Machinability Investigation of Inconel 657 in High-speed Turning

Amir Hossein Khoei[1], Hasan Fathi[1], Masoud Farahnakian[1]*, Mohammad Reza Razfar[1]
[1]Faculty of Mechanical Engineering, Amirkabir University of Technology, Tehran, Iran
*Email of Corresponding Author: farahnakian@aut.ac.ir
Received: 29 April, 2014; Accepted: 3 August, 2014

Abstract
A high strength nickel chromium alloy (50Cr-50Ni-Nb alloy), commonly referred to as IN-657, is specifically used for components in furnaces which are fired by low grade fuel oils containing high levels of vanadium, sodium and sulphur. The purpose of this study is to experimentally investigate the effect of machining parameters on mach inability in turning of Inconel 657. The considered parameters were cutting speed, feed and tool material. Cutting force components, tool flank wear and surface roughness were measured based on design of experiments, and then analysis of variance was performed. Experimental results show that tool wear of CBN tools is 50 %lower than that of carbide tools. The Tool material with percentage contribution of 48% and 56% is the main parameter that influences the cutting forces and the flank wear, respectively. Also, the cutting speed with percentage contribution of 48% is the main parameter that effects the surface roughness. The lowest surface roughness is attained by the cutting speed of 250 m/min and the feed of 0.05 mm/rev by the CBN tool.

Keywords
Inconel 657, Machinability, Cutting force, Tool flank wear, Surface roughness.

1. Introduction
Nickel-based alloys play an import role in aerospace industry and steam power because they exhibit a good combination of the mechanical properties and heat resistance at high temperature. In petrochemical and power steam plants, economical criteria lead to the adoption of low cost fuels, characterized by highly corrosive ashes. Vanadium Pentoxide (V_2O_5) and alkali metal sulfates are the primary ash constituents responsible for oil ash corrosion. Although a number of methods have been used or proposed to mitigate oil ash corrosion, it is best controlled by the selection of proper alloys. The 50/50 type nickel-chromium alloys are well established materials for resisting oil ash corrosion.
At temperature ranging from 900 to 1090^{o}C, the higher chromium alloy is recommended. However, due to its superiority as cast ductility, machinability, and weldability, the 50Ni-50Cr alloy is used in the majority of applications in power plants, oil refinery heaters, and marine boiler involving temperatures lower than about 900^{o}C. A high strength nickel chromium alloy, commonly referred to as IN-657, has been developed that provides the same good resistance to fuel oil ash corrosion as the standard 50Ni-50Cr alloys, but with improved creep and stress rupture properties [1]. For manufacturing of these parts, first the Inconel 657 partsare casted, and then in order to reach the required tolerance and surface roughness, workpieces are machined.
Nickel alloys, like austenitic stainless steel, work harden rapidly. The high pressures developed during machining produce a hardening effect that retards further machining and may also cause distortion in those parts that have small cross sections [2-5]. There is little information available on

the machining of Inconels, particularly Inconel 657. Although there are some papers that describe the machinability of Inconel 718.

In 1993, Narutakiet al. presented an experimental study on the high speed machining for Inconel 718 with Sic whisker reinforced alumina, silicon nitride and TIC added alumina ceramic tools. The SIC whisker tool showed the best performance in terms of notch wear at the cutting speed of under 300dmin. However, when the speed exceeded100dmin, the Tic added alumina ceramic tool showed the smallest wear compared to other tools [6]. Thakur et al. carried out an experimental work to understand the behavior of super alloy Inconel 718 when machined with cemented tungsten carbide (K20) insert tool. Their results indicated that the above-mentioned mach inability indices are important and necessary to assess the mach inability of Inconel 718material effectively during high-speed machining [7].

Li et al. investigated the machinability of Inconel 718 by using carbide coated tools and ceramic tools with different tool rake angle. The optimum cutting speed was calculated for each tool, based on the Taylor tool life's equation and minimum production time. They found that the important wear mechanisms of Nickel alloy are adhesion and chipping [8]. Altin studied the effects of the cutting speed on tool wear and tool life when machining Inconel 718. A series of tool life experiments has been carried out using silicon nitrite based and whisker reinforced ceramic tools. The obtained results of these experiments show that crater and flank wears are usually dominant wear types in ceramic square type inserts, while flank and notch wear are dominant in round type inserts [9].

