Springer

KSME

Journal of Mechanical Science and Technology 24 (5) (2010) 1053~1059
www.springerlink.com/content/1738-494x
DOI 10.1007/s12206-010-0319-2

Study of cutting speed on surface roughness and chip formation when machining nickel-based alloy †

Basim A. Khidhir* and Bashir Mohamed

Department of Mechanical Engineering, Faculty of Engineering, Universiti Tenaga Nasional, Malaysia

(Manuscript Received March 30, 2009; Revised November 24, 2009; Accepted February 18, 2010)

Abstract

Nickel- based alloy is difficult-to-machine because of its low thermal diffusive property and high strength at higher temperature. The machinability of nickel- based Hastelloy C-276 in turning operations has been carried out using different types of inserts under dry conditions on a computer numerical control (CNC) turning machine at different stages of cutting speed. The effects of cutting speed on surface roughness have been investigated. This study explores the types of wear caused by the effect of cutting speed on coated and uncoated carbide inserts. In addition, the effect of burr formation is investigated. The chip burr is found to have different shapes at lower speeds. Triangles and squares have been noticed for both coated and uncoated tips as well. The conclusion from this study is that the transition from thick continuous chip to wider discontinuous chip is caused by different types of inserts. The chip burr has a significant effect on tool damage starting in the line of depth-of-cut. For the coated insert tips, the burr disappears when the speed increases to above 150 m/min with the improvement of surface roughness; increasing the speed above the same limit for uncoated insert tips increases the chip burr size. The results of this study showed that the surface finish of nickel-based alloy is highly affected by the insert type with respect to cutting speed changes and its effect on chip burr formation and tool failure.

Keywords: Cutting speed; Surface roughness; Chip formation; Nickel-based alloy

1. Introduction

Increasing the productivity and the quality of the machined parts are the main challenges faced by the manufacturing industry. Modern cutting tools allow cutting at high speeds, thus increasing the volume of chips removed per unit time. Such objective requires better management of the machining system corresponding to cutting tool and machine tool-workpiece combination in order to move toward a more rapid metal removal rate. Exploring higher cutting speeds depends to a great extent on the cutting tool material [1]. General information on operating parameters employed when turning nickel-based alloys are available in both academic [2-5] and industrial literature [6, 7]. From the very beginning, the development of an adequate predictive theory of the process was a major concern for all researchers. In relation to machining operations with defined cutting edges, workpiece surface integrity aspects are important when turning Inconel 718 with coated carbide cutting tools [8, 9]. The high temperature strength and high corrosion resistance of nickel-based alloys have led to their use in the manufacture of aircraft and space engines components considered by machinists as one of the most challenging fields due to the necessity of dealing with a complex set of material properties [10, 11]. These properties include: low thermal conductivity leading to increased temperatures at the tool point rake face, work-hardening tendency during machining, high thermal affinity to tool materials resulting in welding-adhesion of workpiece material to the cutting edge, and presence of hard abrasive particles (e.g. carbides, oxides) resulting in intense tool wear [12]. The heat generated during a cutting operation is the summation of plastic deformation involved in chip formation and the friction between tool and workpiece and between tool and chip [13]. In addition, for the majority of these metals, work hardening takes place rapidly. A hardened surface created during machining can result in depth-of-cut-line notching of the tool and may also compromise the fatigue strength and geometric accuracy of the part [14]. The geometry of the tool plays a big part in controlling wear. It must allow for chip removal in order to take the heat out with the chip. This study intend to investigate the effect of the cutting speed of different inserts coated and uncoated on surface finish and tool wear when machining of nickel-based alloys - 276.

