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Evaluation of surface finish by machining with subzero cooled tool in CNC turning

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Abstract: This paper investigates the effect of process parameters in turning of aluminum circular rods in a CNC lathe. The parameters namely the spindle speed and feed rate are varied to study their effect on surface roughness along with varying the temperature of the cutting tool from subzero (-34 degrees) to normal working temperatures. The experiments are conducted using one factor at a time approach. The study reveals that the surface roughness is directly influenced by increased temperature, spindle speed and feed rate. It is observed that the surface roughness decreases with increased temperature and is lower at lower temperatures and vice versa for all feed rates.

Keywords: Subzero Cooling, CNC turning, Surface finish,

1. Introduction: In metal cutting and process businesses, surface finish of a product is very extremely important in determining the quality and acceptability. Good surface finish not only promises quality, but also reduces manufacturing and associated cost. Surface finish is important in terms of tolerances, it reduces time and avoids the need for secondary operation, this way reduces operation time and leads to overall cost reduction. Besides, good-quality turned surface is significant in improving fatigue strength, corrosive resistance, and creep life. Due to the increasing demand of higher quality parts/pieces for its functional aspect, surface roughness of a machined part plays an important role in the modern manufacturing process. Turning is a machining operation, which is carried out on lathe. The quality of the surface plays a very important role in the performance of turning as a good quality turned surface very much improves fatigue strength, corrosion resistance, or creep life. Surface roughness also affects more than two, but not a lot of functional attributes of parts, such as contact causing surface friction, wearing, light reflection, heat transmission, ability of distributing and holding an oil/grease, load bearing ability, coating or resisting fatigue. Therefore, the desired surface finish is usually specified and the appropriate processes are selected to reach the needed quality. Surface roughness plays an important role which often affects friction, wear and lubrication of bodies in contact. Surface roughness is one of the guidelines that greatly influence the friction under certain running conditions. Surface roughness of the contacting surfaces influences the frictional properties of those surfaces during the forming processes. It is clear now that surface roughness geometry strongly influences the manner in which the contacting surfaces.

2. Literature Review: A few previous publications were studied in order to ascertain the research gap.

Shokrania et al.: This paper presented one of the very first studies on the cryogenic CNC milling of Inconel 718 nickel based alloy. A series of experiments were conducted using PVD TiAlN coated solid carbide end mills in order to investigate the effects of cryogenic cooling on the machinability of Inconel 718 in comparison with dry machining. Statistical analysis of the results revealed that cryogenic cooling has resulted in 33% and 40% reduction in Ra and ISO Rz surface roughness of the machined parts as compared to dry machining without noticeable (1.9%) increase in power consumption of the machine tool. Despite the improvements in surface roughness of the machined parts, cryogenic cooling significantly reduced the tool life of the coated solid carbide end mills. Due to the nature of the tool failure in this experiments, chipping and fracture of the nose, quantitative analysis of the tool wear was not practical. Thus the tool life was monitored from the surface roughness of the machined parts

Outeiroc et al. : The following conclusions were obtained from this paper:

1. Cryogenic cooling results in lower machined surface and tool rake temperatures. This is basically attributed to the fact that the coolingLN2jet is applied to theclearance side;
2. Cryogenic cooling results in a slightly shorter chip-tool contact length, which could be attributed to the slightly lower tool temperatures that would result in a smaller sticking region;
3. The effect of cryogenic cooling on shear angle is not very clear;
4. Cryogenic cooling tends to induce higher tensile plastic strain in the machined surface;
5. Cryogenic machining generates slightly higher cutting forces. This is attributed to the slightly lower primary shear zone temperatures; i.e., less softening effects; An improved model is to be developed in order to better simulate the process, and better predict chip segmentation.

