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ORIGINAL ARTICLE

Performance Evaluation of Cryogenic Treated and Untreated Carbide Inserts during Machining of AISI 304 Steel

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ABSTRACT – The cutting tool in the machining process plays an important role as it acts on the working material. There are a few methodologies have been persued to improve tool life, for example traditional cooling, single layer coating, multilayer coating, heat treatment process, nitrogen cooling and latest being the cryogenic treatment which reported a significant improvement in cutting tool life, chip morphology, reduction in heat generation. Hence, the cryogenic treatment is emerged as the sustainable machining process. This paper presents machining of AISI 304 steel using both cryogenic treated (CT) and untreated (UT) cutting tool insert. The commercially available uncoated carbide insert has been cryogenically treated at -196°C for 24 hours soaking period. The machining test has been conducted under four different cutting speeds. The material characterization of cutting insert is studied by using scanning electron microscopy (SEM), hardness test, and microscopic image analysis has been carried out before and after cryogenic treatment. The cutting tool performance is assessed in terms of of wear, cutting temperature, chip morphology, surface roughness under the influence of cryogenic machining and the results are contrast with UT one. The exploratory findings reveals that the deep cryogenic treatment (DCT) with 24 hours soaking period, performed better wear resistance and improved surface roughness of the cutting tool. Also considerable reduction in the flank wear, crater wear, cutting temperature is obtained and found improved chip morphology.

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KEYWORDS
Cryogenic treatment, Tool wear, Cutting temperature, Chip morphology.

INTRODUCTION

The machining study aims to increase tool life and better surface quality. Over few years, a tremendous research took place on the tool material to overcome the heat generation in order to enhance tool life. The flow of chip on the tool rake face causes an excessive heat generation. The raise in temperature during machining influences on tool life, quality of machining, tool wear, cutting force and formation of serrated chips etc. [1]. Consequently the machining industries are consistently making an endeavor to discover new material that is lighter and more grounded to withstand high temperature. In this regards selection of good cutting tool material before machining operation is very essential. Different types of tool inserts are available commercially, namely uncoated, coated, multilayer coated inserts. However; tungsten carbide (WC) insert is the majority suitable cutting insert for machining with stainless steel [2,3]. A continues effort has been made to enhance properties of the tool material. There are a few methodologies have been persued to improve tool life, for example traditional cooling, single layer coating, multilayer coating, heat treatment process, nitrogen cooling and latest being the CT, which reported a significant enhancement in cutting tool life and reduction in heat generation due to formation of carbide particles over the surface roughness.

In an cryogenic turning of AISI & MDN 250 steel, found a reduction in wear and improved surface finish, are other considerable findings which enhanced machinability [4,5]. Similarly, Varghese et al. [6] in his inveatigation, also claimed significant reduction in tool wear in CT machining in contrat with non CT machining, respectively. In this regard, Chetan et al. [7] reported that CT insert significantly improved in wear resistance, reduced cutting force and chip tool contact length. In another study, da silva et al. [8] studied the performanc of cryogenically high speed tools in contrast with tool of a similar material however, conventional heat treated, during machining and during sliding abrasion tests. It was observed that the CT tools compared to the UT one. Likewise, Padmakumar et al. [9] investigated the tool performance for crystal structure and magnetic properties between DCT and sintered with cobalt (Co) on WC cutting insert. The authors claimed that the presence of cobalt in the cutting insert experience transformation of phase when subjected to DCT. In another work by Deshpande et al.[10] revealed an improvement in hardness due to the presence of cobalt after CT to carbide insert. Gill et al. [11] also claimed CT performed better in continuous and interrupted machining operation. In another study Gill et al. [12] analysed the effect of CT on metallurgical and mechanical characterization of cryogenically treated (CT) tungsten carbide. The insert were exposed to two different treatment, namely (a) shallow

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cryogenic (-110°C) (b) deep cryogenic (-196°C). It was found that the DCT insert exhibited formation of precipitation of multiple carbide particles that has the indication of η-phase. The results also revealed a phase transformation from retained austenite to martensite which leads to enhance wear resistance and hardness. Likewise, Seah and Zang et al. [13,14] claimed CT process shows significant improvement in wear resiatnce in comparision with UT insert. Similarly, Gill et al. [15] analysed the effect of adhesion strength of coating deposit of carbide substrate. The experimental results revealed a positive result for deep cryogenic insert followed by shallow cryogenic treatment.