† This paper was recommended for publication in revised form by Associate Editor Dae-Eun Kim
*Corresponding author. Tel.: +603 8921 2020, Fax.: +603 8928 7166
E-mail address: bak-time@hotmail.com

2. Experimental procedure

The machining tests were performed by single point, continuous turning of nickel-based alloy Hastelloy-276, specimen in cylindrical form on a CNC lathe machine. The workpiece specimen was 300 mm long and 57.15 mm in diameter divided into four parts of 20 mm length each with undercut between parts equaling to 3 mm width. The chemical composition and physical properties of the workpiece material are given in Tables 1 and 2 respectively.

Two different grades of cemented carbide cutting tool inserts of CCMT-12 and CNGN-12 were clamped mechanically for two rigid tool holders SCLCR and CCLNR-M12 respectively [15]. The cutting speeds used were 100, 150, 200, and 270 m/min the feed rate and the depth-of-cut were fixed at 0.2 mm/rev and 1.5 mm, respectively using a dry cutting process. Surface roughness measurement was carried out on the machined surfaces using a handheld Roughness Tester TR200 instrument, taking three measurements for each surface. The worn-out cutting tools were also examined under a Philips XL 30 ESEM type scanning electron microscope (SEM).

2.1 Workpiece surface roughness

Fig. 1 shows a surface roughness profile sample measured by the Roughness Tester TR200 instrument. Fig. 2 shows the relation of cutting speed versus surface roughness. Cutting speed is shown to have a significant influence on the surface roughness produced. The highest surface roughness value is observed at 150 m/min cutting speed using CCMT-12 coated insert and a very rough surface (exceeding Ra of 8 µm) with tool failure by removing a part of the main cutting edge when CNGN-12 uncoated insert is used beyond 200 m/min. The general trend in the curves of Fig. 2 for the CCMT-12 coated insert is that when cutting speed is increased from 100 to 150 m/min the surface roughness values increase slightly. This could be the effect of chatter or vibration which occurs at this cutting speed, thus explaining the increase of the value of surface roughness with the insert CCMT-12 (Fig. 2). After increasing the cutting speed beyond 150 m/min it decreases until a minimum value is reached beyond such increase for the insert type CNGN-12 uncoated insert, however the curve increases linearly by increasing the speed.

Table 1. Chemical composition.

Component	Weight %
Ni (Wt. %)	57
Co (Wt. %)	1.62
Cr (Wt. %)	15.44
Mo (Wt. %)	15.34
Fe (Wt. %)	5.43
W (Wt. %)	3.67
V (Wt. %)	0.41
Mn (Wt. %)	0.52
C (Wt. %)	0.004
Others (Wt. %)	Si < 0.02; P - 0.005; S < 0.01

Table 2. Physical properties.

Density	Electrical Resistively	Dynamic modulus of elasticity	Thermal conductivity	Specific heat
8.89 g/cm^3	1.3 µ Ω-m	229 MPa	10.2 W/m.K	427 J/Kg.K

2.2 Tool wear

Tool wear is an extremely important factor to be considered in machining. Cutting speeds considerably affect the temperature field in machining, which is characterized by an exceedingly high temperature. This temperature field strongly affects the physical properties of the cutting tool material such as toughness, chemical resistance and hot hardness. Hot hardness is the most critical property for resisting abrasive wear. At high temperature the tool material becomes soft and thus its ability to resist particle penetration and abrasive wear decreases significantly. The worn-out tool inserts used in the cutting tests of the present study were examined using SEM. These images have identified different wear areas on the tool rake and flank faces and have also shown that the tool wear mode changed when the cutting conditions changed from lower to higher speed. The flank wear was measured in this investigation using the conventional measurement technique according to ANSI/ASME B94.55M-1985–1995. The surfaces of the CCMT-12 and CNGN-12 used to machine the nickel-based alloy Haynes-276 workpiece material were ex-

Fig. 1. Surface roughness (Ra) profile chart sample for cutting speed of 100 m/min, feed rate of 0.2 mm, and depth of cut of 1.5 mm at Ra of 1.509 µm.