This paper presents comparison of the cutting performance of several cemented carbide and CBN tools in finish turning of Inconel 657. The evaluation of the tools was based on three criteria: cutting forces, surface roughness, and tool life. In order to attain minimum operation numbers and decrease the cost of machining, an experimental scheme was arranged by using Taguchi method. The considered parameters were cutting speed and feed. Cutting force components, surface roughness and flank wear were measured, and then analysis of variance was performed.

2. Experimental details

2.1. Material

Three bars of Inconel 657 with the diameter of 120 mm and length of 180 mm were used in the experiments. The chemical composition of Inconel 657 is listed in table 1.

Table 1. Chemical composition of Inconel 657

Chemical composition	*Ni*	*Cr*	*Nb*	*Fe*	*Si*
Percentage %	*45.98*	*50.95*	*2.24*	*0.57*	*0.25*

Fig.1. Actual machining operation setup

2.2. Tool and machine tools

The machining experiments were executed for finishing longitudinal turning on a high precision geared lathe (Machinsazi-Tabriz TN50BR Universal) with 5.5 kW spindle motor and maximum spindle speed of 2000 rpm. The actual machining operation setup is illustrated in figure 1. The used inserts are cemented tungsten carbide with CVD (TiN/TiCN/Al2O3/TiN) coated and TN7125 grade. The CBN tools are 3NUTNGA160408-BN700.The tool-holder was MTJNR 20x20 k16 (AKKO Co.). All inserts had similar geometries with zero obliquity and approach angle (e.g. orthogonal cutting) and without chip break.

2.3. Experimental setup

Turning dynamometer (9121 model, KISTLER Co.) with three components was utilized to measure the cutting forces. The dynamometer was fixed on the tool post and the tool-holder was mounted on it. During the cutting operation, forces applied on the tool are converted to signals by dynamometer and amplified by charge amplifier. The amplified signals are then transferred to data acquisition card to be evaluated by DynoWare software in computer. The surface roughness tool of SURTRONIC 3+ from

Taylor–Hobson Company was used to measure the Ra of each experiment. The resolution of the instrument resolution was 0.01 μm, and the tracing velocity was fixed at 0.5 mm/s.

Tool wear measurements were carried out using a digital microscope (Dino-Lite, AM-413ZT). For each measurement of tool wear, a fresh tip was used. Each cutting tip was subjected to high-speed turning for a specified time period before measuring the tool wear (flank wear).

2.4. Design of experiments

Cutting parameters are selected based on similar studies on the machinability of similar alloys such as Inconel 718 and the recommended data of tool manufacture catalogues.

In this work, two-nine samples based on full factorial design of the experiments employing three-level for feed, three-level for cutting speed for each tool are given in Table 2. A constant depth of cut of 0.5 mm was used because of rigidity of the machine tool and the tool holder.

Table 2. Levels of variables

	Variables	level 1	level 2	level 3
Tool	Tool	cBN tool	Carbide tool	-
f	Feed (mm/tooth)	0.05	0.11	0.16
Vc	Cutting speed (m/min)	60	125	250

3. Results and discussion

The purpose of this paper is the investigation of cutting parameters such as cutting speed, feed on the two different tools on the cutting force, surface roughness and tool wear and interaction of parameters to find the optimal condition of each tool.

3.1 Influence of the cutting parameters on cutting force (Fw)

Fig. 2 shows the measurement of three components of cutting force while turning of Inconel 657 by using the CBN tool.In this study, the analysis of variance has been employed by Minitab to investigate the influence of cutting parameters on the cutting force components (Tables 3). This analysis was carried out for a level of significance of 5%, i.e., for a level of confidence of 95%. The sensitivity of the cutting force with respect to the above parameters is illustrated in the last column of Table 3. It indicates the degree of influence of each parameter on the results. It can be seen that the tool material of 48%, feed of 39% and cutting speed of 8% are the significant factors.