In another work, Dhananchezian et al. [16] studied the cause of CT machining on stainless steel and modified physical vapor diposition coated carbide insert. The results indicated a lower cutting temperature by 45%, cutting force by 16%, and surface roughness was reduced by 25% when the insert was exposed to cryogenic cooling.Whereas, Venugopal et al. [17] concluded that cryogenic cooling method during machining has shown remarkable improvement in the wear resistance and decrease in the cutting temperature. Whereas, Rahman et al. [18] studied the performance of CT and UT carbide insert for moderated carbon (C) steel. The experimental results rendered a positive result for intermittent machining operation. Likewise, Ozbek et al. [19] found that DCT-24 sample showed highest hardness rate due to precipitation and homogeneous distribution of η phase particles. He et al. [20] performed a numerical study on stainless steel AISI 304 with coated and carbide insert. The results found the coated tool showed lower cutting temperature in comparision with uncoated tool. Dhar et al. [21] analysed the effect of cryogenic cooling by liquid nitrogen and performance of the cryogenic cooling insert found to be better compared to conventional cooling.

In another study, Dhar et al. [22] claimed a significant decrease in the temperature during machining, chip tool interface temperature and reduced wear rate after CT. kaynak et al. [23] investigated on NiTi alloys and results revealed a lower value of the tool-chip contact length, chip thickness, cutting force in comparison with dry condition. Nayak et al. [24] studied the improvement in tool life of Nitrile Rubber after lower-temperature machining as compared with dry machining. They found that the reduction in cutting force and radial force after lower-temperature machining. Singh et al. [25] studied the effects of minimum quantity lubrication machining over dry and flooded machining on tool wear and surface roughness. They observed that tool lives were increased by 9.68% and 32.26% after a dry and minimum quantity lubrication machining respectively. The literature on extensive experimental study on cutting temperature, flank wear rand surface roughness and chip morphology of the carbide insert on stainless steel is lacking and this spells the need of comprehensive experimental study. Hence, in the present investigation, focused to carry out the performance evaluation of CT on cutting temperature, wear rate and surface roughness and chip morphology is considered in the present work. The machining test has been carried out under different machining parameters. In addition, the investigation has been carried out with microscopic images analysis to support the experimental results.

METHODS AND MATERIAL

An AISI304 austenitic stainless steel workpiece having a dimension of 40 mm diameter and 300 mm length in size was machined under dry machining condition and has been used a workpiece material in the current study. The composition of the workpiece, consists of 0.085% C, 18% Cr, 66.34% Fe, 2% Mn, 8% Ni, 0.045% P, 0.035S, 1% Si. The cryogenic process involved mainly cooling, soaking, raise in temperature. CT of the insert has been performed in a cryogenic chamber. Initially, the inserts were cooled from room temperature to -196°C at a controlled condition and kept it for 24 hours maintaining the same temperature once it attained -196°C followed by increase in temperature till it attains ambient conditions. The temperature has been raised further up to 200ºC for 2 hours. The machining trails are executed on CNC Machine (ace jobber xl) and uncoated carbide insert (Seco CNMG 120408 Grade MF3 029) supplied by Seco Tools India Pvt. Ltd and the cutting tool were rigidly mounted on tool holder designated by DCLNR 2525 M12.

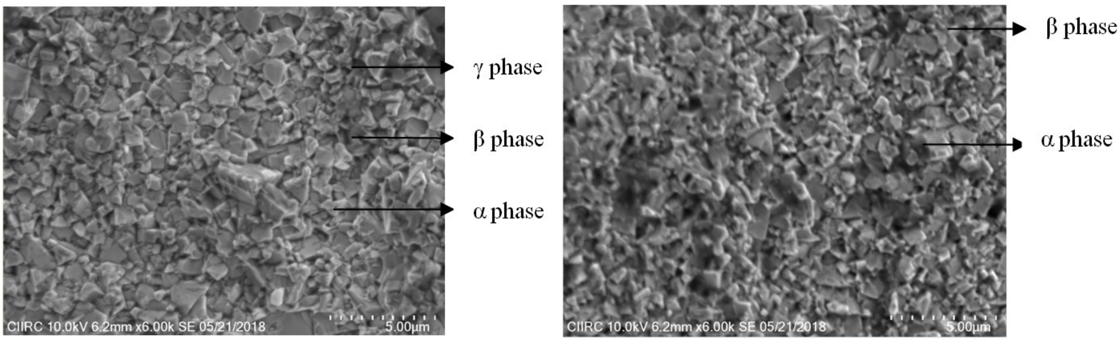
To investigate the effect of CT on tool wear, surface roughness, cutting temperature and chip morphology were performed at different cutting parameters on both CT and UT carbide insert. The wear test was performed on CNC Machine, at different cutting speed (100.52m/min, 125.66m/min, 150.79m/min and 175.92m/min), constant feed rate 0.14mm/rev and depth of cut 0.5mm. In the course of experimentation, different types of wear tests were formed on the cutting tool at different speeds. To investigate the performance of wear mechanism, microscopic study of the tungsten carbide inserts has been carried out in terms of maximum tool wear for every 2 minutes of machining operation. The machining process was stopped at every 2 minutes and the amount of flank wear and crater wear formed on the inserts has been measured before and after machining using digital microscope (Model: AM3113T: Range: 20 to 250x). The maximum flank width of the flank wear when it reaches 0.6 mm during machining is considered as tool life of the cutting tool as ISO standard.

