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Comparative study of high speed machining of Inconel 718 in dry condition and by using compressed cold carbon dioxide gas as coolant

N.G.Patil [a*],Ameer Asem[a], R. S. Pawade[b], D.G. Thakur[c], P.K. Brahmankar[b]

[a]*Department of mechanical engineering,Marathwada Institute of Technology,Aurangabad,431028,India*
[b]*Dr. Babasaheb Ambedkar Technological University, Lonere, India*
[c]*Defence Institute of Advanced Technology, Pune, India*
* Corresponding author. Tel.: +02402375140; .*E-mail address:*nilesh.patil@mit.asia

Abstract

Difficult-to-cut materials like Inconel 718 are used for aerospace, steam turbine, bearing industry, nuclear and automotive applications. In machining, friction and heat generation at the cutting zone are the frequent problems, which affect the tool life and surface finish. Heat generation pose limitations during the turning of such modern materials due to their peculiar characteristics such as poor thermal conductivity, high strength at elevated temperature, resistance to wear and chemical degradation. A good understanding of the methods of lubrication/cooling at the cutting zone, reduction of heat generation will lead to efficient and economic machining of these modern materials. This paper presents use of compressed cold carbon dioxide for cooling at machined affected zone. Effect of cold compressed carbon dioxide as coolant on process forces, surface roughness, micro hardness, specific cutting pressure has been studied in comparison to dry turning for same set of cutting parameters.

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*Keywords:*Machining;CO_2 gas cooling;Inconel 718; Cutting forces;Surface integrity

1. Introduction

Nickel based super alloys are widely employed in the aerospace industry, in particular in the hot sections of gas turbine engines due to their high temperature strength and high corrosion resistance (Pawade*et al.*, 2006).Inconel 718 is one of the proven high-performance materials, which can withstand stringent operating conditions in aerospace, gas turbine and automobile industries. However, nickel alloy is difficult to machine due to rapid work hardening. Severe tool failure and rapid tool wear in machining has long been recognized as a challenging problem(Ezugwu,2005).

The thermal conductivity of Inconel is much lower than that of commonly used alloy steels. Therefore, the cutting temperature in the tool and the workpiece are significantly high during machining of these materials. Hence, to enhance the machining performance in cutting these materials, the heat generated during cutting should be dissipated rapidly. Although very few reports have been made on application of carbon dioxide in machining, the desirable influences of CO_2 cooling on tool performance show lot of promise for its uses (Siekmann, 1955; Machai and Biermann, 2011). Compressed CO_2 can be an efficient way of maintaining the temperature well below the softening temperature of the cutting tool material. Moreover, compressed CO_2 cooling is an environmentally safe alternative to conventional coolants. Reduction in tool temperature reduces the crater and flank wear (Machai and Biermann, 2011). Besides being environment friendly as compared to conventional fluid, compressed CO_2 cooling, if properly employed, can provide significant improvement in both productivity and product quality and hence overall machining economy even after covering the additional cost of cooling system. The present work has been undertaken to investigate the effects of compressed cold carbon dioxide (CO_2) as coolant in turning of Inconel 718.

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2. Experimental details

2.1. Material and methods

The specimens, diameter 45 mm, of Inconel 718 were used for the experiments. The chemical composition of the Inconel 718 used is presented in Table 1. A Sandvik make PVD (TiAlN) coated carbide inserts designated as SNMG120408-SM 1105 was used. The turning experiments were performed on CNC Turning Lathe (Make – Micromatic, Model- Jobber XL) with a maximum spindle speed of 5000 rpm. The input parameters varied during the machining are cutting speed and feed rate both at five levels. A depth of cut is kept constant at 0.5 mm considering the finish machining regime. The machining was performed for a little time to avoid the effect of tool wear on the surface generation therefore no tool life criterion was chosen. The cutting length for each turning trial was 45 mm. Cutting force components were measured using a three component piezoelectric dynamometer (Kistler Corporation, Model 9257). The output from the dynamometer is amplified through a charge meter (Kistler Corporation Model 5015A).

Mitutoyo SJ-401 is a portable, self-contained instrument for the measurement of surface roughness of machined surfaces (*Ra*). Workpiece surfaces are usually created by successive machining passes such as roughing, semi-finishing, and finishing which causes alterations in mechanical properties of the workpiece surface. Mitutoyo Microhardness tester HM211 has been used to measure microhardness.