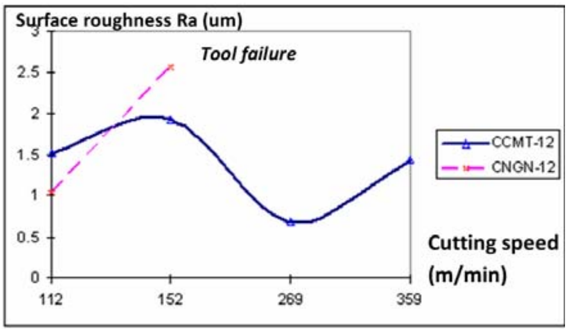


Fig. 2. Cutting speed versus surface roughness for turning nickel-based Hastelloy C-276 using CCMT-12 insert at a feed rate of 0.2 mm/rev and a depth-of-cut 1.5 mm.

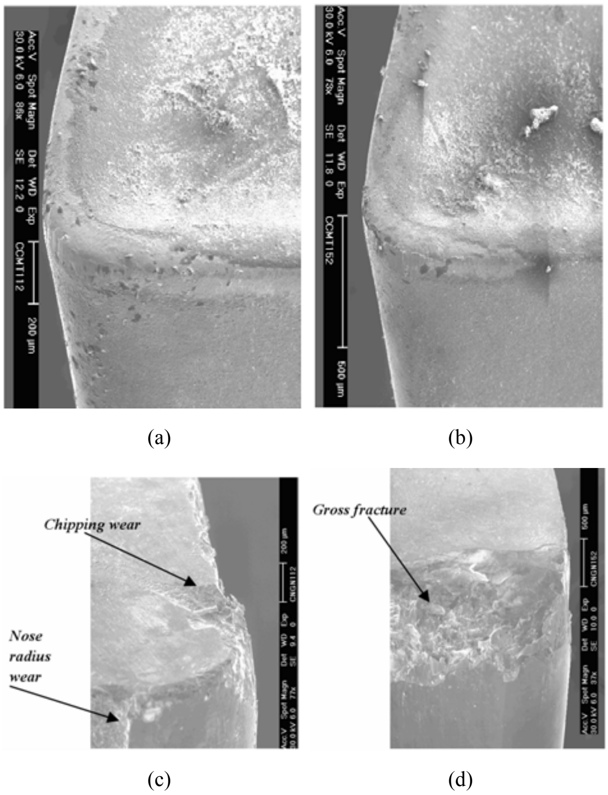


Fig. 3. SEM images showing the wear of the CCMT-12 after machining nickel-based alloys, Haynes-276 at (a) 100 m/min, and (b) 150 m/min, and CNGN-12 after machining nickel-based alloy, Haynes-276 at (c) 100 m/min and (d) 150 m/min cutting speeds.

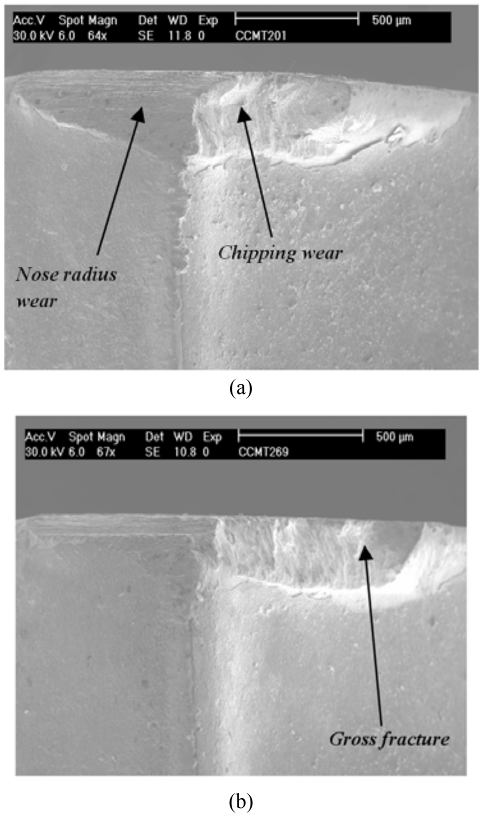


Fig. 4. SEM images showing the wear of the CCMT-12 after machining nickel-based alloy Hastelloy-276 (a) at 200 m/min, and (b) at 270 m/min.