Among the three parameters, feed and tool material have more influence on the cutting force. By considering the interaction of the main parameter with the cutting force, it can be seen that with increase of feed, the cutting force increases and with decrease of cutting speed the cutting force decreases. The cutting force of the CBN tool is less than the carbide tool. Fig. 3 shows that the cutting force decreases with the increases in cutting speed due to the thermal softening which changes the shear angle, and thus the necessary plastic deformation. Cutting forces increase with the increase in feed, due to an increase in the ratio of the chips removed from the work piece material.

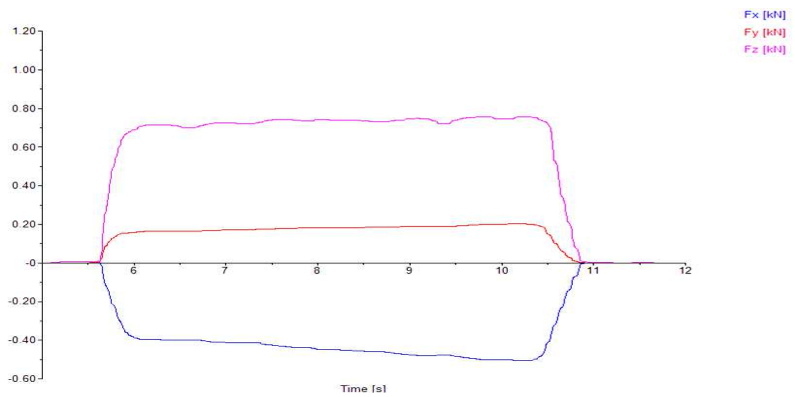


Fig. .2. Measurement of three components of cutting force during turning, V_c=125 m/min and f= 0.16 mm/rev

Table 3. ANOVA for cutting force (Fw)

Source	DF	Seq SS	AdjMS	F	P	C (%)
V_c(m/min)	2	0.18471	0.03249	4.59	0.028	8.1
f(mm/rev)	2	0.89774	0.44887	63.47	0	39.2
Tool	1	1.10153	1.10153	155.76	0	48.1
Error	15	0.10608	0.00707			4.6
Total	20	2.29006				

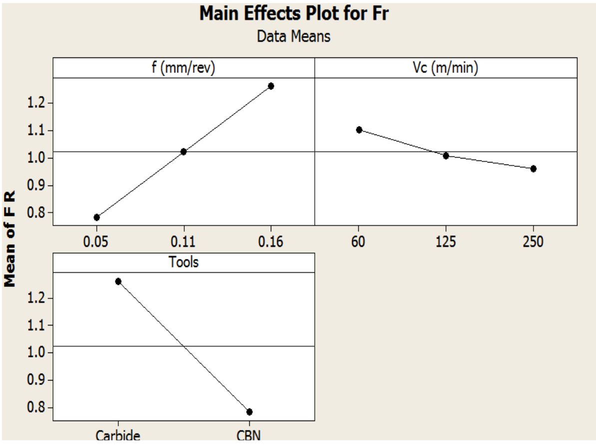


Fig.3.Main effect of parameters on the cutting force

3.2 Influence of the cutting parameters on tool flank wear

The ANOVA for V_B shown in Table 4 indicates that contributions of tool material, feed and cutting speed are 56%, 19% and 15%, respectively. The effect of tool material is significant among other parameters. Fig. 4 shows that the flank wear increases with the increases in cutting speed and feed. Also, the tool wear in the CBN tool is less than the carbide tool. By increasing the cutting speed above the 125 m/min, the tool wear in both tools decreases due to decrease of the built up edge. The effect of the cutting speed and tool on the tool wear is more than feed.