Ampara Aramcharoen : This paper presented the investigation of the effects of cryogenic turning, using a developed modular cryogenic system, on the machinability of Ti6Al4V materials, and compared with that under oil-based coolant condition.The study showed that the modular cryogenic system was able to integrate with commercial cutting tool holder for positive implementation. It successfully improved machinability of turning titanium alloys in terms of tool wear, chip formation and friction between tool-chip interfaces. A greater penetration of cryogenic media improved efficiency in cooling, hence reduced friction between tool-chip interfaces, influenced the chip formation mechanism and resulted in tool wear reduction. Additionally, a smaller radius curvature of chip with helical shape led to easier control during chip removal and enhanced process stability**.**

Shokrania et al. : A series of machining experiments were conducted to investigate and compare the effects of various machining environments, namely flood, MQL and cryogenic in CNC milling of CoCr alloy at 200m/min cutting speed. The following conclusions were identified:

- Cryogenic cooling has resulted in a 35% and 42% reduction in surface roughness Ra as compared to MQL and flood conditions.
- Significant reduction in tool flank wear was achieved using the cryogenic cooling approach. The flank wear was 26 and 17 times larger for MQL and flood cooling environments when compared to cryogenic cooling.
- Diffusion and abrasive wear were dominant irrespective of the machining environment. However, microscopic images of the cutting tools indicated that cryogenic cooling has effectively controlled the extent of tool wear where minimum crater wear was observed.

Khare et al. : It was observed that the Taguchi's parameter design is a simple, systematic, reliable, and more efficient tool for optimization of the machining parameters. The effect of various machining parameter such as cutting speed, feed rate, depth of cut and rake angle has been studied though machining of AISI 4340 steel. 1. It was identified that the cutting speed and depth of cut have influenced more than the other parameters considered in this study. 2. The confirmation experiment has been conducted. Result shows that the error associated with SR is only 5.32 %.

The selection of optimum values is essential for the process manufacturing system. Thus the optimized condition, not only makes the cryogenic turning a more commercially viable process for industrial applications, but also turns a spotlight on cryogenic turning process as a promising field for further advancements.

Tapoglou et al. : Tool life trials used the cooling options dry, flood emulsion, through tool emulsion, MQL, CO2, CO2 plus air and CO2 plus MQL. The best performance at 100 m/min was achieved using flood emulsion coolant, which easily achieved a tool life of 30 minutes. The best performing cryogenic method was CO2 plus MQL which achieved a tool life of 18.5 minutes in equivalent testing. The successful performance of cryogenic machining is dependent on a number of factors, including work piece material and machining process details. Further, within cryogenic coolant methods, the dual mechanism of cooling and lubrication have been shown to be equally important in improving tool life as in conventional emulsion coolant techniques. This is evidenced by the improvement in tool life of both CO2 alone and MQL alone by combining the two media together (hence the best results being achieved with CO2 plus MQL). However, there is a limit to this effect, as indicated by MQL alone contradicting CO2 plus MQL in five insert testing at 100 m/min. Again, this limit (in surface speed), is also dependent on the specific details of the machining process being studied.

Handawi et al.: Hardened AISI 420 stainless steel (hardness of 47 – 48 HRC) was turned under MQL technique using wiper coated carbide cutting tool at different cutting speeds(100, 135 and 170 m/min) and feeds (0.16, 0.2 and 0.24 mm/rev). Results showed that, using small amount of lubricant of 50 ml/h during turning process was given the tool the ability to perform at high range of cutting speed and feed. MQL technique can be a good technique to turning hard stainless steel using coated carbide cutting tools up to 170 m/min and 0.24 mm/rev. Empirical models for tool life was developed within the range of cutting parameters selected. The developed tool life model represented the data of tool life very well within the range of cutting speeds and feeds. Tool life is inversely proportional to both cutting speed and feed, with the effect of cutting speed is more significant than feed.

Shokrania et al.: Inconel 718 is an important material increasingly used across various industries such as aerospace, oil and gas, marine and gas turbine industries. The use of Inconel 718 is limited in industries due to its poor machinability often associated with high manufacturing costs, low productivity, poor surface quality and short tool life. In this research, a novel cooling-lubricating system consisting of cryogenic cooling with liquid nitrogen and MQL with vegetable oil was used. It was found that using cryogenic cooling on its own is not beneficial in improving the machinability of Inconel 718 as it results in increased material hardness and therefore rapid tool wear. Analysis of the tool wear demonstrated that using CryoMQL machining environment does not change the tool wear mechanism. Nevertheless, it reduces the tool wear growth rate resulting in longer tool life. The results clearly indicated that using the proposed method almost doubled the tool life and improved surface roughness.

