Proceedings of the
International Conference on Mechanical Engineering 2005
(ICME2005) 28- 30 December 2005, Dhaka, Bangladesh

ICME05-AM-49

PREHEATING, CRYOGENIC COOLING AND COMBINED APPROACH TO IMPROVE MACHINIBILITY OF STAINLESS STEEL IN TURNING

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ABSTRACT

This paper presents the impact of application of cryogenic cooling and plasma preheating used separately and in combination on chatter and machinability of stainless steel during turning. An effective cryogen delivery system was developed to supply liquid nitrogen. The low temperature of liquid nitrogen could effectively bring down the chip temperature close to embrittlement temperature for better chip breakage and effective cooling of the tool to reduce wear rates. An adapted TIG setup was used as the heat source to preheat the workpiece. Preheating improved the plasticity of the work material, stabilized the chip formation process and absorbed vibrations due to higher damping capacity the work piece. Combination approach was an attempt to combine cryogenic cooling and TIG pre-heating techniques to investigate its effect in terms of chip breakability, chip flow, chatter, tool wear and surface finish.

Keywords: Cryogenic cooling, Plasma preheating, Machinability, Chatter, Turning.

1. INTRODUCTION

During machining of steel at high speeds enormous heat is generated which results in sharp rise in temperature at the cutting zone. This is the primary cause of high diffusion wear rate leading to shorter tool life. High tool wear also leads to chatter and poor surface finish of the machined part. High temperature adversely affects the properties and dimensional accuracy of the work material as well. Different kinds of coolants are used to remove the heat from the cutting zone. However, in high speed-feed machining, coolant fails to penetrate into the chip-tool interface and thus can not remove the heat effectively [1-3]. In addition, conventional mineral oil-based coolants pose environmental problems [4]. Liquid nitrogen (LN_2) as a cryogenic coolant has been widely investigated, especially for machining hard to cut materials [5-7]. Most of the research works demonstrated improvements in various aspects of the machinability. Since the tool wear in high speed-feed machining is mainly due to diffusion and thermo-plastic deformation, it is worthwhile to cool the cutting zones using an effective cooling medium. Since the heat generated in the process usually affects highly localized areas, it is necessary to apply LN_2 in well-controlled jets to properly selected zones close to the cutting edges, instead of flooding the general cutting area. Therefore, various cooling approaches can be devised, by targeting the LN_2 jets to the workpiece (prechilling), tool rake face, tool side and end flank faces, or many combinations of these. Comparison of different ways of applying LN_2 was done; the results pointed out simultaneous rake and flank cooling delivers best result [8]. The other approach suggested to apply LN_2 to chip in a properly scaled jet locally and selectively to bring the chip temperature down to embrittlement temperature while minimizing the cooling effect on the primary shear plane, which can otherwise would cause increased cutting resistance. Improvement of chip breakability in machining ductile materials could reduce tool wear and improve machiability [9-12].

Some researchers came out with the idea of improving machinability of hard to cut material by pre-heating of the work piece to make it easier to be machined. Softening of the material is proposed as an innovative way to overcome the poor machinability problems. It was established earlier that preheating leads to reduction of chatter during machining due to reduction of the instability of chip formation and an increase in the plasticity of the workpiece, as a result of an improvement in the damping capacity of the system [15]. There are various ways of preheating the workpiece during turning, such as Laser assisted machining (LAM) [13], furnace heating [14], high frequency induction heating [15], oxy-acetylene flame heating [16]. The cost of LAM is naturally very high and the heating rates provided by high frequency induction heating was found to be too low to raise substantially the temperature of the rotating workpiece [16].

Since TIG plasma heating had much higher heating capacity and at the same time the use of inert gas was able to protect the work surface during machining, it was decided to try this preheating technique in the present research. Liquid nitrogen was chosen as the coolant because of its low boiling point (-197°C). LN_2 was also found to be the most economical cryogen to be considered for this application and the portable cryogenic tank for LN_2 is more common compared to other cryogens.

TIG plasma heating was used supply heat to pre-shear zone before the material enters into the shearing zone. Liquid nitrogen jet was designed to hit the chip to make it brittle and break easily as it knocks the chip breaker and also to cover the tool rake and flank faces to absorb the heat.