Table 4. ANOVA for tool flank wear (V_B)

Source	DF	Seq SS	AdjMS	F	P	C (%)
V_c(m/min)	2	0.008287	0.004144	2.43	0.13	15.7
f(mm/rev)	2	0.010487	0.005243	3.08	0.053	19.8
Tool	1	0.029687	0.029687	0.001	0.001	56.1
Error	12	0.004437	0.001703			8.4
Total	17	0.052898				

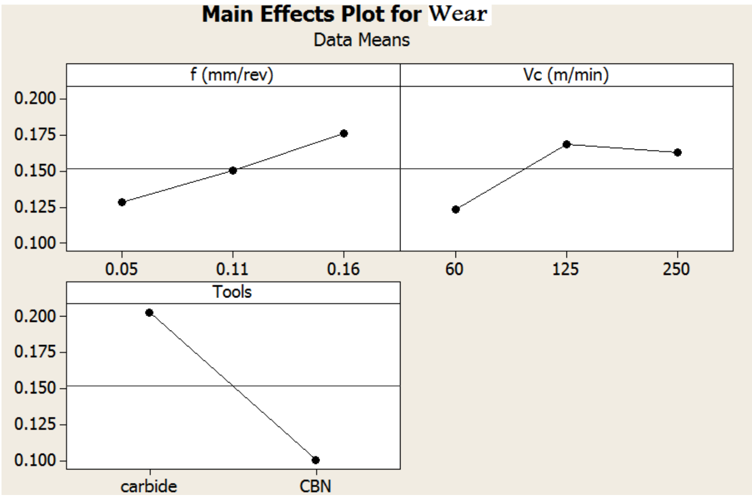
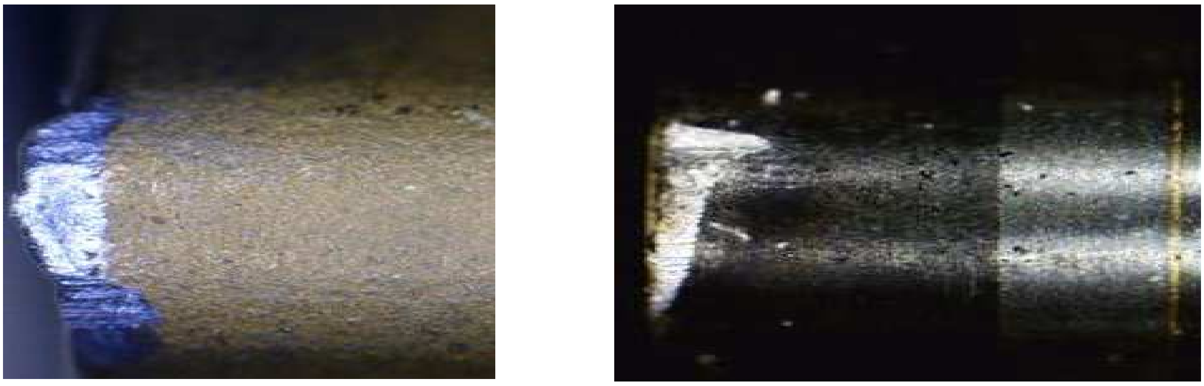


Fig.4. Main effect of parameters on tool flank wear

The effect of cutting speed is more than feed on tool flank wear. Two sample of tool wear are shown in Fig.5. By increasing the cutting speed, the temperature at cutting zone and contact zone increase due to more adiabatic heat transfer. By increasing the temperature, the hardness of tool decreases and results in the increase of the wear rate. It could also be observed from this figure that the tool wear increased with the increase in feed. This could also be due to the fact that more severe deformation and more load at high feeds result in the increased wear rate.



WC tool CBN tool

Fig.5. Tool wear of the carbide tool andthe CBN tool ,Vc=250 m/min, f=0.05 mm/rev, zoom=200

3.3 Influence of the cutting parameters on surface roughness

The ANOVA for Ra shown in Table 5 indicates that contributions of cutting speed, feed, and tool material are 48%, 24% and 18%, respectively. Turning at low feed usually leads to the generation of low surface roughness. As shown in Fig. 6, while the Vc increases, surface roughness is reduced. The surface roughness of the CBN tool is lower than the carbide tool. The minimum surface roughness is related to the CBN tool at cutting speed of 250 m/min and feed of 0.05 mm/rev.

