Proceedings of the 15th International Conference on Manufacturing Systems – ICMaS
Published by Editura Academiei Române, ISSN 1842-3183

“Politehnica” University of Bucharest, Machine and Manufacturing Systems Department
Bucharest, Romania, 26–27 October, 2006

INFLUENCE OF CUTTING PARAMETERS ON THE CUTTING FORCES WHEN SLOTTING INCONEL 617

Gabriel BENGA, Stephen VELDHUIS

Abstract: *The paper presents a study concerning the influence of cutting parameters i.e. cutting speed and feed rate on the cutting forces during a machining process of Inconel 617, when a multi-layer TiAlN coated carbide end mill was employed. Slotting tests of Inconel 617 were performed to investigate the effect of cutting speed and feed rate on tool’s performance and on surface finish under wet conditions. A 2 factor full factorial design experiment with 3 level of variation was used to asses the influence of cutting speed and feed rate on the cutting forces developed during the cutting process.*

Key words: *Inconel 617, TiAlN coated carbide, cutting forces, slotting.*

1. INTRODUCTION

Inconel 617 is solid-solution nickel-based super alloy containing chromium, cobalt, molybdenum and aluminum. Solid solution strengthening is provided by the cobalt and molybdenum. Inconel 617 alloy has superior high temperature properties and the alloying elements of chromium and molybdenum make the alloy resistant to corrosion [1]. The aluminum and chromium on the other hand, provide oxidation resistance at high temperatures and the high content of nickel and chromium offer high resistance to a variety of oxidizing media [2]. Inconel 617 as most of the nickel-based alloys is considered to be a difficult-to-cut material due to its work hardening tendency, high shear strength and low thermal conductivity [3]. Vankahtesh and Rack [4] observed that at low temperature two stages of hardening occurred. The increase in temperature initiated the third type of hardening which occurreddue to structure change to cellular substructure. Sharman et al [5] mention that one of the main problems when cutting Inconel 718 is not only the short tool life but also the workpiece surface damage and moreover the subsurface microstructural modifications due to the tendency of work hardening of this material.

Kitagawa *et al.* [6] mentioned that the poor thermal conductivity for Inconel 718 (11.4 W/m°C) leads to high cutting temperature with values around 1 200°C in the shear zone when using carbide tools. The thermal conductivity for Inconel 617 is 13.6 W/m°C and it is reasonable to assume the same trend for cutting temperature in the shear zone when cutting Inconel 617. Due to the fact that Inconel 617 does work-harden during machining and it has a high “gumminess” which is not common for other steels, a stiff machining equipment and tooling should be used. In order to obtain a good surface finish and small burr it is imperative to have rigid machine tools and fixtures.

Melting range and some physical constants at room temperature are shown in Table 1. The alloy's low density, compared with tungsten-containing alloys of similar strength, is significant in applications such as aircraft gas turbines where high strength-to-weight ratio is desirable.

Table 1

Physical Constants of Inconel 617

Density $[kg/dm^3]$	**Melting Range [°C]**	**Specific Heat at (20°C) [J/kg-°C]**	**Electrical Resistivity at (20°C) [μΩ-m]**
8.36	1332–1380	419	1.22

Inconel alloy 617 has high mechanical properties over a broad range of temperatures. One of the alloy's outstanding characteristics is the strength level it maintains at elevated temperatures [7]. The resistance of the alloy to high-temperature corrosion enhances the usefulness of its strength. Inconel 617 exhibits good metallurgical stability for an alloy of its strength level. The strengthening is attributable to carbide formation and, at exposure temperatures of 650°C to 760°C to precipitation of gamma prime phase. INCONEL alloy 617 displays exceptionally high levels of creep-rupture strength, even at temperatures of 1800°F (980°C) and above. That characteristic, combined with good resistance to oxidizing and carburizing atmospheres, makes the alloy especially suitable for long-term, high-stress use at elevated temperatures.