The micro-hardness test was performed for both insert using Vickers hardness test with a load of 0.5N for a dwell time of 15sec. To investigate the performance of wear mechanism, microscopic study has been carried out before and after machining by using digital microscope and the energy dispersive spectroscopy (EDX) test was carried out to identify the weight percentage of foreign particles on the tool surface area. Formation of built-up edges during high speed machining is evaluated using Mitutoyo SJ210 surface roughness tester. The experiment has been repeated for three trails and the average of the three readings has been considered for the analysis to overcome the experimental error. During machining operation the chip was flowing over the rake face of the tool due to rubbing action that leads to heat generation, was measured in terms of increased temperature using infrared thermometer (Make: Equinox ED-DT530A:range: -32°C to 530°C), Accuracy: ± 2 ºC or 2%: Resolution 0.1 ºC / 0.1ºF: Emissivity: 0.95 (fixed).

RESULT AND DISCUSSION

Cutting Tool Characterisation by using SEM and EDX

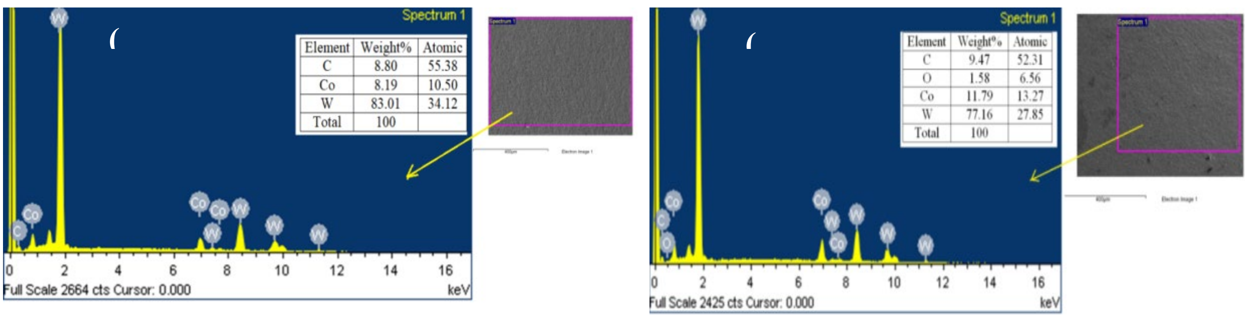
Figure 1(a) and 1(b), represents the microstructure of CT and UT inserts. Following phases present in the microstructure; alpha (α) phase which indicates WC particles, beta (β) phase indicates cobalt binder, gamma (γ) phase consists of (tantalum carbide) TaC, (titanium carbide) TiC and Eta (η) that contains multiple carbide. It is clearly observed from SEM images in Figure 1. The angular pattern with light grey in the microscopic image represents the WC particles while dark grey in between the lighter grey are the cobalt binders as shown in Figure 1(a), the α phase of CT insert is seen in a triangular shape which is the most balanced state, whereas the α phase in UT insert is unstable. The most balanced α phase helps to improve the wear resistance and hardness of CT insert due to stress-free appearance of the microstructure which leads to precipitation of fine η phase carbide on the top surface of the carbide insert. This enhanced the wear resistance in comparison with UT insert. A similar finding was also claimed by previous researchers [26, 27].



(a) CT (b) UT

Figure 1. Microstructure of carbide inserts.

EDX analysis was carried out to examine the weight percentage of CT and UT carbide insert. EDX spectra along with the chemical composition of both the carbide insert shown in Figure 2(a) and 2(b). From the Figure, observed a change in the chemical composition in cryogenic inserts. The growth in the Co and carbon (C) percentage are seen over the top surface of the cryogenic insert, after the CT. The weight percentage of C and Co of CT insert (C: 9.47% and Co: 11.79%) was found to be higher in comparison with UT (C: 8.80% and Co: 8.19%). This indicated the densification of Co binder for CT inserts. The growth in carbon percentage leads to precipitation of η phase carbide, which is hard in nature, leads to an increase in the wear resistance in comparison with UT insert. Similar finding were also claimed by the previous researchers [28, 29].