Two different type of cutting environment strategies have been used during machining.The turning operation on Inconel-718 was performed under dry and compressed CO_2 environment. Carbon dioxide gas was applied to the turning process at the tool tip through the nozzle. Thus, the compressed CO_2 gas with a temperature of θ = - 65°C to - 70°C is applied in machine affected zone. Carbon dioxide can be stored in pressurized tanks and is fed into the cutting zone atroom temperature and cools down at expansion at the nozzle tip with respect to theJoule Thomson effect (Machai and Biermann, 2011).

Table 1 Inconel 718 composition

Major Elements	Alloy Content weight percentage				
	Cr	Ni	Mo	Nb	Ti
Min.	17	50	2.8	4.75	0.65
Max.	21	55	3.3	5.5	1.15
Actual	18.48	52.91	3.05	5.3	0.89

2.2. Design of experiments

In this study, Response surface methodology (RSM) wasused for design of experiment. The details of are shown in Table2. In the present study, experimental design was based on the technique proposed by Box and Hunter (1957). The uniform precision rotatable central composite experimental design (CCD) as demonstrated by Myers and Montgomery (1995) was used to improve the reliability of the results and to reduce the size of experiments without loss of accuracy.

Table 2 Machining parameters and their levels

Parameters	Levels				
	-2	-1	0	1	2
Cutting speed, Vc (m/min)	70	85	100	115	130
Feed, f (mm/rev)	0.10	0.17	0.24	0.32	0.40

3. Results and discussion

3.1Response surface modeling

In this experiment, outputs are process forces and surface roughness. The inputs are cutting speed, Vc, m/min and feed rate, f, mm/rev. The mathematical models have been developed that illustrate the relationship between the inputs and output responses. The behaviour of the process is explained by the following empirical second-order polynomial model.

$$Y = \beta_0 + \sum_{i=1}^{k} \beta_i X_i + \sum_{i=1}^{k} \beta_{ii} X^2{}_i + \sum_{i=1}^{k-1} \sum_{j=2}^{k} \beta_{ij} X_i X_j \quad (1)$$

Based on the results of experiments, the coefficients and constants of the above equation have been determined. Finally, following models have been developed for process forces and surface roughness.

Fx_{Dry}=191-3.02Vc+945f+0.0166V²c-239f²-2.55Vc×f (2)
R-Sq = 99.9% R-Sq (adj) = 99.8%

Fx_{CO_2}=96-0.21Vc+856f-0.246V²c-366f²-0.16Vc×f (3)
R-Sq = 97.6% R-Sq(adj) = 95.6%

Ra_{Dry}=3.62+0.0184Vc-34.2+0.000248V²c+157f²-0.267Vc×f (4)
R-Sq = 98.0% R-Sq(adj) = 96.3%

Ra_{CO_2}= 3.38 - 0.0543 Vc - 2.87 f + 0.000444 V²c + 68.1 f² - 0.153 Vc×f (5)
R-Sq = 99.5% R-Sq(adj) = 99.1%

Analysis of variance of equations 2 to 5 shows that the predictability of all these models is more than 95%.

3.2 Discussions

3.2.1 Cutting and feed force

Compared to dry turning, cutting and feed forces have found to increase in CO_2 environment. The difference between cutting and feed forces under dry and CO_2 cutting might be attributed to increase in compressive residual stresses in the workpiece due to cooling effect of CO_2 (Pusavec *et al*., 2011). Moreover, lower temperature might result into stronger and harder workpiece material and, in turn, the cutting forces increase (Hong et al., 2001). Besides, lower tool wear, and lower coefficient of friction at the chip-tool interface might also play vital role on cutting and feed forces. The cutting forces in figure 1 to 4 show similar trend with respect to cutting speed. In both the cases the cutting force reduces at higher cutting speeds. The magnitude of forces is relatively higher (350N) in dry turning than that of turning with CO_2 cooling (300N) and 70 m/min. This can be attributed to the increased friction at rake-chip interface. However, the trend is not same for all parametric combinations. Moreover, the effects of cutting speed and feed rate have found to surpass the effects produced by CO_2 cooling and lubrication at certain levels of speed and feed (figure 1 and 2).