The present work planned to study what is the influence of cutting speed and feed rate on he cutting forces and how can the cutting forces be decreased by the variation of cutting parameters. The concept of response surface was employed to determine the influence of both variables *i.e.* cutting speed and feed rate on the cutting force components. Response surface methodology is a collection of mathematical and statistical methods that are useful for analysis and optimization of the processes, which implies a response of interest and the process, is influenced by several variables [8].

2. EXPERIMENTAL PROCEDURE

The tests were performed on a Matsuura FX5-G Vertical Milling center capable of performing high speed machining (27,000 rpm). A high helix carbide-cutting tool with a micro grain multi-layer TiAlN coating with water-based coolant was used for slotting. The diameter of the cutters used was 6.35 mm. The codification of the cutters is: OSG Exocarb-SHP 4045. The cutting forces were measured using a Kistler dynamometer.

The workpiece material consisted in transition panels of 177.8 ×177.8 mm and 3.175 mm thickness. The depth of the channels was 1.5 mm, which was also the depth of cut.

The transition panel is presented in Fig. 1.

Fig. 1. Transition panel made from Inconel 617.

The chemical composition of the workpiece material is presented in Table 2.

Table 2

Chemical composition of Inconel 617

Chemical element wt.%	Ni	Cr	Co	Mo	Al	Fe	Si	Ti
Comp	51.8	21.2	13.8	10.36	0.61	1.03	0.76	0.3

The limiting chemical composition of INCONEL alloy 617 is listed in Table 2. The high nickel and chromium contents make the alloy resistant to a variety of both reducing and oxidizing media. The aluminum, in conjunction with the chromium, provides oxidation resistance at high temperatures. Solid-solution strengthening is imparted by the cobalt and molybdenum.

A 3^2 full factorial design with two independent variables (cutting speed and feed rate) each of them having three levels of variation was employed. This implies nine cutting tests. The feeds and speeds have been chosen in a range from 150 mm/min to 300 mm/min for feed rate and from 2 800 rpm (50 m/min) to 4 200 rpm (84 m/min) for the cutting speed. The lowest value used for the feed rate and the cutting speed corresponds to –1, while the highest value used for feed rate and cutting speed corresponds to +1. The variation interval was 75 for feed rate, which means that the third level of variation corresponding to the central point will be 150 + 75 = 225 mm/min. In a similar way was determined the third level of variation for cutting speed using a variation interval of 700 rpm, which results in 2 800 + 700 = 3 500 rpm central point.

Table 3 presents the physical and codified values for each parameter.

Table3

Cutting parameter for a 3^2 full factorial design

Parameter	Codified value	Physical values	
		$X_1 = V_c$ [rpm]	$X_2 = f_n$ [mm/min]
Central point $X_i = 0$	0	3500	225
Variation interval D_j	Δj	700	75
Superior level X_i	+1	4200	300
Inferior level X_i	–1	2800	150

The matrix that corresponds to a 3^2 full factorial design is presented below:

Table 4

The matrix for a 3^2 full factorial design with 9 runs

Run	Cutting speed [rpm]	Feed rate [mm/min]	F_x [N]	F_y [N]	F_z [N]
1(7)	**–1** (2800)	**1** (300)	200	209	53
2(3)	**1** (4200)	**–1** (150)	90.1	105	12.3
3(2)	**0** (3500)	**–1** (150)	198	43.3	5.16
4(9)	**1** (4200)	**1** (300)	16	99.6	13.1
5(1)	**–1** (2800)	**–1** (150)	91.7	129	84.8
6(6)	**1** (4200)	**0** (225)	108	136	51.7
7(4)	**–1** (2800)	**0** (225)	103	205	65.4
8(8)	**0** (3500)	**1** (300)	152	208	48.2
9(5)	**0** (3500)	**0** (225)	131	172	52.3

In the first column are presented the nine runs of the experiment and in the brackets is presented the order in which each run was performed. The runs were performed in a random order trying to avoid the possible systematical errors. Specific columns of the physical values cutting force's components F_x, F_y and F_z are presented for each target function.