1.1 Aims and Objectives

The aim of the research was to develop the methods of application of TIG plasma heating, cryogenic cooling separately and in combination and to evaluate the effectiveness of these three approaches in reducing chatter and improving machinability of stainless steel (304) work piece. The specific objectives of the research were as follows:

a. To investigate the influence of different approaches on chatter, tool wear and surface roughness.
b. To conduct chip analysis to evaluate the performance of the proposed techniques in terms of chip breaking capability.
c. To perform study of the worn tools under SEM to understand the mechanism of tool failure during each of these approaches.

2. EXPERIMENTAL SET UP AND METHODOLOGY

2.1 Experimental Setup

Fig. 1 shows the schematic diagram of the experimental setup. Investigations were carried out by plain turning of a shaft of initial diameter 300 mm and length 1500 mm of grade 304 stainless steel. Machining was performed on a powerful and rigid lathe model Harrison M600 using Sandvick inserts model CNMG 120408-WM and SNMG 12 04 08 MR. Signal conditioning system DEWETRON with 16 channels was connected to Dell Pentium 4 workstation to establish a data acquisition system. A KISTLER ceramic shear accelerometers of type 8774A50 was connected to DAQ Card PCI6023E. Datalog DASYLab version 5.6 software was used as interface to project the signal for analysis.

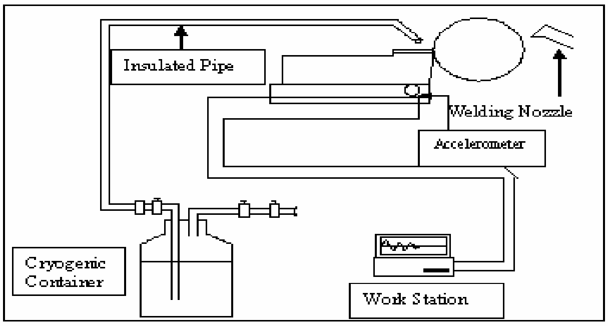


Fig 1. The experimental setup.

For liquid nitrogen storage, a portable cryogenic container (PCC) was selected to supply the liquid nitrogen under desired pressure. Specially designed tri-flow nozzle system enabled LIN jet spray to rake face and flank surface of the insert and one more jet from top to cool the chip to embrittlement temperature.

Experimental evaluation of pre-heating approach was performed using a plasma heating system with a torch and a control unit. WIM TIG 300 welding machine was chosen as the pre-heat source to soften work piece. For this experiment, the crater current was fixed at 100A and the welding current at 50A.

2.2 Methodology

Cutting parameters, such as cutting speed, feed and depth of cut, were selected in a range based on manufacturer’s recommendation and common industrial practices. The range of cutting parameters is shown in Table 1. Vibration data under dry (room temperature) cutting, cryogenic cooling, pre-heating and combined application of cryogenic cooling and pre-heating (COOLHEAT) were taken. Chatter data was recorded by the data acquisition system.

Table 1: Cutting Parameters for Experiment

Feed mm/rev	DOC (mm)	RPM	Speed (approximate) (m/min)
0.1, 0.2	1, 2	100	94
		125	118
		160	151
		200	188

Free vibration analysis of the spindle, chuck, tool and tool holder was conducted first. The free vibration charts were recorded to determine the natural frequencies of the tool chuck system in dry run. Later, vibration data for various cutting parameters and the heating/cooling approaches were recorded. The vibration data were picked up by an accelerometer attached to the tool holder. Fast Fourier Transformation (FFT) plot of the vibration signals in power spectrum were used to determine peak amplitudes and respective frequencies. The trends of vibration amplitude were used for further analysis and making comparison of effectiveness among different approaches.

Chips shape is one of the important indicators to evaluate cutting performance. Chips formed at various cutting conditions were collected to analyze the stability of chip formation. Microscope model Olympus CK 40M was used for observation and analysis.

To further verify whether vibration data and chip analysis go in line with the actual cutting condition, surface roughness at each cutting condition was measured. A portable surface roughness meter Mitutoyo Surfacetest ST-400 was used for this purpose.

To make an obvious comparison, tool wear rate was measured at the highest cutting speed of 235 m/m. Four combinations of feed rate and depth of cut were used. The tool wear was measured after every 800-mm cut length measured along the job axis. The same insert was used to cut three passes of the same length requiring about 48 minutes in every pass. The tool wear on principal flank surface was measured under metallurgical microscope (Hisamet, Model OM). To further understand the tool wear condition of each inserts, they were viewed under scanning electron microscope (JEOL, Model JSM 5600) at the end of the tool wear tests.