Figure 1 and figure 2 show the effects of cutting speed and feed rate on cutting force and feed force under dry and CO_2 cutting. The cutting force was found to increase with increased feed rate in dry as well as CO_2 cutting. However, the effects of cutting speed have found to be more significant in CO_2 cutting as compared to that in dry conditions, refer to figure 1 to figure 4. The degree of reduction in cutting force was greater at increased cutting speed in CO_2 machining. At low levels of speed and feed, the cutting force was found to be more during CO_2 cutting compared to dry machining. However, at higher speeds and feed rates, the effects of CO_2 have found to cause lesser cutting forces compared to dry machining. This could be attributed to the effects of rapid generation of more heat and higher temperatures of work material at greater speeds and feed rates causing reduced degree of hardening of work material due to CO_2. In addition, during CO_2, the cutting tool wear might be significantly low compared to dry cutting. The lubrication caused by CO_2 might have been vital in reducing the cutting and feed forces. Besides, the improved chip formation during CO_2 cutting due to relatively non-sticky behaviour of the material compared to dry machining. Moreover, the chip adhesion to tool was more frequent during dry machining.

At higher cutting speed and higher feed rates the heat generation rate is higher which makes the material soft at cutting zone. This helps in removing the material at lower cutting forces. With increased feed rate, cutting forces have been found to increase in both dry and CO_2 environment. At low cutting speed and higher feed rates the cutting forces are higher because of the higher coefficient of friction between the tool and the work material compared to higher cutting speed and lower feed rates (Thakur et al., 2009).

