Cryogenic Machining of SS304 Steel

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Abstract: Cryogenic coolants as cutting fluids are gaining importance as they are eco-friendly, recyclable and moreover, they do not produce any harmful by-products. Liquid nitrogen at -196°C is commonly used coolant in cryogenic machining. In the present work machining of SS304 was carried out on a lathe using coated carbide tool with cryogenic and flood coolants. Tests were carried out at cutting speed of 200 and 250 m/min, and the feed rate, depth of cut was kept constant at 0.2 mm/rev and 1.5 mm respectively. Coated carbide CNMG 120404 Insert was used as a cutting tool. Tool wear, tool life and cutting forces were measured. The results have revealed that cryogenic machining has yielded better tool life as compared to conventional flood machining.

Keywords: cryogenic machining; tool wear; tool life; cutting forces; coated carbide tool

1 Introduction

Machining of difficult-to-machine materials such as high alloy steels, SS304, titanium alloys, Inconel alloys and tantalum usually results in poor surface finish, irregular tool wear, built-up-edge (BUE) and premature tool failure as reported by Khan, A.A et al (2010). This is due to high strength, high fracture toughness, high fatigue and corrosion resistivity as compared to plain carbon steels. The presence of BUE will cause an increase in tool wear rate and deteriorate the surface integrity of the work. Low thermal conductivity together with high strength and high heat capacity has made stainless steel a difficult-to-machine material. Nalbant, M and Yildiz, Y (2011) reported that the work hardening capability of stainless steel together with its mentioned mechanical and thermal properties results in severe tool wear and low surface quality of the machined surface. Flood coolants are used in conventional machining. However, conventional flood coolant contains chemicals that may cause water pollution, soil contamination and health problems if disposed without required treatments.

Cryogenic machining is a nascent technology where in cryogenic coolants are used to overcome the problems faced in flood coolants. Cryogenic machining is a term referred to machining operations conducted at very low temperatures typically lower than 120°K as mentioned by Timmerhaus, K.D and Reed, R.P (2007). In cryogenic machining a super cold medium, usually liquefied gases, is directed into the cutting zone in order to reduce the cutting zone temperature and cool down the tool and/or work piece. The cryogen medium absorbs the heat from the cutting zone and evaporates into the atmosphere. As most cryogenic coolants used in machining operations such as liquid nitrogen and liquid helium are made from air, they are not considered as pollutants for the atmosphere. Nitrogen in particular is an inert gas which forms 78% of the atmosphere and is lighter than air. As a result it is dispersed into the atmosphere and does not harm the workers on the shop floor. Hong, S (2001) reported that spraying cryogenic coolant at the cutting zone could reduce the chip-tool interface temperature and thus reduce the chemical reaction between the cutting tool and chips. This reduces the adhesion and diffusion wear of the cutting tool hence increase the tool life. Venugopal et al (2007) reported that applying LN2 as a coolant in turning Ti-6Al-4V alloy resulted in 77% and 66% reduction in crater and flank wear respectively as compared to dry machining. In view of the above it is focused to perform experiments on the Cryogenic Machining of SS304 steel.
2 Experimental work

The SS304 of size Ø60x180 mm was selected as work piece material. The composition of the material was evaluated by using spectrometer and is given in Table 1 as follows

| Table 1 Nominal chemical composition of SS304 material, % |
|-----------------|------|-----|-----|-----|---|-----|
| Ni   | Cr   | Mn  | C   | P   | S  | Si  |
| 8.5  | 19   | 2   | 0.08| 0.04| 0.03| 1   |
|      |      |     |     |     |    | Rest|

TiAlNi coated carbide tool Insert CNMG 120404 was selected as cutting tool. The tool holder PCLNL 2525 M12 was selected to hold the coated carbide tool. The tool holder along with a coated carbide insert was mounted on a 3-component dynamometer. Charge amplifier along with oscilloscope was used to record the cutting forces during the experimentation. Suitable arrangement was made for connecting nozzle of cryogenic coolant and directing the liquid nitrogen to the tool-work interface as shown in Fig. 1

![Fig. 1 Experimentation setup](image)

Dynamometer was mounted on the cross slide of the CNC lathe. Tests were carried with flood coolant and cryogenic coolant. Liquid nitrogen at -196 °C was used as a cryogenic coolant. Cutting tests were carried out at cutting speed of 200 and 250 m/min while the feed rate and depth of cut was maintained constant at 0.2 mm/rev and 1.5 mm respectively. Tangential cutting forces were recorded in the oscilloscope and the flank wear was measured by optical microscope at an interval of 1 min. The tests were carried until a flank wear of 0.3 mm as per ISO: 3685. After machining hardness of the work piece was measured and it was found that the work piece machined with cryogenic coolant has shown increase in hardness varying from 2 to 3 HRC compared to flood machined work piece.