3. RESULTS AND DISCUSSIONS

The following histograms present which one of the two variables (cutting speed and feed rate) affects more each component of the cutting force.

Fig. 2 shows that the main influence on the F_x cutting force is given by the correlation between than two variables rather than by each variable by itself. According to Fig. 3 the F_y cutting force is mostly influenced by the feed rate than the cutting speed. Cutting speed seems to have the highest influence on the F_z cutting force as it is shown in Fig. 4.

The response surfaces for the three components of the cutting force are presented in the figures below.

Fig. 5 illustrates that both cutting speed and feed rate have a significant influence on the F_x cutting force. The

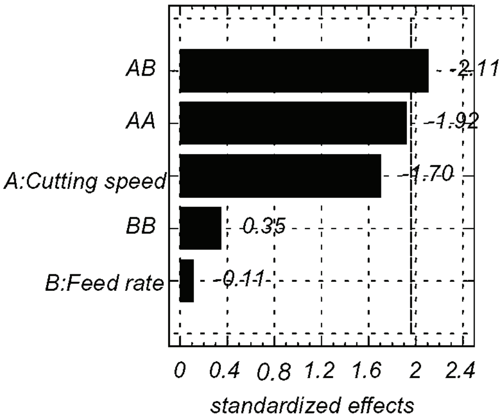

Fig. 2. Histogram of standard effects for F_x.

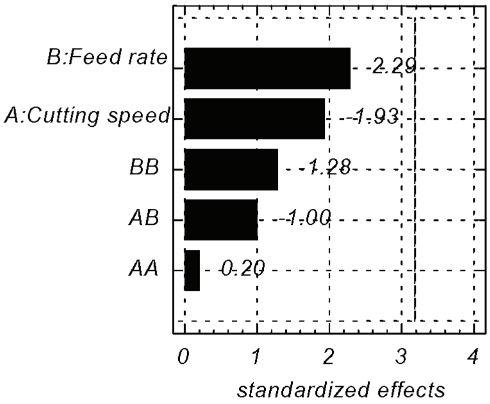

Fig. 3. Histogram of standard effects for F_y.

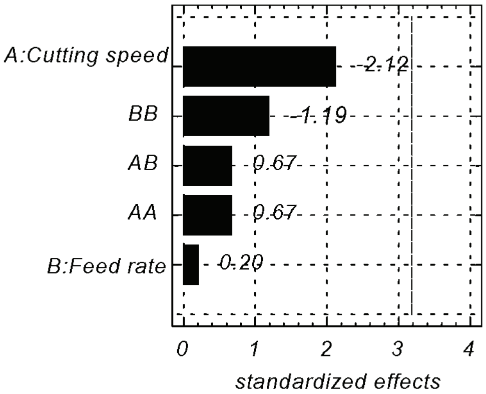

Fig. 4. Histogram of standard effects for F_z.

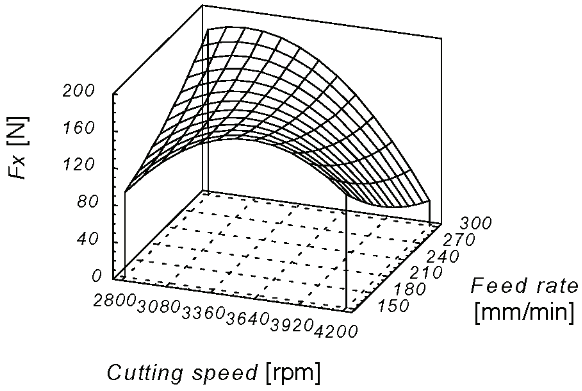

Fig. 5. Response surface for F_x as a function of cutting speed and feed rate.

highest value for F_x was obtained for a cutting speed of 2 800 rpm and a feed rate of 300 mm/min. The lowest value for F_x was reached for the highest cutting speed employed *i.e.* 4 200 rpm. It is reasonable to assume that in this case the chip load was minimum and consequently the F_x component of the cutting force decreased significantly. On the other hand using a feed rate of 150 mm/min we can obtain the lowest cutting force F_x for two values of the cutting speed *i.e.* 2 800 rpm and 4 200 rpm.