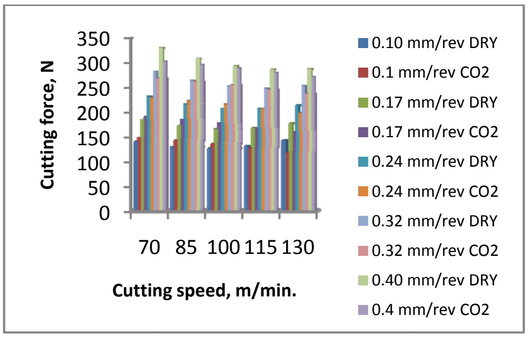

Fig.1 Effects of cutting speed and feed on cutting force

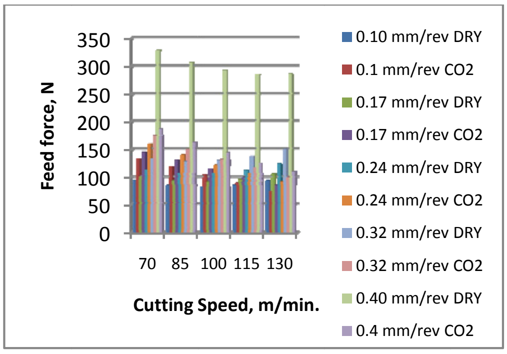

Fig.2 Effects of cutting speed and feed on feed force

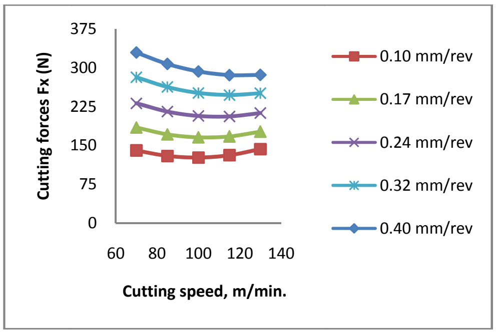

Fig. 3 Effects of speed and feed in dry cutting

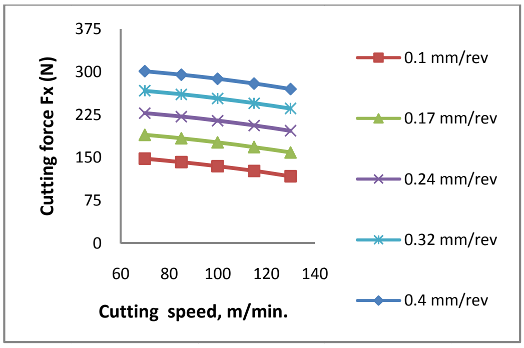

Fig. 4 Effects of speed and feed in CO_2 cutting

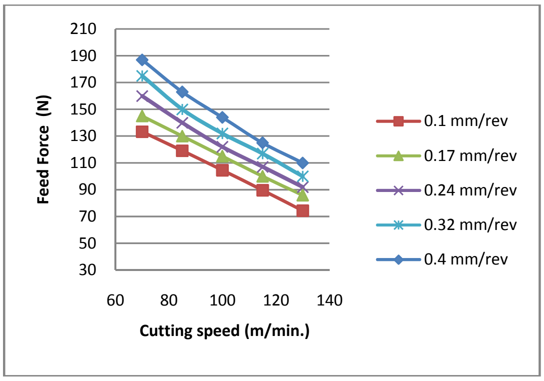

Fig. 5 Effects of speed and feed in CO_2 cutting

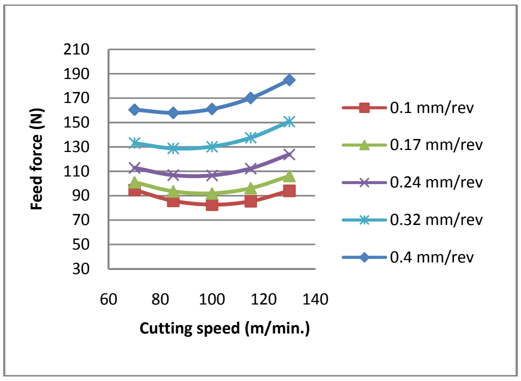

Fig.6 Effects of speed and feed in dry cutting

As far as the effect of speed on the feed forces is concerned, the opposite trend is seen in CO_2 cooling. The feed forces were found to be higher at lower cutting speed and gradually decreases as the cutting speed increases to 130 m/min. during machining with CO_2 cooling. However, the feed forces were found to be smaller initially at the lower cutting speed and increased with the increased cutting speed to 130 m/min. In this case the force magnitude was lower at the middle level of cutting speed at 100 m/min.

The relative decrease in feed force during CO_2 turning can be attributed to greater cooling at higher feed rate. This is in agreement to the reports by Khan and Ahmed (2008) during machining stainless steel. During dry turning, the feed forces are distinctly higher at 0.4 mm/rev. relative to other feed rates. At the highest feed rate the deformation is rapid which causes increased strain and strain rate during machining. Hence, the force required to remove material might be larger.

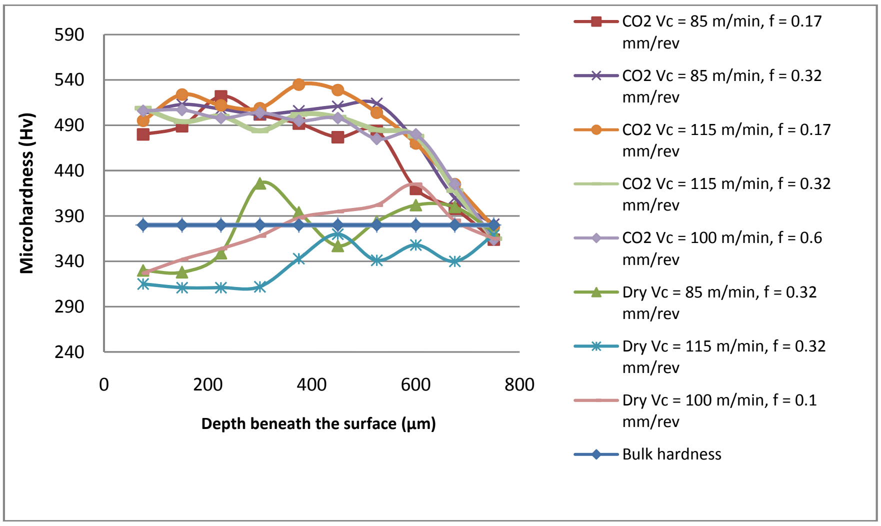

*Fig.*7 Variation of micro hardness with depth beneath the machined surface

In earlier studies, liquid Nitrogen (LN2) was found to offer the greatest cooling effect at high feed rates and the most efficient penetration into the cutting zone. Moreover, the rapid generation higher cutting temperature was found to allow the greatest cooling efficiency with liquid nitrogen (Birmingham et al., 2011).

The feed forces were found to increase with increase in feed rate as shown in figure 5 and figure 6 during dry as well as CO_2 turning. With an increase in feed rate, material removal rate, and hence rate of plastic deformation increases. As the strain rate increases strength of the material also increases, causing increased process forces (Kalpakjian and Schmid, 2011). However, this distinct nature of feed force was not observed during CO_2 machining. Moreover, during CO_2 turning the feed forces decreased with increase in cutting speed. Feed force, which is closely related to the frictional force of the chip acting on the tool, was found to decrease at higher speeds because of lower friction in CO_2 cutting. The decrease in feed force in CO_2 cutting might also be attributed to better penetration of the lubricating CO_2 into the chip-tool interface at greater cutting speed and feed rate (Shokrani et al., 2013).

3.2.2 Surface integrity

Surface integrity is important for the components subjected to high thermal and mechanical loads (Shokrani et al., 2013). Surface integrity includes surface finish (roughness and waviness), macro and microstructure and hardness of the surface, structural changes in the machined surface layer and residual stresses.