3. RESULTS AND DISCUSSION

3.1 Free Vibration Analysis

Fig. 2 shows the free vibration chart of lathe machine in its dry run at 250 rpm. Fig. 2 clearly indicates that the natural frequencies of the lathe machine components fall in the 0-1500 Hz range. An apparent peak is observed at 700 Hz. Free vibration spectrum at different speeds: 100 125, 160 and 200 rpm were also recorded for reference. Vibration level was found to increase as the rotational speed increased. However the shape of vibration spectrum remained intact without noticeable differences.

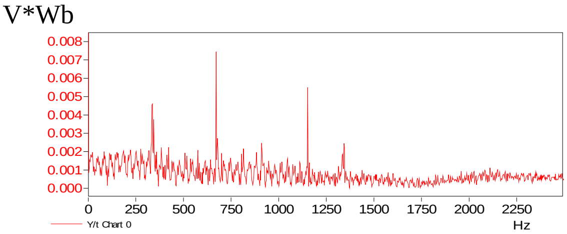


Fig 2. Free vibration spectrum at 250 rpm

3.2 Analysis of Vibration During Machining

Experiments were carried out to identify the effectiveness of three approaches namely, plasma pre-heating, cryogenic cooling and combined application of plasma pre-heating and cryogenic cooling (PHCC) in improving machinability of stainless steel compared to room temperature machining. The recorded frequency spectrum under each condition was used to make comparison and further interpret the stability of the cutting process. A sample of the frequency spectrum at cutting speed of approximately 235 m/min, feed rate of 0.2 mm/rev and depth of cut 2 mm is shown in Fig. 3.

The maximum amplitude of vibration for different combinations of cutting parameters are plotted against cutting speed in Fig. 4a-d to analyze the impacts of the different machinability improvement approaches in terms of vibration stability. In the analysis the maximum acceleration amplitude which occurred at the natural frequency range of 500-1500 Hz were only considered. It can be observed from Fig. 5a-d that at all the four combinations of cutting parameters except at the lowest feed and depth of cut combination, the preheating approach shows the best performance in terms of chatter suppression. The performance of preheating approach is followed by the plasma preheating and the combined approaches. However, the differences in the performance of the last two approaches are not substantial. At the lowest feed and depth of cut combination cryogenic cooling shows advantage in lowering vibration amplitude at the highest cutting speed (by 48%). The performance of cryogenic cooling seems to be fluctuating at different cutting speeds. This may indicate that proper application of cryogenic cooling has the potential to improve vibration stability.

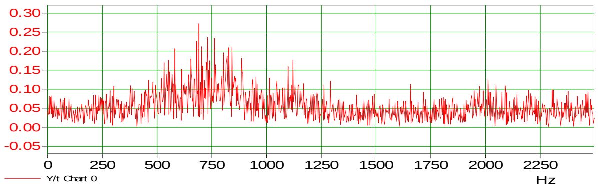
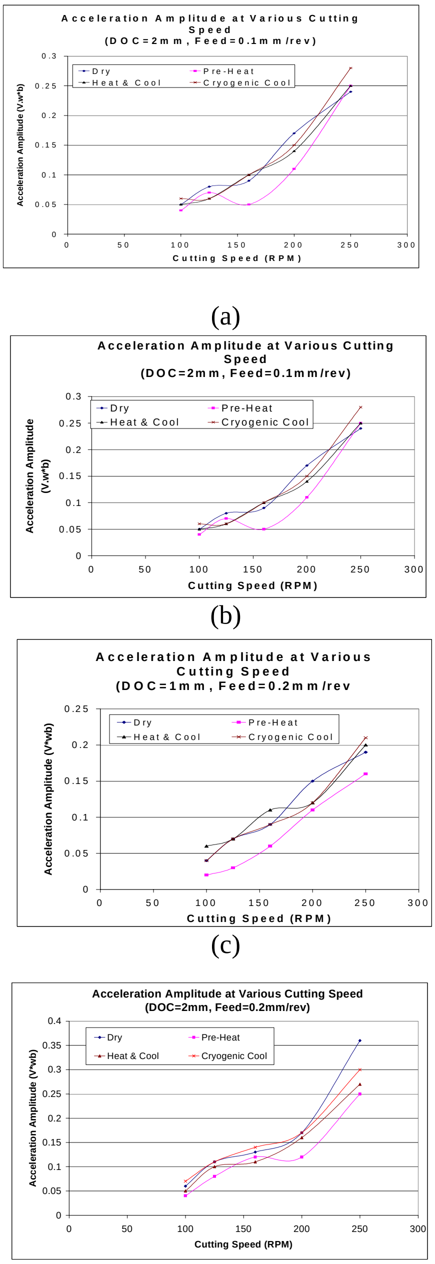