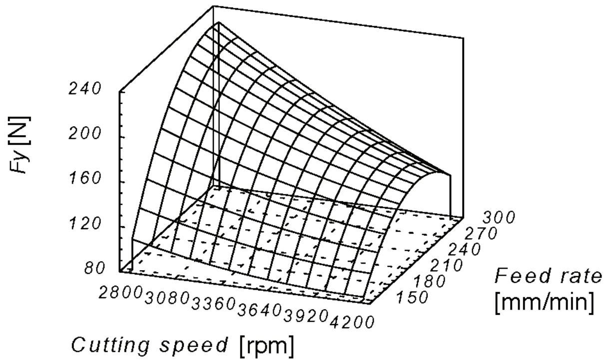

Fig. 6. Response surface for F_y as a function of cutting speed and feed rate.

Fig.6 shows that the influence of the feed rate is considerably higher than the influence of cutting speed and one of the lowest values for F_y is obtained when a speed rate of 4 200 rpm and a feed rate of 150mm/min were used. Nevertheless, in this case, the influence of cutting speed is not very significant by itself but is rather significant when is correlated with the feed rate. Is is important to keep F_y cutting force in reasonable limits in order to avoid occurrence of vibrations that could damage the workpiece surface and lead to the tool fracture. The highest value for F_y was obtained for a cutting speed of 2 800 rpm and a feed rate of 300 mm/min. It is obvious that in this case the chip load has reached the highest value and therefore the F_y component of the cutting force reached the highest value as well. It should be pointed out the tendency of decreasing of the F_y component of the cutting force with the increasing of cutting speed from 2 800 to 4 200 rpm. Another aspect presented in Fig. 6 concerns the values of F_y component of the cutting force comparing with other components, F_x and F_z.. The value for F_y has reached a maximum of 240 N, higher than F_x, which was 200 N and also higher than F_x, which has reached 100 N.

Fig. 7 outlines the influence of both variables on the F_z component of the cutting force. It is obvious that the cutting speed has a greater influence on F_z than the feed rate. When increasing the cutting speed from 2 800 to 4 200 rpm a significant decrease in the F_z value can be observed. This is valid for all components of the cutting force, taking into account the fact that the lowest values for cutting forces were reached when the highest cutting speed was used. Alauddin *et al.* [9] also mentioned this

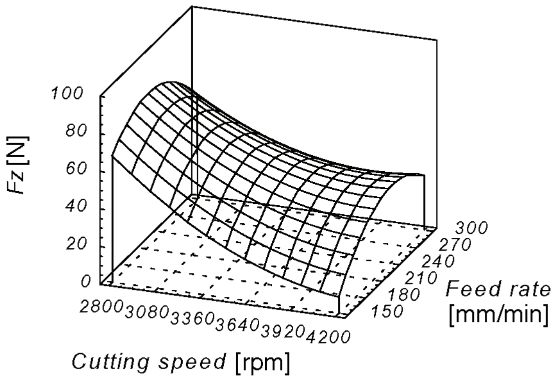

Fig. 7. Response surface for F_z as a function of cutting speed and feed rate.

kind of behavior. Alauddin et al. explained that a decreasing of cutting forces with an increasing of cutting speed is possible because of the reduction of chip thickness having as a result a lower chip load.

By analyzing all of these three graphics we can conclude that the highest values for all the three components of the cutting force F_x, F_y and F_z are obtained for the cutting conditions that offer the highest tool wear and the highest chip load (these aspects were mentioned in a previous paper) *i.e.* V_c = 2 800 rpm and f_n = 300 mm/min [10]. Under these circumstances it is reasonable to assume that this cutting regime is not appropriate for the machining of Inconel 617 with OSG Exocarb-SHP 4045 multi-layered TiAlN micrograin carbide tools.

