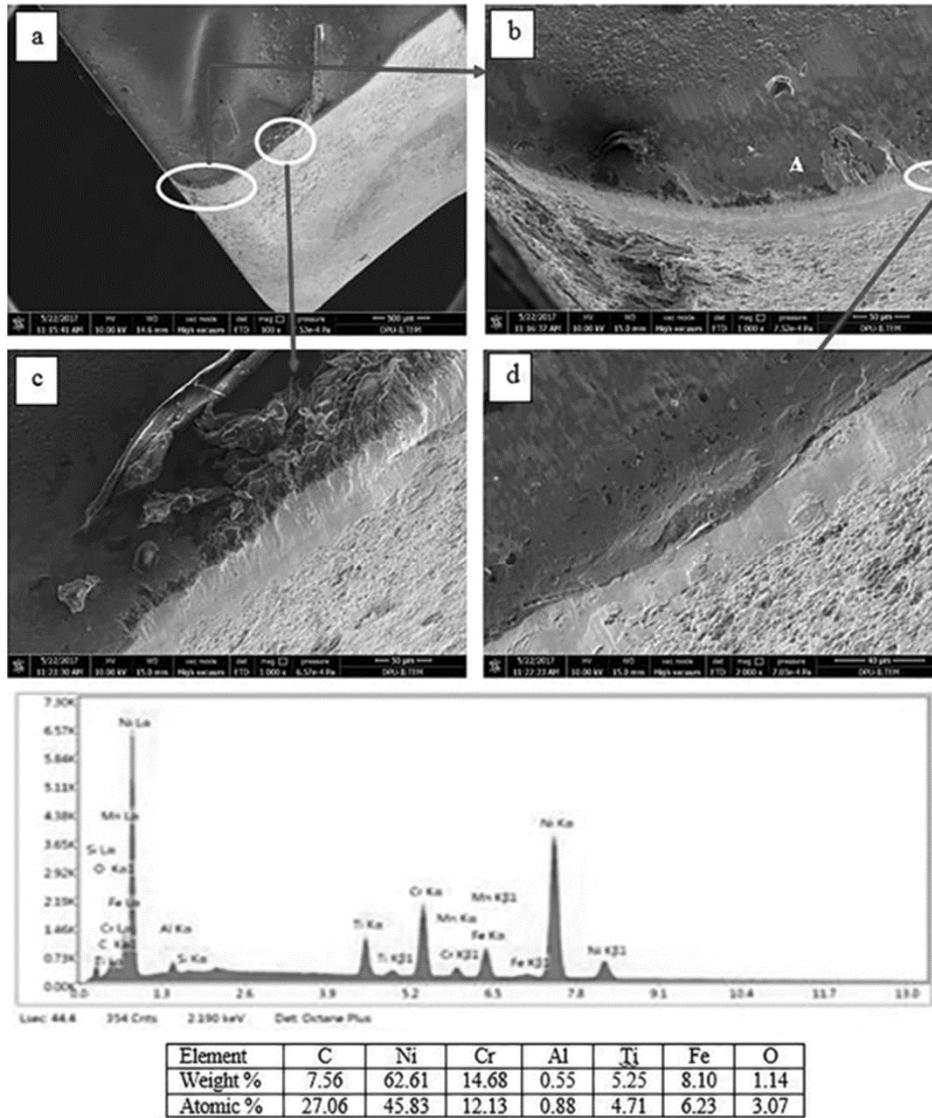


Fig. 3 — SEM images and EDX results of point “A” of wears on cutting insert ( $V_c$ : 100 m/min.,  $f$ : 0.2 mm/rev.).

were also observed in the same regions. In light of the above, the ideal parameters for cutting force, surface roughness and tool wear which are determined by evaluation criteria for turning Inconel X750 alloy with PVD TiAlN-TiN coated carbide inserts are 60 m/min for the cutting speed and 0.1 mm/rev for the feed rate. As a result of the evaluation criteria for this parameter, it was observed that the lowest value for  $R_a$  was 0.87, the approximate minimum value was 352.11 N for the cutting force, with relatively less BUE.

**Conclusions**

In this research, cutting forces, cutting tool wear, surface roughness and chip formation were investigated experimentally in dry turning of Inconel

X-750 super alloy using coated carbide cutting tool. The results obtained from turning tests are given in below;

- The value of the  $F_c$ ,  $F_f$  and  $F_p$  cutting force components increased with increasing feed rate at all four cutting speeds. This shows that increased cutting speed reduced the  $F_c$  slightly. The most significant reduction was observed at a feed rate of 0.2 mm/rev. Low cutting speed and high feed rate created high  $F_c$  and  $F_f$  values.
- The feed value was significantly influential on the  $R_a$ , and  $R_a$  values increased with an increase in the feed rate. The effect of cutting speed on  $R_a$  was less than the effect of the feed rate. Raised  $R_a$  values were observed in experiments with BUE,

due to stable BUE formations changing the cutting geometry.

- It was seen in the SEM and EDX photographs that the prominent wear mechanisms were adhesive, abrasive and, to a lesser degree, diffusion.