Table 5.ANOVA for surface roughness (Ra)

Source	DF	Seq SS	AdjMS	F	P	C (%)
V_c (m/min)	2	2.919	1.1903	7.18	0.007	48.6
f (mm/rev)	2	1.4795	0.7397	4.46	0.03	24.6
Tool	1	1.1194	1.1194	6.75	0.02	18.6
Error	15	0.4879	0.1659			8.1
Total	20	6.0058				

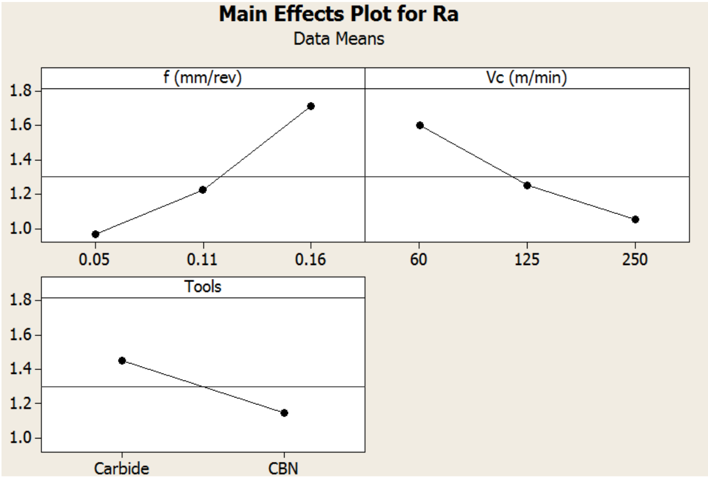


Fig.6 Main effect of parameters on surface roughness

4. Conclusions

Based on the experimental results presented above, the following conclusions can be drawn from turning of nickel chrome:

The contribution percentage of the tool material, feed, and cutting speed for cutting force were 48, 39, and8, respectively. Cutting forces increase when the feed increases, and increase in the cutting speed leads to decrease in cutting forces. In other words, with a higher cutting speed and a lower feed, it is possible to obtain lower cutting forces. The cutting force of the CBN tool is less than the carbide tool.

The contribution percentage of tool material, feed and cutting speed for tool flank wear were 59, 19, and15, respectively. The flank wear increases with the increases in the cutting speed and feed. Also, the tool wear in the CBN tool is less than the carbide tool. The effect of the cutting speed and tool on the tool wear is more than feed. The lowest surface roughness is attained by the cutting speed of 250 m/min and the feed of 0.05 mm/rev by the CBN tool.

References

[1] Caironi, G., Gariboldi, E., Silva, G. and Vedani, M.1993. Influence of heat treatments on the mechanical properties and microstructure of a 50Cr-50Ni niobium containing alloy, Journal de Physique; 3, 111-120.

[2] Aaron, T.E, et al. 1989.Metals Handbook. 9th ed. ASM Handbook Committee, 835-838.

[3] Kasim, M.S.,CheHaron, C.H., Ghani, J.A.,Sulaiman,M.A. andYazid, M.Z.A. 2013. Wear mechanism and notch wear location prediction model in ball nose end milling of Inconel 718.Wear;302(1–2), 1171–1179.

[4] Jawaid, A., Koksal, S. and Sharif. S. 2001. Cutting performance and wearcharacteristics of PVD coated and uncoated carbide tools in facemilling Inconel 718 aerospace alloy. Journal of Material Process Technology; 116, 2–9

[5] Kitagawa, T., Kubo, A. and Maekawa, K. 1997. Temperature and wearof cutting tools in high-speed machining of Inconel 718 and Ti–6Al–6V–2Sn. Wear; 202, 142–148.

[6] Narutaki, N., Yamane, Y. and Kitagawa,T. 1993. High-speed Machining of Inconel718 with Ceramic Tools, Annals of the ClRP, 4, 103-106.

[7] Thakur, D., Ramamoorthy,B. and Vijayaraghavan, L. 2009. Optimization of high speed turning parameters of superalloy Inconel 718 material using Taguchi technique. Indian Journal of Engineering and Materials Sciences;1, 44-50.

[8] Li,L., He, N., Wang, M. and Wang, Z.G. 2009. High speed cutting of Inconel 718 with coated carbide and ceramic inserts. Journal of materials processing technology; 129, 127-130.

[9] Altin. A., Nalbant, M. and Taskesen, A. 2007. The effects of cutting speed on tool wear and tool life when machining Inconel 718 with ceramic tools, Materials and Design; 28 ,2518–2522.