4. CONCLUSIONS

An analysis of the cutting forces values during the cutting process reveals that a cutting regime involving high cutting speeds 3 800–4 000 rpm and low feed rates 150–170 mm/min will keep both F_y and F_z cutting forces at the lowest possible level. It is important to keep F_y cutting force in reasonable limits trying to avoid the appearance of chatters, which may hasten the tool wear and affect the surface finish taking in account the “gumminess” of the Inconel 617 and the tendency of work hardening.

There is a tendency of decreasing the values of the cutting force components F_x, F_y and F_z, while increasing the value of the cutting speed from 2 800 to 4 200 rpm. This tendency is more significant for F_y and F_z, than for F_x, where the shape of the response surface is more complicated. The F_x component of the cutting force is affected more by the correlated effect of cutting speed and feed rate, rather than the effect of each variable. On the other hand, F_y was affected mostly by the feed rate and F_z, mainly by the cutting speed.

Taking into account that in a previous study was demonstrated that the longest tool life was obtained for a cutting regime with a cutting speed in the range of 3 600–3 900 rpm and a feed rate of approximately 200 mm/min it seems that the correlation with the values obtained for cutting forces is reasonable.

Acknowledgements. The authors would like to thank to the staff members of the MMRI (McMaster Manufacturing Research Institute), McMaster University (Canada) who provided the facilities in order to perform the tests and to Siemens-Westinghouse Company for providing the workpiece material. The authors would also like to thank to NSERC (Natural Sciences and Engineering Research Council of Canada) for the financial support.

REFERENCES

[1] Yilbas, B. S., Khaled, M., Gondal, M. A. (2001). *Electrochemical response of laser surface melted Inconel 617 alloy*, Optics and lasers in Engineering, **36**, pp. 269–276, Elsevier, Zurich.

[2] Sahn, P. R., Speidel, M. O. (1974). *High temperature materials in gas turbines*, Elsevier, New York.

[3] Jawaid, A., Koksal, S., Sharif, S. (2001). *Cutting performance and wear characteristics of PVD coated and uncoated carbide tools in face milling Inconel 718 aerospace alloy*, Journal of Materials Processing Technology, **116**, pp. 2–9.

[4] Vankahtesh, V., Rack, H. J. (1998). *Elevated temperature hardening of Inconel 690*, Journal Mech. Mater., **30**, *1*, pp. 69–81.

[5] Sharman, A., Dewes, R. C., Aspinwall, D. K. (2001). *Tool life when high speed ball nose end milling Inconel 718*, Journal of Materials Processing Technology, **118**, pp. 29–35.

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

[7] Smith, G. D., Yates, D. H. (1991). *Optimization of the Fatigue Properties of INCONEL alloy 617*, Paper No. 91-GT-161, ASME International Gas Turbine and Aeroengine Congress and Exhibition, Orlando, FL

[8] Montgomery, D. C. (2001). *Designs and Analysis of Experiments*, Fifth Edition, Wiley & Sons.

[9] Alauddin, M., Mazid, M. A., El Baradie, M. A., Hashmi, M.S.J. (1998). *Cutting forces in end milling Inconel 718*, Journal of Materials Processing Technology, **77**, pp. 153–159.

[10] Benga, G., Veldhuis, S., Khanna, M. (2006). *Optimization of a machining process of Inconel 617 using statistical-mathematical methods*, Proceedings of the 39th CIRP International Seminar on Manufacturing Systems – The Morphology of Innovative Manufacturing Systems, Ljubljana, Slovenia, pp. 317–322.

Authors:

Dr. Gabriel BENGA, Associate Professor, University of Craiova, Faculty of Engineering and Management of Technological Systems, Romania,

E-mail: `gabrielbenga@yahoo.com`

Dr. Stephen VELDHUIS, Assistant Professor, McMaster University, Department of Mechanical Engineering, Hamilton, Ontario, Canada, E-mail: `veldhu@mcmaster.ca`