## References

- 1 Antonialli A Í S, Magri A & Diniz A E, Tool life and tool wear in taper turning of a nickel-based superalloy, *Int J Adv Manuf Technol*, **87** (2016) 2023-2032.
- 2 Motorcu A R, Kus A & Durgun I, The evaluation of the effects of control factors on surface roughness in the drilling of Waspaloy superalloy, *Measurement*, **58** (2014) 394-408.
- 3 Hao Z P, Fan Y H, Lin Q & Yu Z X, Wear characteristics and wear control method of PVD-coated carbide tool in turning Inconel 718, *Int J Adv Manuf Technol*, **78** (2015) 1329-1336.
- 4 Lotfi M, Jahanbakhsh M & Farid A A, Wear estimation of ceramic and coated carbide tools in turning of Inconel 625: 3D FE analysis, *Tribology International*, **99** (2016) 107-116.
- 5 Sharman A R C, Hughes J I & Ridgway K, The effect of tool nose radius on surface integrity and residual stresses when turning Inconel 718TM, *J Mater Proces Technol*, **216** (2015) 123-132.
- 6 Petrů J, Zlámál, T, Čep R, Sadílek M & Stančeková D, The effect of feed rate on durability and wear of exchangeable cutting inserts during cutting Ni-625, *Tehnički vjesnik*, **24 -1** (2017) 1-6.
- 7 Xavior M A, Manohar M, Jeyapandiarajan P & Patil M M, Tool wear assessment during machining of inconel 718, *13th Global Congress on Manuf and Manage* (Zhengzhou; China) 2017, 1000 – 1008.
- 8 Koseki S, Inoue K, Morito S, Ohba, T & Usuki H, Comparison of TiN-coated tools using CVD and PVD processes during continuous cutting of Ni-based superalloys, *Surface & Coatings Technology*, **283** (2015) 353-363.
- 9 Thakur A, Gangopadhyay S & Maity K P, Effect of cutting speed and CVD multilayer coating on machinability of Inconel 825, *Surface Engineering*, **30 -7** (2014) 516-523.
- 10 Sarikaya M, Yılmaz V & Güllü A, Analysis of cutting parameters and cooling/lubrication methods for sustainable machining in turning of Haynes 25 superalloy, *J Cleaner Produc*, **133** (2016) 172-181.
- 11 Ramkumar K D, Ramanand R, Ameer A, Simon K A & Arivazhagan N, Effect of post weld heat treatment on the microstructure and tensile properties of activated flux TIG welds of Inconel X750, *Mater Sci & Eng A*, **658** (2016) 326-338.
- 12 Stephenson D A, Skerlos S J, King A S & Supekar S D, Rough turning Inconel 750 with supercritical CO<sub>2</sub>-based minimum quantity lubrication, *J Mater Proces Technol*, **214** (2014) 673- 680.
- 13 Venkatesan K, Patel J K, Raval G V & Shah H V, A Comparative study of tool wears in dry turning of Inconel X-750 and Waspaloy, *Mater Today: Proc*, **5** (2018) 13429–13437.
- 14 Metals S, INCONEL® alloy X-750.
- 15 Tazehkandi A H, Pilehvarian F & Davoodi B, Experimental investigation on removing cutting fluid from turning of Inconel 725 with coated carbide tools, *J Cleaner Produc*, **80** (2014) 271-281.
- 16 Tazehkandi A H, Shabgard M, Kiani G & Pilehvarian F, Investigation of the influences of polycrystalline cubic boron nitride (PCBN) tool on the reduction of cutting fluid consumption and increase of machining parameters range in turning Inconel 783 using spray mode of cutting fluid with compressed air, *J Cleaner Produc*, **135** (2016) 1637-1649.
- 17 Tebaldo V, Confiengo G G & Faga M G, Sustainability in machining: “Eco-friendly” turning of Inconel 718 surface characterisation and economic analysis, *J Cleaner Produc*, **140** (2017) 1567-1577.
- 18 Ulas H B & Ozkan M T, Turning processes investigation of materials austenitic, martensitic and duplex stainless steels and prediction of cutting forces using artificial neural network (ANN) techniques, *Indian J Eng Mater Sci*, **26** (2019), 93-104.
- 19 Arulkirubakaran D, Balasubramanian K, Raju R, Palanisamy D & Manikandan N, Machinability studies on precipitation hardened stainless steel using cryo-treated textured carbide inserts, *J Sci Ind Res*, **78** (2019), 216-222.
- 20 Kumar S, Singh D & Kalsi N K, Experimental investigations of surface roughness of inconel 718 under different machining conditions, *5th Int Conf Mater Proces Charac* (Hyderabad, India) 2017, 1179-1185.
- 21 Paturi U M R, Maddu Y R, Maruri R R & Narala S K R, Measurement and analysis of surface roughness in WS<sub>2</sub> solid lubricant assisted minimum quantity lubrication (MQL) turning of Inconel 718, *13th Glob Conf Sust Manuf, Procedia CIRP*, (Ho Chi Minh City, Vietnam) 2016, 138-143.
- 22 Kumar R, Sahoo A K, Mishra P C & Das R K, Performance assessment of air-water and TiO<sub>2</sub> nanofluid mist spray cooling during turning hardened AISI D2 steel, *Indian J Eng Mater Sci*, **26** (2019), 235-253.
- 23 Xavior M A, Patil M, Maiti A, Raj M & Lohia N, Machinability studies on Inconel 718, *I ConAMMA-2016*, (Bangalore, India) 2016, 1-8.
- 24 Thakur A, Mohanty A & Gangopadhyay S, Comparative study of surface integrity aspects of Incoloy 825 during machining with uncoated and CVD multilayer coated inserts, *App Surf Sci*, **320** (2014) 829-837.
- 25 Debnath S, Reddy M M & Yi Q S, Influence of cutting fluid conditions and cutting parameters on surface roughness and tool wear in turning process using Taguchi method, *Measurement*, **78** (2016) 111-119.