(a) UT (b) CT

Figure 2. EDX analysis of carbide inserts.

Hardness Analysis

In the present experimental study, hardness rate is evaluated for both CT and UT insert. The average value of the micro-hardness along with standard deviation of both carbide inserts are shown in Figure 3. The hardness value of the CT insert having higher value approximately 4% had obtained in comparison with UT. The increase in hardness rate is due to densification of cobalt binder and precipitation of η carbide, which seems to be the harder phase and this, was confirmed in the EDX test. From the EDX it is confirmed that the cobalt binder decreased. Since, due CT of carbide inserts, the α phase is exposed to compressive stresses β phase exposed tensile stress. The quantity of the stresses in the α phase increases with reduction in β phase content due to rapid cooling. The sudden cooling leads to increase in compressive stresses would lead to an increase in the formation of η phase carbide. This leads to increase in the micro-hardness [30]. The DCT in the cutting insert enhanced mechanical properties, especially hardness has improved by 20% in comparison with UT insert, which enhance strength of the material [31].

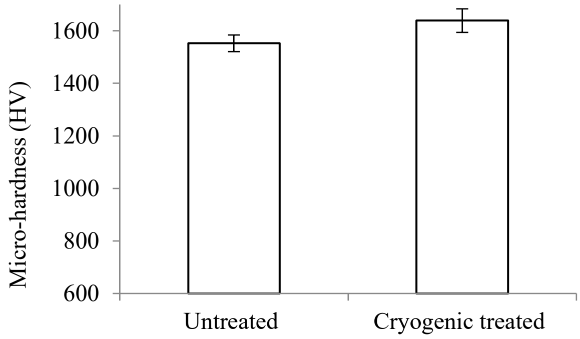
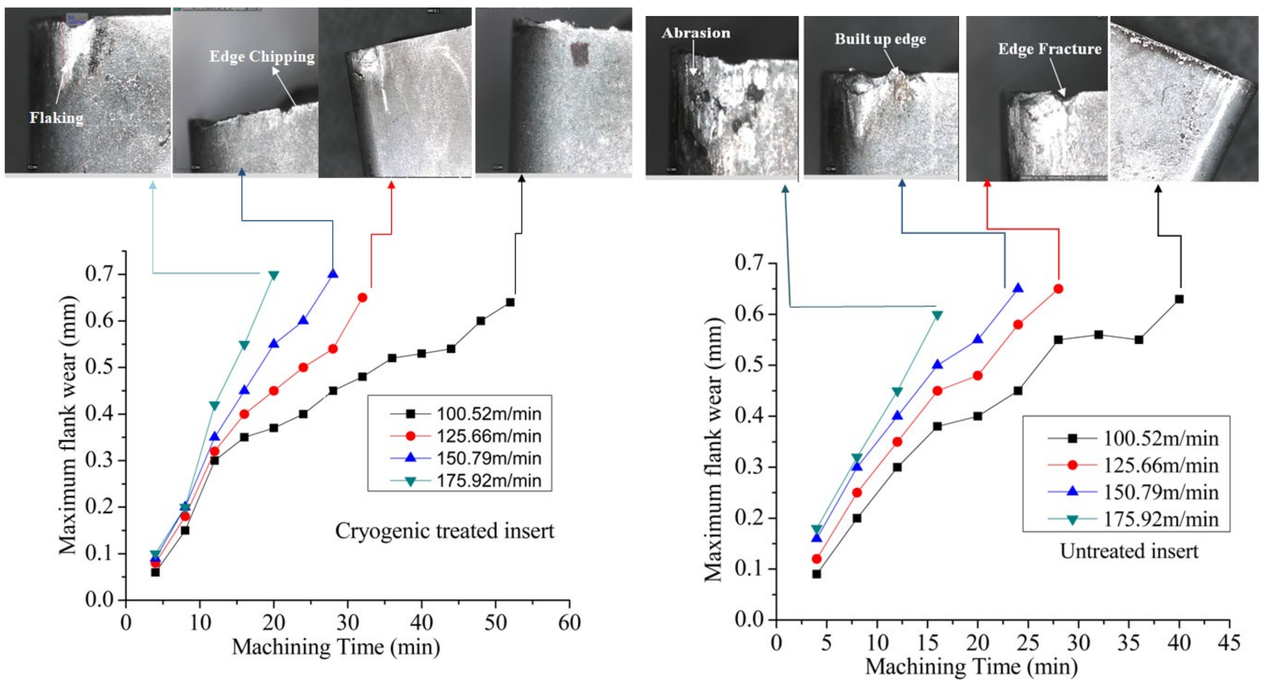


Figure 3. Micro-hardness of carbide inserts.