Fig 3. FFT plot for dry machining, feed = 0.2 mm/rev, depth of cut = 2 mm, speed = 235 m/min (250 rpm)
*Conversion factor 1X10^{-3} V*Wb =9.80665 m/sec^2



(a)

(b)

(c)

(d)

Fig 4. Amplitude trend for four different approaches at: (a) feed rate 0.1 mm/rev and depth of cut 1 mm, (b) feed rate 0.1 mm/rev and depth of cut 2 mm, (c) feed rate 0.2 mm/rev and depth of cut 1 mm and (d) feed rate 0.2 mm/rev and depth of cut 2 mm.

3.3 Chip Analysis

Typical saw teeth formed on the chips during machining due to the adiabatic shear process reflect the instability of chip formation. Researchers working in the area of chatter have established the conditions and shapes of chips can be used to diagnose the chatter level. The ratio of height of teeth and chip body can be used as an indicator of the stability of chip formation, since under relatively stable cutting conditions chips with lower teeth height and thicker chips body are produced. Chip analysis was performed for the extreme cutting condition, i.e. at cutting speed of 235.5 m/min (approximately), depth of cut 2mm and feed 0.2mm/rev. Chips under all machining approaches were analyzed for comparison. Photos of chip specimens are shown in Fig. 5 a-d. Referring to the Fig. 5c, the ratio of height of saw teeth to chip thickness presents the stability of chip formation.

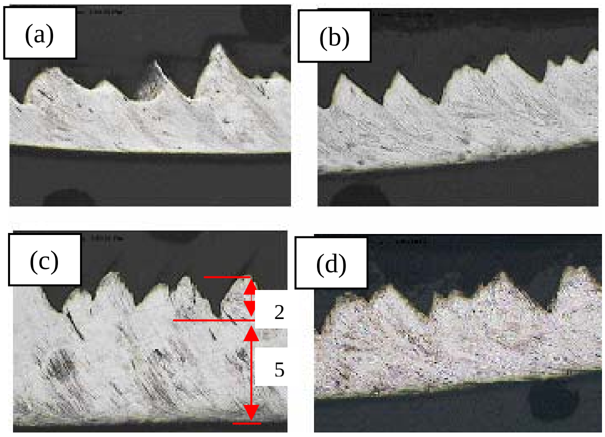


Fig 5. Samples of chip formed during: (a) room temperature machining, (b cryogenic cooling, (c) preheated machining and (d) machining with combined approach.

It reduces the resistance of material against shearing and improves the stability of chip formation. The ratio in this case is 2:5. Cryogenic cooling seems less effective compared to preheating in reducing the instability of the chip (2:3), but since the strategy of this approach is to improve breakability of chip, higher instability may be considered as positive impact with respect to chip breakability. Combination approach leads to higher instability of the chip formation process (2.5:3), which may be considered again as positive in terms of chip breakability.

3.4 Tool Wear Analysis

Tool wear rate is a good indicator to project the effectiveness of different approaches in improving machinability. Tool wear analysis was performed at the highest cutting speed of 235.5 m/min (approximately), depth of cut of 1mm and 2 mm and feed rate of 0.1 and 0.2mm/rev. Fig. 6 a-d shows the average flank wear vs. cutting time curves for the four different approaches including the room temperature machining approach. It is observed from these figures that all the three approaches outperformed dry machining, and pre-heating approach yielded the best tool life. Preheating was able to locally soften the pre-shear zone layer, as a result the shear strength and strain hardening of the material are reduced at elevated temperature [14, 15] hence, less energy was consumed to remove material from work piece, which also reduced the heat generation on tool surfaces. The performance of plasma preheating was followed by the cryogenic cooling approach. Cryogenic cooling of the rake and flank surfaces reduced the tool chip interface temperature and lowered the diffusion wear rate of the tool caused by heat. The combined approach did not show substantial effect in