Surface roughness (Ra)

There are many methods to quantify the surface integrity of a part, and the most widely used method is the surface roughness. In machining of sticky materials like Inconel, the built-up layer that is formed on the tool flank face can push the tool off from its original route to increase the roughness, and the cutting parameters are also very effective on the changes in surface roughness.

In the present work, figure 8, the surface roughness values were found to increase with increase in cutting speed at 0.1 and 0.17 mm/rev i.e at low levels of feed rates. This might be due to adherence of work material to the tool at high cutting speed at low feed rates due to the high temperature in the cutting zone. However, at high feed rates of 0.32 and 0.4 mm/rev surface roughness was found to decrease with increased cutting speed. This trend was observed in dry as well as CO_2 turning. Generally, with increasing cutting speed and feed rate, surface roughness increases for Inconel 718. However, in the present work at higher feed rates and high speed the surface roughness was found to decrease contrary to results reported earlier. This might be attributed to the instability of the built-up-edge formed on the tool faces at high levels of feed rates reducing the surface roughness. Moreover, thermal softening of workpiece causes easy material removal, heat dissipation and better surface finish. Surface roughness has found to increase with increase in feed rate in both dry and CO_2 environment turning. Increase in feed rate leads to deterioration of surface, leading to higher surface roughness measurements (Ezugwu et al., 2005).

Compared to dry cutting, the surface finish was found to be superior in CO_2 turning. It was found to agree with the findings of Pusavec *et al.*(2011) in cryogenic machining. This can be attributed to relatively low tool wear under cooling/lubrication conditions produced by CO_2.

Greatest improvement in surface finish achieved is 65.29% as compared to dry turning. This can be attributed to low feed rate 0.1mm/min and velocity of 100m/min.

Micro hardness

The micro hardness has been determined at every 75 µm up to 750 µm beneath the machined surface till bulk hardness (380 HV) of material is reached. The results for micro hardness are presented in figure 7 in dry and CO_2 gas cooling environment.

In dry turning, the micro hardness was found to be less than or in the range of the bulk hardness in most of the cases. However, in CO_2cutting the microhardness was found to be above bulk material hardness of 380 HV. This is attributed to cold work hardening of work piece in CO_2 environment. In CO_2 turning the general trend observed was greater micro hardness of the surface and subsurface. This increased hardness of surface and subsurface are considered to be desirable (Shokrani et al., 2013).

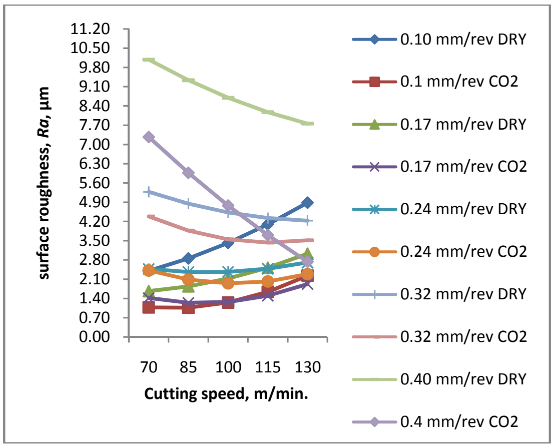

Fig. 8 Surface roughness vs. cutting speed in dry turning

4. Conclusions

Based on the present work, following conclusions can be drawn:

Due to cold work hardening of workpiece during turning under CO_2 environment the process forces have found to be increased as compared to dry turning. However, the effects of cutting speed and feed rate have found to surpass the cold work hardening effect of CO_2 at high levels of speed and feed. This is attributed to thermal softening of work material at high speed and feed.

Surface roughness decreased in CO_2 environment machining due to reduction in tool nose wear under cooling/lubrication conditions. Surface roughness was found to increase with the increase in feed rate and cutting speed in both dry and CO_2 environments.

The machined surfaces and sub surfaces showed increased microhardness in range of 495 HV to 505 HV against the bulk material hardness of 380HV due to cold work hardening of workpiece in cold CO_2 environment. In dry turning also some machined surfaces have recorded higher microhardness.

Increasing cutting speed was found to decrease the depth of work hardening in turning Inconel-718 in both environments. Microhardness variation from surface to bulk was found to decrease with increase in feed rate in dry turning condition,whereas micro hardness variation from surface to bulk increased with increase in feed rate under CO_2 environment turning.

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