Ambrosy et al.: Observation of the surface layer after machining of AISI 4140 steel shows microstructural changes affected by the ratio rß/h and cooling type, which have significant effects on the mechanical aspects within the surface layer. The micro geometry of the indexable inserts with a large ratio rß/h affects the initiation of strong plastic deformation in the near-surface area of the workpiece by squeezing material underneath the cutting edge. The hardness near the machined surface was increased compared to the initial value during all machining conditions. The largest increase occurred under cryogenic cooling when using higher ratio rß/h. Thus, a final machining process with relevant conditions imposed enables the production of nanocrystalline surface layers. Higher rß/h ratios clearly lead to deeper plastic deformation as a result of the pronounced squeezing of the material, which is beneficial to the generation of nanocrystalline grains. The intensity of grain refinement was more remarkable under cryogenic conditions by inducing higher cutting forces. With respect to tribological properties of the generated surfaces, cryogenic machining tends to increase surface roughness, but leads to reduced grain size and increases surface hardness, which overall, can be beneficial for tribological applications. Furthermore, higher cutting edge radii rß can hereby reduce surface roughness.

Gintinga et al.: This research was undertaken to help eliminate the liquid waste problem resulting from coolant escapinginto the ground at a local manufacturing facility. The demand for environmental sustainable manufacturing is the primary driving force to reduce the use of liquid coolant. However, determining the effectiveness of the alternative MQL and CA process cannot be judged simply by considering the cooling function only. As metal cutting is a very complex process, and a small change in cutting conditions can have major consequences. To determine the best cooling method it was only necessary to consider the energy factors needed for cooling as the machining aspects have been established.It was established that the optimum solution would still need to maintainthe same throughput of workpieces. Research showed that using MQL and CA was feasible as an alternative to flood as it provided some cooling and lubrication at the tool tip interface. Tool tips from the cutting process used in the company were examined and showed that the tips exhibited less wear when MQL was used. Similar results were obtained from the cutting test carried out in the laboratory, and can be seen as the surface finish improved.

Abhishek Prakash: The following re the observations after studying the paper:

The feed has the greatest influence on metal removal rate and Surface roughness in the turning operation of EN36C steel followed by speed and depth of cut.

The optimal conditional for Metal removal rate as the feed (0.1 rev/min) is a dominant parameter on the tested specimens, followed by speed (600 rpm) and depth of cut (0.1 mm).

The optimal condition of Surface roughness, such as the depth of cut (0.1 mm), feed (0.5 rev/min), and speed (900 rpm) can be used to achieve better surface roughness in EN36C

Shokrani et al.: Study of literature has shown that despite industrial introduction of cryogenic milling systems together with a long history of cryogenic machining, there are limited numbers of scientific studies on cryogenic milling of titanium alloys. In this paper a full factorial design of experiments was used to investigate the effects of cryogenic cooling using liquid nitrogen in CNC milling of aerospace grade titanium alloy namely, Ti-6Al-4V with uncoated solid carbide tools. A series of machining trials were conducted and surface roughness of the machined test pieces and power consumption during machining operations were monitored. Analysis of the experimental results proved that cryogenic cooling is capable of improving surface finish up to 2.5 times as compared to dry machining without a notable increase in energy consumption of the machine tool. Observations of the cutting tools after machining trials shown the capabilitiy of cryogenic cooling in improving tool life by reducing tool wear. However, as sever chipping of the cutting edge was recognised as the main tool failure mechanism, quantitative study of the tool wear was not applicable.

Lu and Jawahir : A comprehensive process sustainability evaluation based on the Process Sustainability Index (ProcSI) method is carried out. The manufacturing cost composition and energy consumption composition are discussed. In general, the conditions where high cutting speed is used give the best overall sustainability performance, due to their excellent performance in product quality and short processing time. Although the influence of coolant flow rate is not major in this case, a lower flow rate is favoured against a higher flow rate . This could be understood as once a sufficient, but small amount of liquid nitrogen is applied, it will give the same cooling performance as higher flow rate. Thus, to achieve a truly sustainable condition, the cryogenic machining should be applied in a similar way as the machining with minimum quantity lubrication (MQL) in near-dry machining. When more cooling capacity is needed, the solution is to enlarge the coolant coverage area to increase the coolant exposure time instead of increasing coolant flow rate. Determining the minimal, but sufficient amount of coolant flow rate is a key issue in cryogenic machining applications.