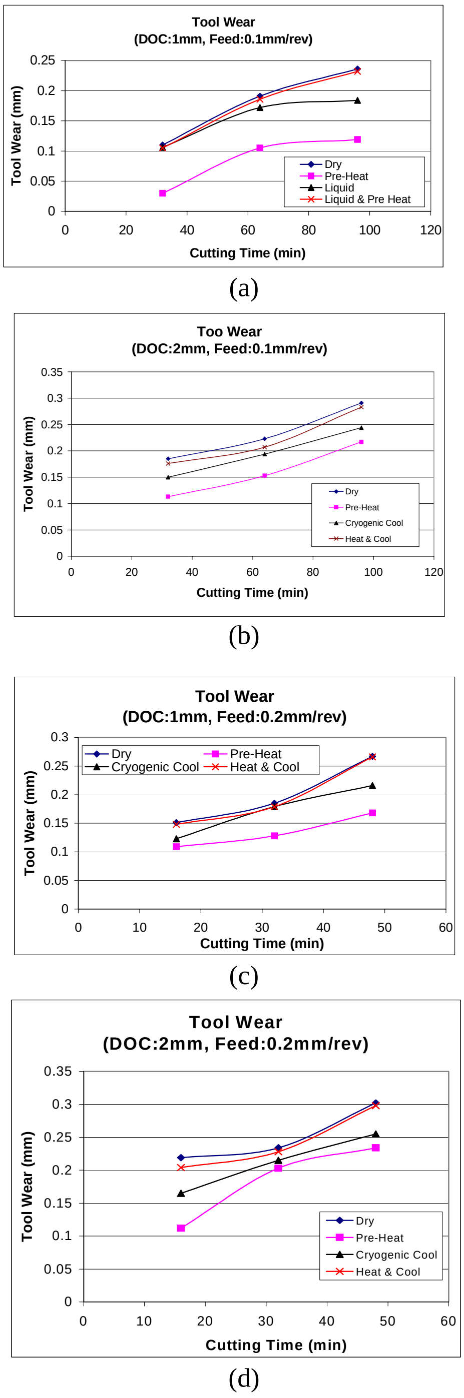


Fig 6. Tool wear curve of different cutting approaches at cutting speed 235 m/min at: (a) DOC = 1 mm, Feed = 0.1 mm/rev., (b) DOC = 2 mm, Feed = 0.1 mm/rev., (c) DOC = 1 mm, Feed = 0.2 mm/rev., (d) DOC = 2 mm, Feed = 0.2 mm/rev.

terms of tool wear compared to room temperature machining, though it out performed slightly the latter. Since plasma preheating and liquid nitrogen cooling was again a very difficult task, since the liquid nitrogen vaporized instantly as it got in touch with the air and surrounded the cutting zone, it gave contradicting impact. It appeared to be vital to precisely regulate the application of liquid nitrogen to avoid cooling the shear zone and the work piece, which

Fig. 7 shows the trend of tool wear intensity for all the four approaches. It can be observed from the figure that an increase in feed rate from 0.1 mm/rev to 0.2 mm/rev resulted in a higher tool wear intensity compared to that when the depth of cut is increased from 1 mm to 2 mm. This observation goes in line with the observation with respect to chatter amplitude.

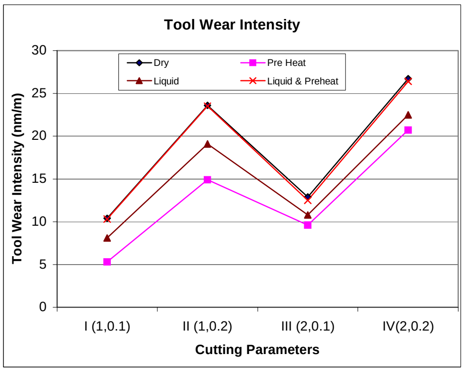


Fig 7. Intensity of tool flank wear at different cutting conditions.

Fig 8 a-d shows the SEM pictures of tool wear under different approaches at the cutting speed of 235.5 m/min, depth of cut of 2mm and feed rate of 0.2 mm/rev. It is observed from the figures that during room temperature machining the notch wear appears as a prominent mechanism of wear. Apart from that micro and macro cavities are also observed at the flank surface, which lead to intensive wear of the tool. During preheated and cryogenic machining the notch wear is substantially reduced and the flank wear is found to be more uniform compared to room temperature machining, with less micro and macro fracture at the flank surface. In the case of the combined approach when the cryogenic application is properly regulated tool wear is quite uniform and the notch wear is not too high (Fig. 8d). When heating and cooling are performed simultaneous the outer layer of the work material undergoes higher amount of strain hardening instead of softening, which is the objective of preheated machining. It is because the cryogen is evaporated as soon as it gets in touch with the air and the cryogen fume cools the surrounding area, including the heated work surface causing hardening. This is evident from the SEM photo of the tool (Fig. 8d), where higher wear is noticed at the section of the tool, which was in contact with the outer surface of the workpiece. The same trend of wear is also evident on the tool surface during room temperature machining (Fig. 8a).