amined by the SEM images of the worn-out cutting edges. It can be seen from these images that wear predominantly occurs in two regions during the tests at the depth-of-cut line and the nose radius, as shown in Figs. 3(a), 3(b), 3(c), and 3(d). The wear at the depth-of-cut line does not have any influence on the machined surface roughness [16]. However, the wear at the nose radius of cutting edge directly influences the machined surface roughness since the nose edge is in direct contact with the newly machined surface. Fig. 3(a) shows the form of nose radius wear for the speed of 100 m/min with another wear appearing when the speed changes to 150 m/min as a flank wear as indicated in Fig. 3(b). This explains the increasing of the value of surface roughness with insert CCMT-12 as shown in Fig. 2. When the SEM images in Figs. 3(c) and 3(d) are closely examined, the highest tool wear can be seen on the CNGN-12 insert type (Fig. 3(d)) used at the 150 m/min cutting speed compound with the highest surface roughness. However, further increasing in the cutting speed increases the extent of tool wear. In Fig. 3(c) flank wear and edge-chipping wear are seen on the edge of the cutting tool used at the 112 m/min cutting speed.

2.3 Rake angle and type of entry

One type of entry was used in the experiments for two rigid tool holders SCLCR and CCLNR with rake angles of 0^o and -6 respectively making an S-type entry [17].

From Figs. 3(a) and 3(b) both built-up-edge (BUE) and Flank wear appear with the cutting speed of 100 m/min to 150 m/min for the insert tip of CCMT–12 while different tool wear as chipping wear and gross wear associated with insert tip of CNGN–12 for the same cutting speed and totally wear-out after 150 m/min as shown in Fig. 3(d).

The chipping wear with gross fracture appears by increasing the speed in the range of 200 m/min and 270 m/min, respectively, as shown in Figs. 4(a) and 4(b) for the insert tip of CCMT–12. From the SEM images one can clearly notice that the chipping in Fig. 5(a) is mostly done on the clearance plane with less harm on the cutting edge, while gross fracture is extremely done on the rake face by removing a part from the cutting edge.

3. Simulation of tool temperature

Tool temperature is a key factor that accelerates the tool wear and limits cutting speed and productivity in nickel-based alloys machining. Experimental measurement of tool temperature is difficult. In contrast, the finite element simulation can provide a quick and accurate prediction of tool temperature under various cutting conditions. As such the effect of cutting speed on tool temperature was investigated. However, the sharp cutting edge was difficult to measure experimentally as

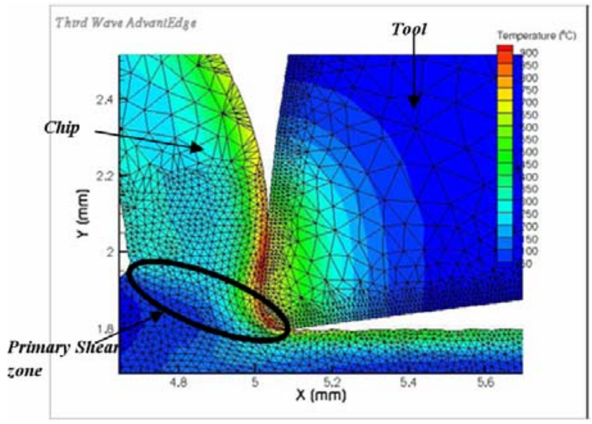


Fig. 5. Finite element simulated sample of machining Hastelloy-276 for a cutting speed of 270 m/min.

it was consistently changing during the machining process. The effect of cutting speed, rake angle, coatings, and peak tool temperature was nonetheless analyzed successfully. The process parameter for the selected example were 270- m/min cutting speed, 0.2-mm/rev feed, 1.5-mm depth cut, and 0.8-mm tool edge radius. The high temperature was concentrated around the straight major cutting edge and the round nose of the tool. Fig. 5 illustrates the temperature distribution of the chip in the tool-chip contact area. The highest temperature, about 980°C, is concentrated in regions near the nose and major cutting edges with peak temperature slightly higher than that of the tool.