Hong et al.: A new economical cryogenic machining approach has been developed. This approach uses a minimum amount of LN2 injected through a micro-nozzle formed between the chip breaker and the tool rake and assisted by the secondary nozzle for flank cooling. In this manner, LN2 is not wasted by cooling unnecessary areas and reduces the negative impact of increasing the cutting force and the abrasion of pre-cooling the workpiece material. This cryogenic machining approach yields the best tool life compared with any machining method from current known sources.

Pradeep et al.: From the cutting forces observed in the experimentation, the total power consumed was calculated.

Yap et al.: An experiment was conducted to study dry, wet and cryogenic turning of carbon steel S45C. The experimental result shows that cryogenic liquid nitrogen jet reduces friction coefficient in turning the carbon steel and also improves the chips produced. However, turning with liquid nitrogen deteriorates the surface roughness of the machined surface. Dry machining is able to produce best surface roughness in low speed machining but it also produces unfavourable long chip and high friction coefficient. Therefore, the conventional wet machining is still the best method to produce good machined surface of carbon steel at higher machining speed.

Kumar and Singh: In the present study performance of cryo-treated tools during the machining of hardened steel under dry conditions has been studied. The machining of hard materials at higher speeds is improved by using cryotreated tools. From the investigation it is observed that cryo-treated tools give better results as compared to coated tools in turning. The performance of cryo-treated cermet inserts was better than that of multilayer coated cermet inserts for the surface roughness and tool wear under the same experimental conditions. Whereas material removal rate was found better with the multilayer coated cermet inserts. The experimental results show that with the selection of proper cutting parameters; the cryo-treated tools are best suitable to produce superior surface finish of products.

Avec et al.: these were mainly the advantages of cryogenics over normal lubricant that was discussed in this paper: (i) improved environmental friendliness, (ii) reduced cost, (iii) reduced energy consumption, (iv) reduced waste and more effective waste management, (v) enhanced operational safety, and (vi) improved personnel health.

Sadik et al.: the following are the observations from this journal paper:

Tool life is not determined by flank wear in either cooling condition (CO2 or emulsion). The flow rate of coolant has limited influence on the rate of flank wear development.

The main type of wear determining tool life is notch wear, irrespective of the nature of the coolant. Cryogenic cooling with CO2 reduces the tendency of thermal cracks to propagate laterally, delaying the chipping of the cutting edge.

3. Research Gap: From the literature review, it was observed that most of the papers focused on reducing chip sizes, grain refinement along with reduce tear and wear of tool and also reduced friction coefficient. Very less number of paper focuses on the chip properties or chip characteristics obtained from CNC turning under normal and cryogenic conditions.

4. Research Methodology: An experiment sequence was generated using design of experiment in which there were two conditions, subzero cooled tool and normal temperature tool in varying parameters like speed, feed and depth of cut. After the machining was done, each work piece was evaluated with Talysurf surface roughness measurement equipment to give the values of average roughness for each specimen. The chips were also collected for further evaluation to further understand the differences in cutting parameters. The rpm was set to 700 for all the runs the feed was set at 0.3, 0.5 and 0.7 respectively. The depth of cut was kept varied between .5,1 and 1.5 for all the runs. The cooling of the tool was achieved by freeing the tool using dry ice and table salt in heavy quantities and kept in a thermal insulated environment for 6 hours. The temperatures reached were in the range of -34 degrees centigrade for every run.

Design of experiment:

Tool at normal temperature			
Cond. No.	**Speed (in RPM)**	**Feed (in mm)**	**Depth of cut (in mm)**
1.	700	0.3	0.5
2.	700	0.5	1
3.	700	0.7	1.5

Table 1. Table of Machining Parameters under normal cutting conditions.