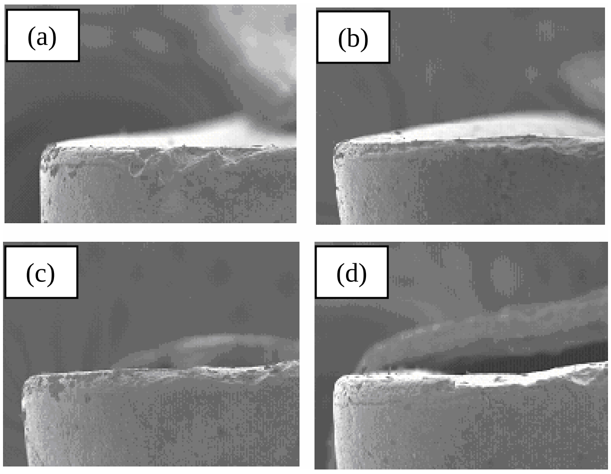


Fig 8. Tool wear at different approaches: (a) room temperature machining, (b) pre-heating (c) cryogenic cooling, (d) combined approach

3.5 Surface Roughness Analysis

A comparison of surface roughness among the different approaches is shown in Fig. 9. These results go in-line with tool wear analysis. Preheating presents a very obvious advantage in surface roughness; it outperforms other approaches in all the four sets of cutting parameters. Cryogenic cooling gives the second best surface roughness and combined approach performs slightly better than dry machining. At the depth of cut of 1 mm an increase in feed rate from 0.1 to 0.2 mm/rot seems to increase the surface roughness for the preheating and the cryogenic cooling approaches. For the dry cutting and combined approaches, the surface roughness values decrease appreciable when the depth of cut is increased from 1 mm to 2 mm at the feed rate of 0.1 mm/rot. At the feed rate 0.2 mm/rev, rougher surfaces were produced for the cryogenic and the preheating approaches. Increase of depth of cut shows less difference at the same feed rate. Dry machining at the lowest feed rate and depth of cut seems to result in the poorest surface roughness and preheated machining with the feed rate of 0.1 mm/rot is found to produce very smooth surface finish.

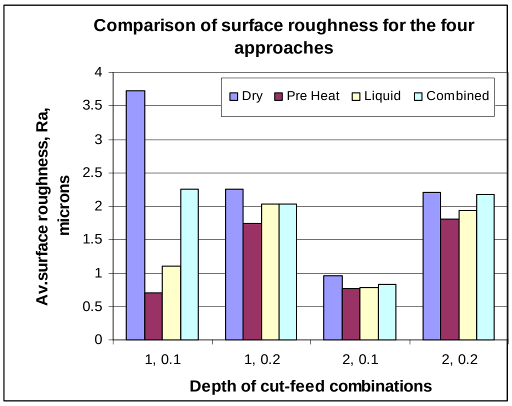


Fig 9. Comparison of surface roughness produced during machining with different approaches.

4. CONCLUSIONS

Comparison of improvement of machinability as a result of adoption of the three approaches, namely pre-heating, cryogenic cooling and combination of preheating and cryogenic cooling, with that of dry machining has been conducted. Following are the specific conclusion:

1. In terms of stability of vibration at high cutting speed , depth of cut and feed rate; plasma preheating approach presented the best reduction of chatter. Combination approach performed slightly better than cryogenic cooling. Cryogenic cooling approach was slightly better that dry machining. At the highest cutting speed but reduced feed rate to 0.1 mm/rev and depth of cut of 1 mm, cryogenic cooling approach showed better performance, where chatter was reduced by 48%.
2. As for chip control, plasma pre-heating approach produced the thickest chip body and showed this approach was good to stabilize the cutting process but chip removal may be a problem. Cryogenic cooling approach produced relatively thinner chips and with higher fluctuation of chip thickness than pre-heating. So the chip can be easily broken. The combined approach produced the thinnest chip body which from the point of view of chip control is good.
3. Pre-heating approach proved to be the best approach to minimize tool wear, followed by the cryogenic cooling approach. Due to contradicting effects of heating and cooling, the combined approach was less effective in lowering tool wear rate.
4. As for the surface roughness, plasma pre-heating approach performed better than cryogenic cooling and the combined approach. Cryogenic cooling outperformed the combined approach.

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