Effect of Cryogenic Treatment on Tool Wear

Flank wear

A rapid wear rate is observed initially, in this region; cutting is quickly broken down, established a wear land and uniform wear is noticed in which the wear rate gradually increases with increase in machining time followed by uncontrolled wear region [32]. Figure 4 and 5 show the maximum width of the flank wear (VBmax) for both CT and UT insert respectively. The tool life criteria (VBmax=0.6mm) is applied for all four cutting speeds by keeping feed rate and depth of cut constant. In this experiment the work piece has been machined at different cutting speed up to it reaches the maximum tool wear (VBmax=0.6mm). In the result it is found that the flank wear appeared after 4 minutes of machining operation for both the types of cutting inserts. The CT insert performed better in all the cutting speed in comparison with UT insert and improved by 40% at 100.52 m/min, 13% at 125.66 m/min, 23% at 150.79 m/min and 21% at 175.92 m/min. Due to the CT, the microstructure of the carbide insert has been improved mainly because of precipitation of η phase carbide particles. This clearly depicts that the CT establishes a prolonged tool life than the UT cutting insert. The DCT improves mechanical properties of the cutting insert, due to homogenous distribution of carbide particles over the surface leads to outstanding enhancement in wear resistance which in turn improves tool life and this was also reported in the literature [33, 34]. The Table 1 represents the tool life (VBmax=0.6mm) of CT insert and UT insert under different cutting speed.



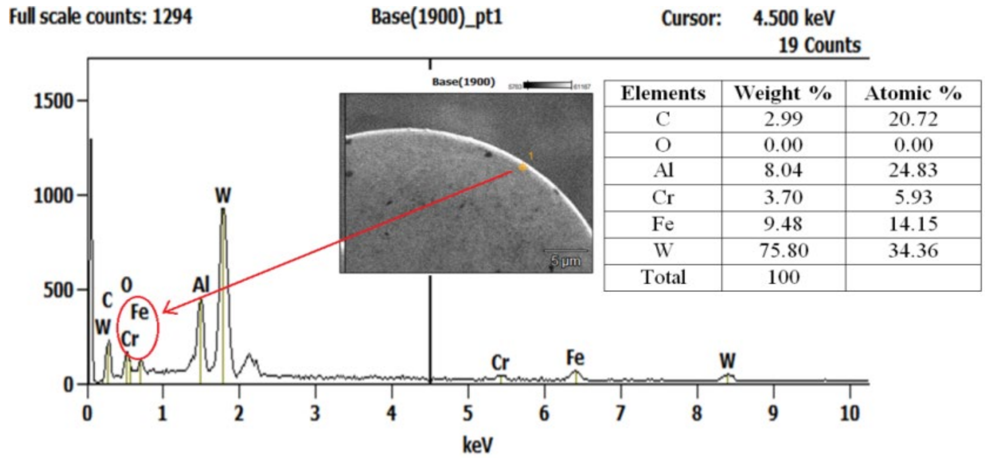
(a) (b)

Figure 4. Variations of flank wear according to machining time of (a) CT and (b) UT insert