Tool at Sub Zero temperature			
Cond. No.	**Speed (in RPM)**	**Feed (in mm)**	**Depth of cut (in mm)**
1.	700	0.3	0.5
2.	700	0.5	1
3.	700	0.7	1.5

Table 2. Table of Machining Parameters under normal cooled conditions.

Programming for Experimental run 1	Programming for Experimental run 2	Programming for Experimental run 3
Tool Status: Room Temp **Feed:** 0.3 **Depth of cut:** 1.0 mm G54 G90 G64 T1 D1 G96 S800 M04 G95 F0.3 G00 X35 Z10 G00 X29 GO1 Z-30 G00 X35 Z10 G00 X28.2 G01 Z-30 G00 X35 Z10 M30	**Tool Status:** Room Temp **Feed:** 0.5 **Depth of cut:** 1.0 mm G54 G90 G64 T1 D1 G96 S800 M04 G95 F0.5 G00 X35 Z0 G00 X29 GO1 Z-30 G00 X35 Z10 G00 X28.7 G01 Z-30 G00 X35 Z10 G00 X28.2 G01 Z-30 G00 X35 Z10 G00 X27.2 G01 Z-30 G00 X35 Z10 M30	**Tool Status:** Room Temp **Feed:** 0.7 **Depth of cut:** 1.5 mm G54 G90 G64 T1 D1 G96 S800 M04 G95 F0.7 G00 X35 Z0 G00 X29 GO1 Z-30 G00 X35 Z10 G00 X28.7 G01 Z-30 G00 X35 Z10 G00 X28.2 G01 Z-30 G00 X35 Z10 G00 X27.2 G01 Z-30 G00 X35 Z10 G00 X25.7 G01 Z-30 G00 X35 Z10 M30
Programming for Experimental run 4	Programming for Experimental run 5	Programming for Experimental run 6
Tool Status: Cooled Tool **Feed:** 0.3 **Depth of cut:** 0.5 mm G54 G90 G64 G71 T1 D1 G96 S800 M04 G95 F0.3 G00 X35 Z10 G00 X29 GO1 Z-30 G00 X35 Z10 G00 X28.5 G01 Z-30 G00 X35 Z10 M30	**Tool Status:** Cooled Tool **Feed:** 0.5 **Depth of cut:** 1.0 mm G54 G90 G64 G71 T1 D1 G96 S800 M04 G95 F0.5 G00 X35 Z10 G00 X29 GO1 Z-30 G00 X35 Z10 G00 X28.5 G01 Z-30 G00 X35 Z10 G00 X27.2 G01 Z-30 G00 X35 Z10 M30	**Tool Status:** Cooled Tool **Feed:** 0.7 **Depth of cut:** 1.5 mm G54 G90 G64 T1 D1 G96 S800 M04 G95 F0.7 G00 X35 Z0 G00 X29 GO1 Z-30 G00 X35 Z10 G00 X28.7 G01 Z-30 G00 X35 Z10 G00 X28.2 G01 Z-30 G00 X35 Z10 G00 X27.5 G01 Z-30 G00 X35 Z10 G00 X26 G01 Z-30 G00 X35 Z10 M30

Table 3. Table of CNC Programs for different runs

5. Result and discussion:

Following are the results obtained from the experimental runs:

Experimental Run 1	
RPM	700
Feed	0.3
Depth	0.5
R_a	2.906
R_q	3.399
R_z	12.123

Experimental Run 2	
RPM	700
Feed	0.5
Depth	1.0
R_a	5.341
R_q	6.230
R_z	22.624

Experimental Run 3	
RPM	700
Feed	0.7
Depth	1.5
R_a	5.909
R_q	7.225
R_z	29.317

Experimental Run 4	
RPM	700
Feed	0.3
Depth	0.5
R_a	3.084
R_q	3.610
R_z	13.046

Experimental Run 5	
RPM	700
Feed	0.5
Depth	1.0
R_a	6.3012
R_q	7.505
R_z	27.886

Experimental Run 6	
RPM	700
Feed	0.7
Depth	1.5
R_a	7.003
R_q	9.044
R_z	33.794

Table 4. Tables of Results from Talysurf Equipment for different runs.