3.1 Dimensions

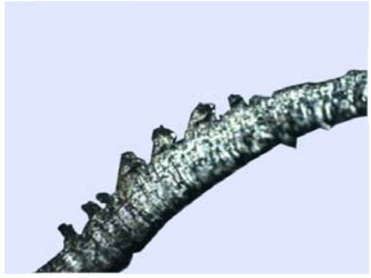
The workpiece used in the simulation model was 3 mm in length by 3 mm in height the tool 5 mm long and 3 mm high, the cutting edge radius is 0.8 mm the clearance angle is 7^o the rake angles are 0^o and -6 the feed 0.2 mm; and the cutting speeds 100, 150, 200, and 270 m/min respectively.

3.2 Mesh

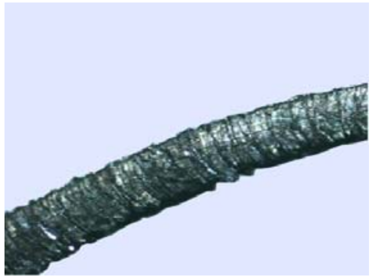
The mesh of the workpiece can be seen in Fig. 5; the remeshing technique used was the "advancing front quad" This mesh generator started by creating elements along the boundary of the given outline boundary. Mesh creation continued inward until the entire region was meshed. The number of elements used was about 6000 with the minimum element size set at 4μm. As seen in Fig. 5, a finer mesh was used around the tool tip, where the material separated. The tool was meshed with approximately 5000 elements with a minimum element size 3 μm. The element type used was node plain strain elements, with bilinear interpolation functions (four integration points) and reduced integration of the volumetric field.

4. Chip burr formation

The burr appeared on one side of the chip with a triangles shape for a cutting speed of 100 m/min as shown in Fig. 6(a), for the coated insert tip CCMT–12. It disappeared when the speed increased beyond 150 m/min as shown in Fig. 6(b). The burr also disappeared when the speed increase to 200 m/min as shown in Fig. 7(a). With further increase in cutting speed up to 250 m/min, the width of the chip increased, showing signs of saw teeth as shown in Fig. 7(b). This was caused by



(a)



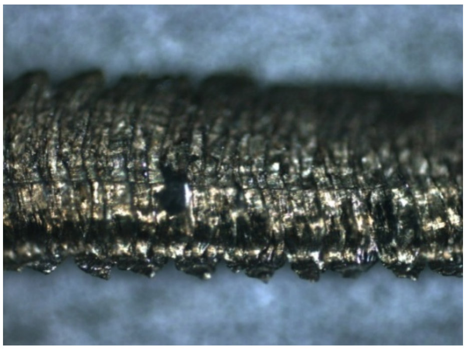
(b)

Fig. 6. Nickel-based alloy chip machined using coated insert tip CCMT–12 at different cutting speeds; (a) at 100 m/min, and (b) at 150 m/min.

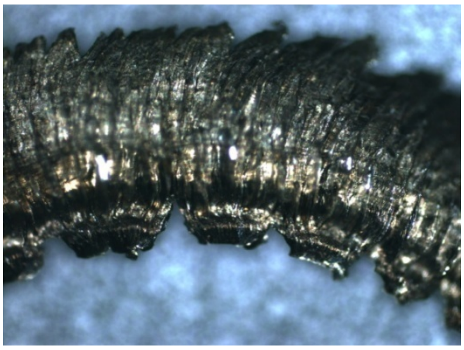
(a)

(b)

Fig. 7. Nickel-based alloy chip machined using coated insert tip CCMT–12 at different cutting speeds; (a) at 200 m/min and, (b) at 250 m/min.