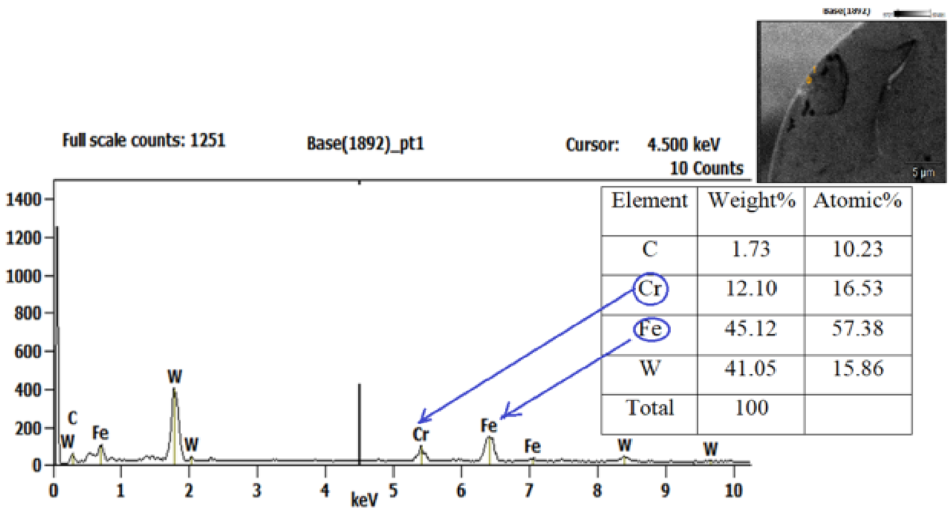
To evaluate the diffusion at the tool-workpiece interface, EDX analysis has been carried out at tool rake face of the both the cutting inserts. Figure 6(a) and 6(b) shows the EDX spectra along with chemical composition of both the insert. The uninterrupted embossment of chip over the rake face for prolonged time duration has resulted in adhesion over the rake face. The reactive nature of iron (Fe), chromium (Cr) and nickel (Ni) is the cause of such behavior. The amount of Fe as per the table indicated in EDX analysis found to be considerably lower in case of CT (9.48%) compared with UT one (45.12%). In addition, lower amount of Cr (3.70%) and Ni (1.06%) is being detected in case of CT inserts. The EDX analysis clearly depicted that the adhesive wear is more intensive in UT inserts. The substantial amount of chemical composition of the workpiece material is found over the rake face which clearly shows the presence of built up edge formation in UT inserts whereas negligible amount of work piece material is seen in case of cryogenically treated (CT) inserts. Hence the adhesive wear and uncontrolled chip removal caused maximum wear in UT inserts whereas less wear has been detected in case of CT insert due to lower rate of built up formation of edges over the rake face.

Table 1. Shows tool life (VBmax=0.6mm) of CT insert and UT insert under different cutting speed.

Cutting speed (m/min)	Cutting insert	Machining time (min)
100.52	CT insert	48
	UT insert	39
125.66	CT inset	30
	UT insert	25
150.79	CT insert	24
	UT insert	22
175.92	CT insert	17
	UT insert	16



(a)

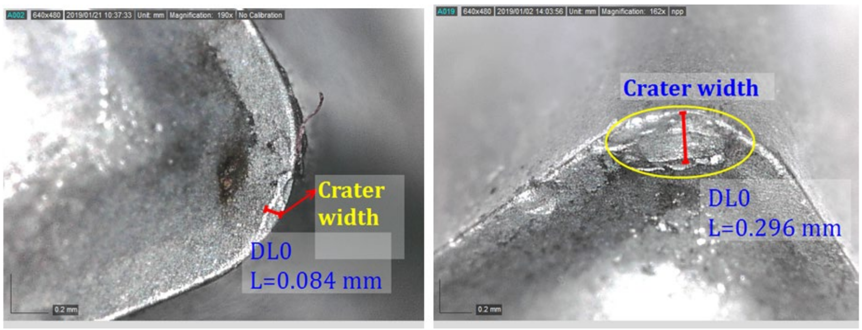


(b)

Figure 6. EDX results after machining for (a) CT (b) UT inserts.

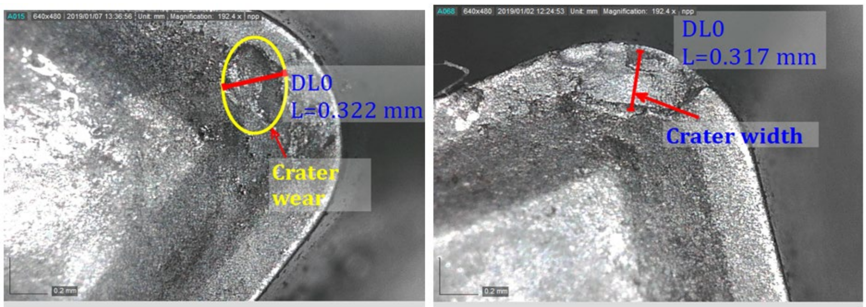
Crater wear

The microscopic images of the rake surface have been carried out at four cutting speeds to study the crater wear. An exhaustive literature along with experimental analysis has been performed on the cutting inserts, observed three different wear mechanisms for all the parameters and this also has been confirmed by various authors [1, 26]. The tip of the cutting insert is normally prone to fracture, adhesion, chip formation due to the excessive generation of built-up edges. In addition, abrasion peeling also being observed at the rake surface region. Figure 7 to Figure 10 shows the crater wear for both the cutting inserts for different cutting speeds. However, as per the microscopic images, the lowest rate of crater wear is being observed for CT as indicated in Figure 7(a). From the Figure 7, it is indicated that the width of crater wear has observed less for CT insert (0.084 mm) and 0.296 mm is obtained for UT one.