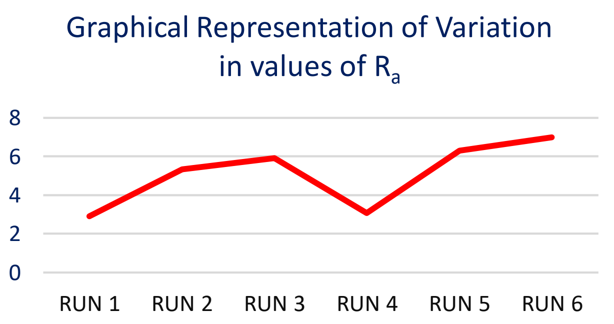

Figure 1. : Graphical Representation of Variation in values of R_a

The above representation shows that the variation in values of R_a is not that much pronounced in both cases. This indicates that the average length between valleys and heights does not deviate much from the median line or value.

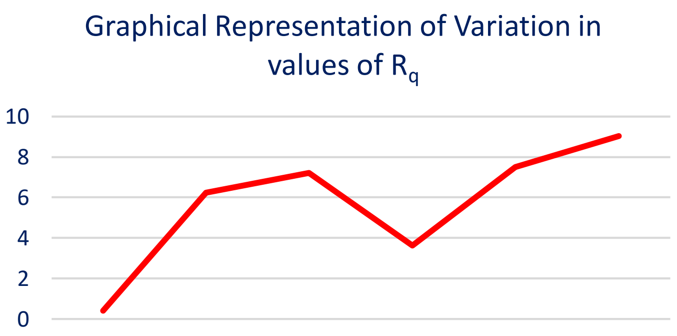

Figure 2. **:** Graphical Representation of Variation in values of R_q

The above representation shows that the variation in values of R_q is very much pronounced in both cases. Indicating that profile height roots or square average of roughness is very high.

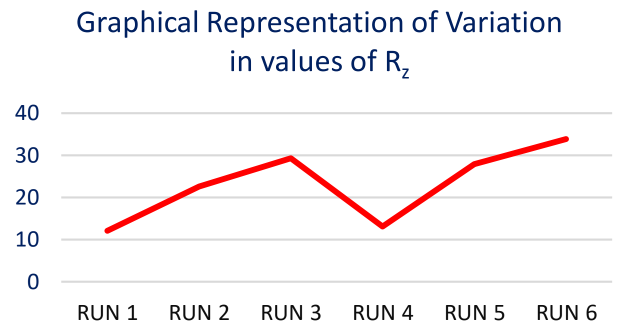

Figure 3. : Graphical Representation of Variation in values of R_z

The above representation shows that the variation in values of R_z is very much pronounced in both cases. This indicates that the vertical distance measured from highest peak to lowest value is distributed un evenly and that there are deeper craters successively