(a)



(b)

Fig. 8. Nickel-based alloy chip machined using coated insert tip CNGN–12 at different cutting speeds; (a) at 100 m/min and, (b) at 150 m/min.

change of chip type from continuous for the coated tool to discontinuous for the uncoated tool.

As seen in Figs. 8(a) and 8(b) different types of burr appeared when the uncoated insert tips CNGN–12 used for the cutting speed ranged from 100-150 m/min. On one side a triangle-shaped burr appeared. While on the other side whose cutting speed was 100 m/min a saw-shaped burr appeared as shown in Fig. 8(a) with higher rotation angle and a speed increase of up to 150 m/min the burr displayed tendencies to shift a square shape and increase its width as shown in Fig. 8(b).

5. Result and discussion

Generally, cutting tool materials are exposed to high mechanical stresses and thermal disturbances when machining nickel-based alloys resulting in cutting tool wear and short tool life. The results obtained show that most tools develop chipping wear at the depth-of-cut form while cutting the Hastelloy-276 due to the chip burr occurs during the process. Chip burr hammered the edge of the tool along its way with intervals from the cutting zone tacking off parts of the edge. Flank wear and BUE were seen at low cutting which along with chipping caused severe damage and tool wear. The wear rate of carbide tools increased dramatically with the increase of cutting speeds. The inserts were tested by cutting Hastelloy-276 under a constant feed rate of 0.20 mm/rev, a constant depth-of-cut of 1.5 mm, and different cutting speeds between 100 m/min and 270 m/min. For each experiment, reference flank wear value of VBB = 0.3 mm was chosen as wear criterion according to ISO 3685. A cutting tool was rejected and further machining was stopped based on one or a combination of the following rejection criteria in relation to ISO Standard 3685 for tool life testing:

- Average flank wear: 0.3 mm.
- Maximum flank wear: 0.4 mm.
- Noses wear: 0.5 mm.
- Notching at the depth of cutline: 0.6 mm.
- Excessive chipping (flaking) or catastrophic fracture of the cutting edge.

Tool tips CCMT-12 and CNGN-12 were used to machine the nickel-based alloys Hastelloy-276 workpiece material. It was examined by the SEM images of the worn cutting edges. It can be seen from these images that wear predominantly occurred in two regions during the tests: at the depth-of-cut line and the nose radius as shown in Figs. 3(a), 3(b), 3(c), and 3(d). The wear at the depth-of-cut line did not have any influence on the machined surface roughness [18]. However, the wear at the nose radius of cutting edge directly influenced the machined surface roughness since the nose edge was in direct contact with the newly machined surface. Fig. 3(a) shows a nose radius wear at a low cutting speed of 100 m/min; when the cutting speed was increased up to 150 m/min flank wear appeared alongside radius wear as shown in Fig. 3(b). This may increase the effect of chatter or vibration which occurrs at this cutting speed, explaining the increase of the value of surface roughness with the insert CCMT-12 as shown in Fig. 2. When the SEM images in Fig. 3(c) and 3(d) were closely examined, the highest tool wear was seen on the insert type CNGN-12 as shown in Fig. 3(d) for the cutting speed of 150 m/min compound with the highest surface roughness. However, further increasing in the cutting speed increased the extent of tool wear. In Fig. 3(c), flank wear and edge chipping wear are seen on the edge of the cutting tool used at the 100 m/min cutting speed. From Figs. 3 and 4, it can be seen that uncoated type cutting inserts CNGN–12 with entrance type S worn-out more quickly than the coated inserts type CCMT–12 with the same entrance type at low cutting speeds. With an increase in cutting speed, tool wear value decreased. Generally good agreement was observed between these experimental results and the existing literature studies. When the cutting speed was increased from 150 m/min to 200 m/min, a decrease was observed in roughness except for CNGN as shown in Fig. 2. However, flank wear values of insert CCMT remained below the reference case at these cutting speeds. Previous investigations on nickel-based machining confirmed that coated carbide inserts had better performance than uncoated carbide inserts and had good performance for cutting of nickel-based alloys. The results of this study are in good agreement with the existing experimental data in the literature: When the cutting speed was increased up to 200 m/min,