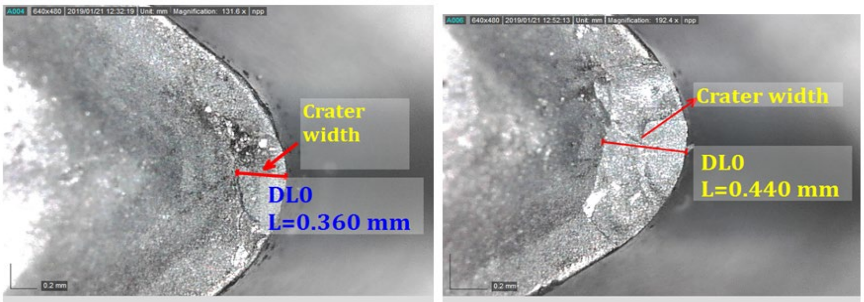
(a) (b)

Figure 7. Microscopic image of crater wear observed at cutting speed of 100.52 m/min on (a) CT (b) UT insert.



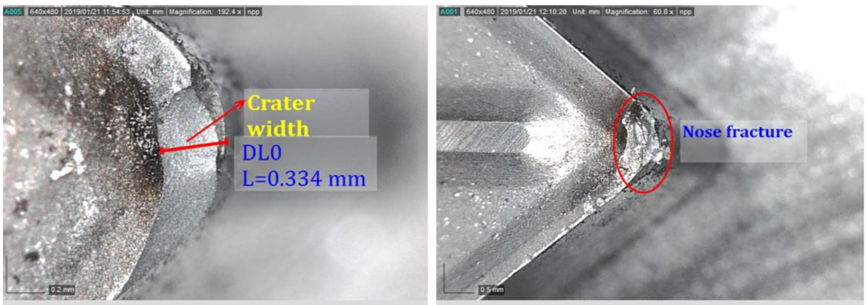
(a) (b)

Figure 8. Microscopic image of crater wear observed at cutting speed of 125.66 m/min on (a) CT (b) UT insert.



(a) (b)

Figure 9. Microscopic image of crater wear observed at cutting speed of 150.79 m/min on (a) CT (b) UT insert.



(a) (b)

Figure 10. Microscopic image of crater wear observed at cutting speed of 175.92 m/min on (a) CT (b) UT insert.

On the other hand for a cutting speed of 125.66 m/min, very less crater wear had found on the tool rake of the tool CT insert in comparison with UT insert as shown in Figure 8. The crater width of the CT found to be less for different cutting speeds in all the cases. Further increase in the cutting speed, the UT insert under goes nose fracture while the CT insert significantly performed better than UT insert. The higher wear resistance due to precipitation of η phase carbide as the reason for the advancement. The increase in cutting speed, advanced into faster removal of material which further triggered to attain higher temperature at the rake face. CT insert has prohibited the built-up edge damage and fracture failure of insert. Along with this, it has curbed the propagation of plastic deformation of the cutting edge. This is happened for the reason that the deployment of CT diminishes the residual stresses developed during sintering of the cutting insert. The improved micro-hardness and toughness as a result of CT followed by tempering treatment assisted to decrease the tool wear, cutting temperature, increased thermal conductivity, heat dissipation capacity are some of the reason which decreases the tool wear under cryogenic machining [35].

Chip Morphology Study

In the present investigation chip morphology study helps to understand the mechanism accountable for emergence of different types of chips formed at different machining conditions, also useful to assess better surface quality of machined work piece and tool life. Figure 11 portrays the SEM images of the crest of the chips formed without treatment and with CT. By observing the Figure it is clear that, both the cutting inserts generates chips in the form zigzag shape while more saw edged chips were seen in case of UT cutting insert compared to CT insert. At 100.52m/min speed no segmented chips are found for both the type of cutting inserts whereas increase in the cutting speed the width of the chip increased, showing more serration chips.