![Fig. 2 SEM Images showing tool wear after failure](image)

3 Results and Discussion

3.1 Surface roughness, Hardness and Chip morphology

Table 2 shows the surface roughness value measured for machined surface of SS304 after an interval of 2 minutes for both cryogenic and flood coolants at cutting speed of 200 and 250 m/min respectively. Roughness value is more for flood machined surface as compared to cryogenic machined surface. This can be attributed to increase in the rate of tool wear during flood machining due to increase in temperature at work tool interface as compared to cryogenic machining.

| Table 2 Surface roughness measurements of SS304 machined surface after an interval of 2 min. |
|-----------------|-------|-------|
| Test Parameters | Surface Roughness-Ra (µm) |
|                 | Cryogenic | Flood |
| 200-0.2-1.5     | 1.17    | 2.59   |
| 250-0.2-1.5     | 1.22    | 3.38   |

| Table 3 Hardness (HRC) measurements of the SS304 material. |
|-----------------|-------|-------|
| Before Machining | After Machining |
|                 | Cryogenic | Flood |
| 30              | 32.5     | 29     |

Cryogenic cooling increases the hardness of the work material as shown in Table 3 and this improves the machinability of the SS304 material due to the reduction in ductility and fracture toughness as reported by Wang, Z and Rajurkar, K(2000). Further
longer chips were formed in flood machining compared to cryogenic machining as shown in Fig. 4 and this reduces the cutting forces in cryogenic machining by reducing the temperature at chip-tool interface.

Fig. 4 Images of the chips collected during cryogenic and flood machining.

3.2 Tool Wear

Fig. 3(a) and 3(b) shows the rate of flank wear for both cryogenic and flood coolants. It is clear from both the figures that there is an increase in flank wear with increase in cutting time. Further the flank wear is less in cryogenic machining as compared to flood machining. The decrease in flank wear is attributed to reduction in chip-tool interface temperature which in turn influences the fast removal of heat at the tool-work interface. This is evidenced by the tool integrity as shown in Fig. 2(a) and 2(b).

The cutting edge and rake surface of the tool stays “clean” during cryogenic machining but builds-up a layer of workpiece material during flood machining as shown in Fig. 2(a) and 2(b). The presence of built-up edge is due to longer chip formation which increases the temperature at the interface. Machining of SS304 by cryogenic coolant resulted in the smallest-sized chips, while the largest-sized chips were formed during flood machining as shown in Fig. 4(a) & 4(b). Surface roughness of the workpiece was also measured using MarSurf GD 25 and it was found that cryogenic cooled workpiece surface has shown better finish compared to flood machined surface and is shown in Table 2. This can be attributed to better integrity of the cutting edge and reduced rate of tool wear.

3.3 Tool Life

From the Fig. 5, it is seen that the tool life decreases with increase in cutting speed. At both the cutting speed, the cryogenic machining has yielded better tool life compared to conventional flood coolant. The improvement in tool life is 61.78 % and 41.78 % at cutting speed of 200 and 250 m/min respectively.

Fig. 3 (b) Flank wear at 250 m/min.
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The improvement in tool life can be attributed to the (a) reduction in chip-tool interface temperature, (b) better integrity of cutting edge due to reduction in tool wear rate and (c) reduction in thermal softening. Thermal softening is a phenomena occurring due to the degradation of strength and hardness at high temperatures. The SS304 is work hardening material which in turn increases the thermal softening. Thermal softening can be reduced by reducing the temperature at the tool-workpiece interface using cryogenic coolant.

3.4 Cutting forces

Fig. 6(a) and 6(b) shows the effect of cutting time on tangential force for both cryogenic and flood coolants at cutting speed of 200 and 250 m/min respectively. It is clear from both the figures that there is an increase in tangential force with increase in cutting time. The tangential force is less in cryogenic machining at any given point of time compared to conventional flood machining.

Further the cutting forces increase with cutting speed in both conventional flood and cryogenic coolant conditions as shown in Fig.7. However, cutting forces are significantly less in cryogenic coolant conditions compared to conventional flood coolant machining. The reduction in tangential force is 19.61 % and 9.97 % at 200 and 250 m/min respectively. The reduction in cutting forces can be attributed to the (a) increase in hardness of the work material as shown in Table 3 which in turn reduces the fracture toughness leading to the reduction in cutting forces, (b) reduction in chip contact length as cryogenic machining has produced smaller sized chips as shown in Fig. 4 which reduces the heat at the interface by reducing the tool wear, (c) absence of built-up edge as shown in Fig. 2. The presence of built-up edge will cause an increase in tool wear rate which in turn increases the cutting forces.

4 Conclusions

Experiments on machining of SS304 with coated carbide tool were carried out under cryogenic and
flood coolants. The major conclusions from this investigation can be summarized as follows:

1. The application of liquid nitrogen as a coolant shows considerable improvement in tool life as compared to flood coolant.
2. Reduced cutting forces were observed for Cryogenic coolant as compared to Conventional flood coolant.
3. Cryogenic coolant showed better surface finish due to the reduction in tool wear as compared to Conventional flood coolant.

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References