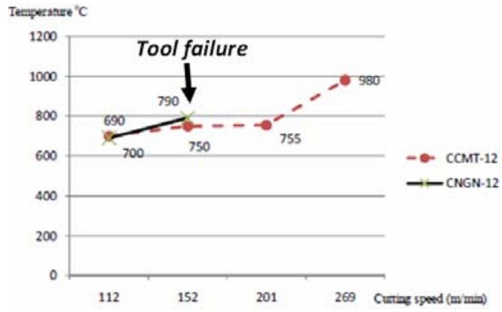


Fig. 9. Cutting speed versus Temperature for turning nickel- ased alloys Haynes-276 using CCMT-12 and CNGN- 12 inserts at a feed rate of 0.2 mm/rev and depth-of-cut 1.5 mm.

CNGN insert worn out to excessively but the other insert remained below the reference case. At this cutting speed, the types of tool wear are shown in Figs. 3(a) and 3(b). All inserts were worn out beyond the reference value of 270 m/min cutting speed. As a result, the CNGN insert resisted only at low cutting speeds. At high cutting speeds, the CCMT insert showed better performance compared to the other insert. The recommendation for tool inserts for cutting the Hastelloy-276 are coated CCMT at high cutting speed, whereas CNGN insert is not suitable for cutting Hastelloy-276 at high speed range.

In this study, flank wear and excessive chipping wear, which are important problems reducing tool life, were mainly observed in the machining experiments carbide tools as shown in Figs. 3 and 4. It is considered that the tools having negative and larger clearance angle should be used in order to solve chipping wear problem.

5.1 Effect of tool coating on tool temperature

Access to the measuring point of contact area was practically limited, with very small area to be measured, and extremely steep gradient of temperature existing in the small area of the cutting edge. The tool and the workpiece must be isolated electrically from the machine tool to obtain an accurate signal [19]. Finite element analysis was used to measure the temperature of cutting tool–workpiece contact area. Fig. 9 shows the peak temperature of the tool rake face for the six baseline cutting experiments at two tool tips and four cutting speeds; the peak tool temperature is independent of the feed which is understandable since the tool cutting edge radius (0.8 mm) was used. The peak tool temperature increased significantly from about 690°C at 100 m/min, cutting speed to 790°C at 270 m/min cutting speed for the insert tip CNGN-12, with tool life ending within this range while it increased from about 700°C at 100 m/min cutting speed to 980°C at 270 m/min for the insert tip CCMT-12 with stability in temperature from 150 m/min to 200 m/min and that explaining the increase of surface finish as shown in Fig. 9.

6. Conclusion

Turning tests were performed on nickel-based alloy Haynes-276 using two different inserts of cemented carbide cutting tools. The influences of cutting speed, tool inserts type and workpiece material were investigated on the machined surface roughness. Based on the results obtained, the following conclusions can be drawn:

Entry type S with negative rake angle showed better performance than same a similar entry with 0^o rake angle for the same approach angle of 95^o.

Nose radius wear, as evidenced by the SEM examinations, were found to be responsible for the surface roughness values.

Based on the experimental results, the optimum cutting speed can be deduced as 200 m/min and the tool life can be affected negatively above this speed.

Increasing cutting speed beyond 150 m/min can end tool life for the uncoated insert type CNGN-12 due to chip burr, while for coated insert type CCMT -12 the limit of cutting speed increased for the same cutting condition beyond 200 m/min due to the absence of the chip burr.