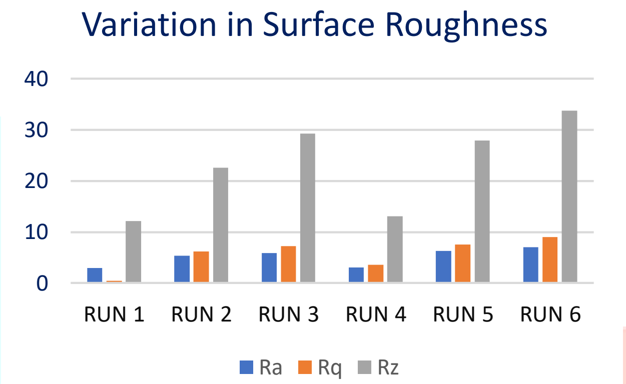

Figure 3. : Graphical Representation of Variation in values Surface Roughness

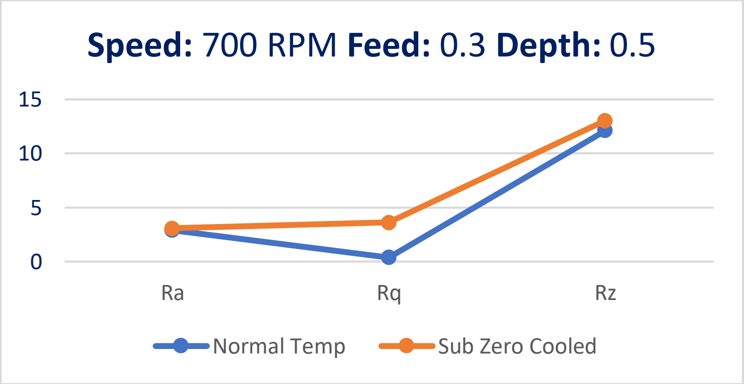

Figure 4. Variation in values of R_a, R_q, R_z for similar machining parameter (Cond: 1)

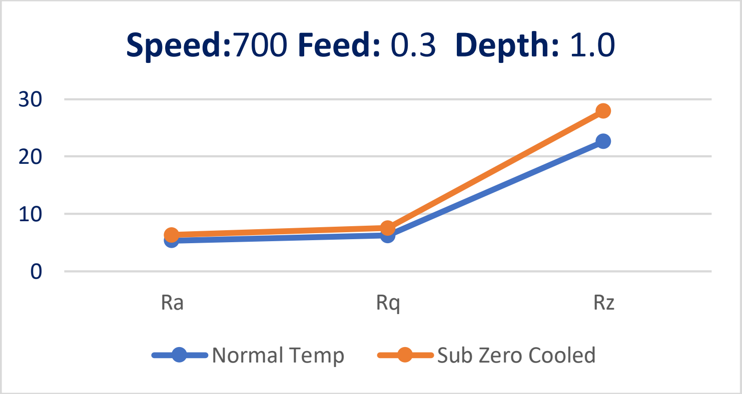

Figure 5. Variation in values of R_a, R_q, R_z for similar machining parameter (Cond: 2)

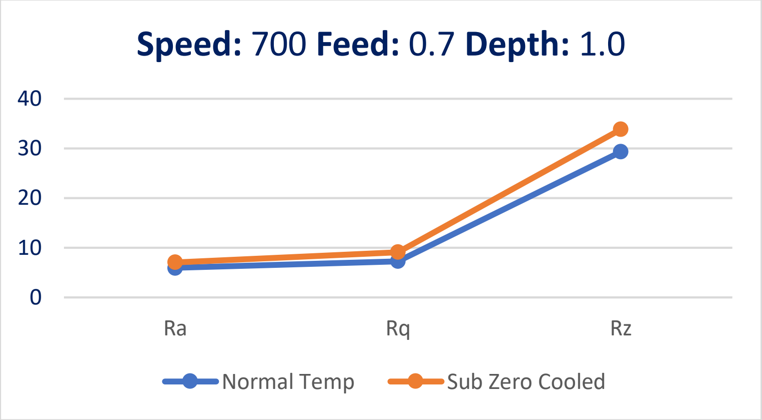

Figure 6. Variation in values of R_a, R_q, R_z for similar machining parameter (Cond: 3)

A series of machining experiments were conducted to investigate and compare the effects of various machining environments, namely normal temperature tool machining and cooled tool machining in CNC turning of aluminum rod sections at 700 m/min cutting speed. The following conclusions were identified. Cooling has resulted in a 35% to 42% increase in surface roughness Ra as compared to cooled tool and normal tool machining. The most pronounced variations is visualized in variation in values of R_q.Diffusion and abrasive wear were dominant irrespective of the machining environment. However, cutting tools indicated that cooling has effectively controlled the extent of tool wear where minimum crater wear was observed.

6. Conclusion:

Cooling results in lower machined surface and tool rake temperatures. This is basically attributed to the fact that the cooling jet is applied to the clearance side; Cooling results in little shorter chip-tool contact length, which could be attributed to the lower tool temperatures that would result in a smaller sticking area; the effect of cooling on shear angle is not very clear. Cooled tool machining creates little higher cutting forces which is visible from the different version in the surface roughness values for almost the same machining conditions. This is attributed to little lower first shear zone temperatures; less softening effects. An improved model is to be developed in order to better understand the process, and better chip morphology study.

7. References

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