Coated S type insert showed better performance compared to uncoated S type insert at low cutting speeds. The recommendation for the tool inserts for machining of Hastelloy-276 is coated S type insert with negative rake angle at a medium cutting speed range.

References

[1] E. O. Ezugwu, Key improvements in the machining of difficult-to-cut aerospace superalloys, Int. J. Mach. Tool Manu. 45 (12/13) (2005) 1353-1367.

[2] G. Byrne, D. Dornfeld and B. Denkena, Advancing Cutting Technology, Annals of the CIRP, 52/2 (2003) 483-507.

[3] L. Settineri and R. Levi, Surface properties and performance of multilayer coated tools in turning Inconel, Annals of the CIRP, 54/1 (2005) 515-518.

[4] Narutaki, N., Yamane, Y., Hayashi, K., Kitagawa, T., Uehara, K., "High-speed machining inconel 718 with ceramic tools, Annals of the CIRP, 42/1 (1993) 103-106.

[5] J. Vigneau, P. Bordel and A. Leonard, Influence of the microstructure of the composite ceramic tools on their performance when machining Nickel alloys, Annals of the CIRP, v 36/(1987) 1:13-16.

[6] Machining data handbook, Mectcut Research Associate Inc., Cincinnati (1980).

[7] Sandvik Coromant, Gas turbine-Application guide, C-2920:18-EN/01.

[8] R. Arunachalam, M. Mannan and A. Spowage, Surface integrity when machining age hardened Inconel 718 with coated carbide cutting tools, Int. J. of Mach. Tools and Manuf., 44/14:1 (2004) 481-1491.

[9] D. Axinte, M. Axinte and J. D. T. Tannock, A multicriteria model for cutting fluid evaluation, Proceedings of the IMECHE Part B, Journal of Engineering Manufacture, 217/10 (2003) 1341-1353.

[10] M. C. Shaw, Metal cutting principles, Clarendon Press–Oxford (1984).

[11] E. M. Trent, Metal cutting, Butterworths (1984).
[12] D. A. Axinte, P. Andrews, W. Li, N. Gindy and P. J. Withers, Turning of advanced Ni based alloys obtained via powder metallurgy route, Annals of the CIRP, 55/1 (2006).
[13] K. Komvopoulos and S. A. Erpenbeck, Finite element modeling of orthogonal metal cutting, Journal of Engineering for Industry, 113 (1991) 253-267.
[14] Deng Jianxin and Ai Xing, Wear behavior and mechanisms of alumina-based ceramic tools in machining of ferrous and nonferrous alloys, Tribology International, 30 (1997) 11.
[15] SANDVIK coromant, Main catalogue, 2009.
[16] Ibrahim Ciftci, Machining of austenitic stainless steels using CVD multi-layer coated cemented carbide tools, Tribology International, 39 (2006) 565-569.
[17] M. Kronenberg, Analysis of initial contact of milling cutter and work in relation to tool life, ASME, 68 (1946) 217-228.
[18] David A. Stephenson, John S. Agapiou, Metal cutting theory and practice, Mercel Dekker, INC, (1997).
[19] Prof. Dr. Ulvi SEKER, Assist. Prof. Dr. İhsan KORKUT, Yakup TURGUT, Mehmet BOY, The measurement of temperature during machining, Gazi University web publications, (2008).

Basim A. Khidhir, PhD candidate 2008, MSc production engineering (Metal Cutting) 1992; BSc Production engineering (metal cutting) 1985. Senior lecturer in Sulaimanyah Technical College. He has published many papers in different journals in the field of metal cutting.

Bashir Mohamad, PhD Mechanical Enginering 1995; BSc Mechanical Engineering 1981. Associate Professor in Universiti Tenaga Nasional, Malaysia. He has published many papers in different journals in the field of manufacturing and metal cutting.