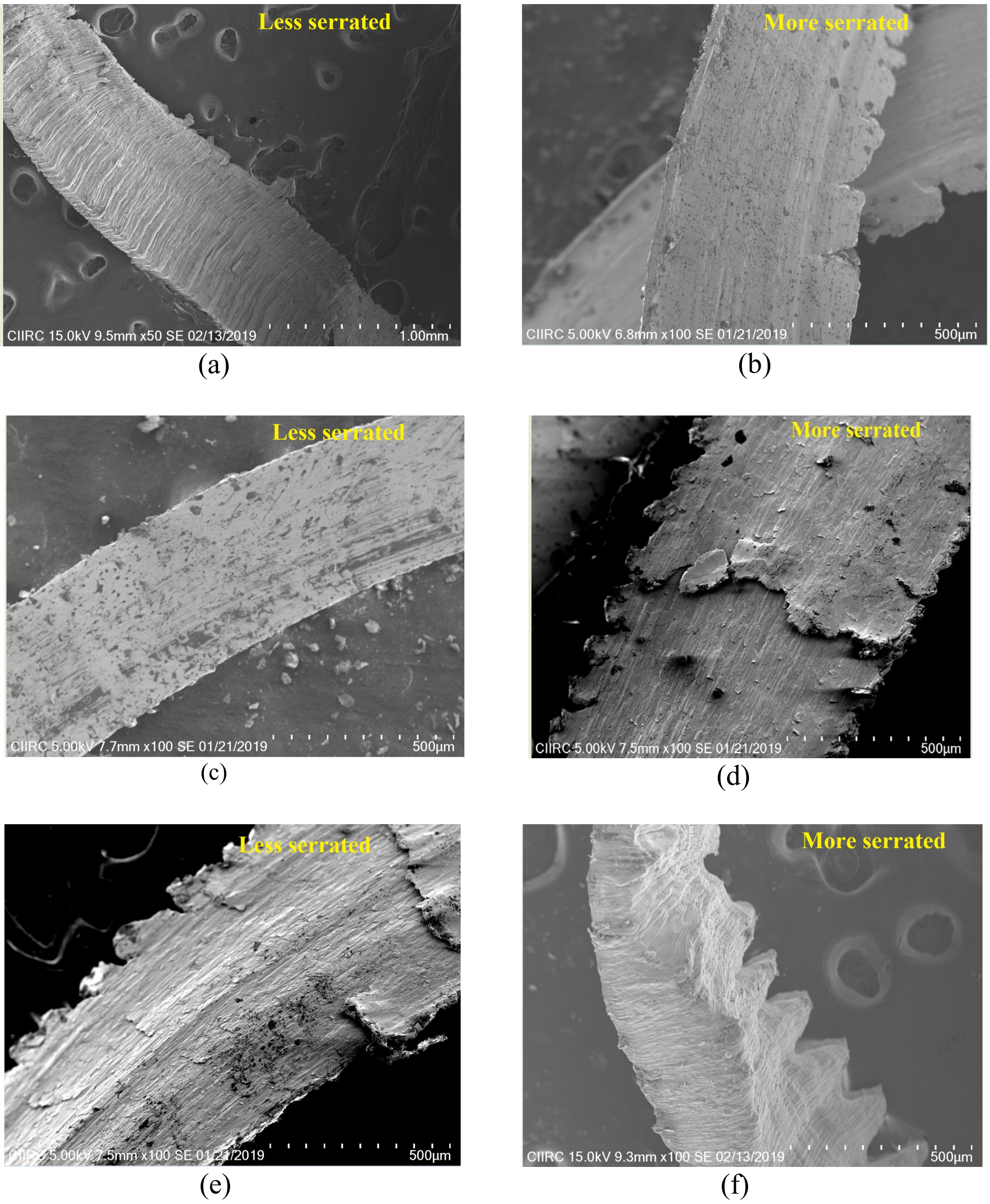


Figure 11. SEM chip morphology at different cutting speed: (a), (c), (e) are CT at100.52m/min, 125.66m/min, 150.79m/min, (b), (d), (f) are UT insert at 100.52m/min, 125.66m/min, 150.79m/min.

The serrated chips size has been expanded with increase in speed. The serrations are more advanced in case of UT than CT one. It has been observed from the Figure 10(b), 10(d) and 10(f) that the UT insert have high degree of serration in comparison with CT insert presented in Figure 10(a), 10(c) and 10(e). The increase in the mechanical properties due to CT would results in enhanced wear resistance, high hardness and increase in toughness leads to less serrated chip in comparison with UT insert. Khan A et [29] reported more serrated chips were found on UT insert at higher cutting speed in contrast with CT insert.

Effect of Cutting Speed on Cutting Temperature under Cryogenic Machining Condition

It was observed from the Figure 11 the temperature increased with increase in cutting speed. The results revealed that the reduction in cutting temperature in case of CT insert found 36% in contrast with UT cutting insert. The difference between CT and UT insert is 27% when the cutting speed increases from 100.52m/min to 125.66m/min followed by 20% for further increase in speed from 125.66m/min to 150.79m/min. At 175.92m/min speed, the difference is found to be 10%. This attributed to the fact that the CT cutting inserts account for the reduction in temperature with increase in speed. A lower value of temperature is found in case of CT insert is mainly due to increase in thermal conductivity and heat dissipation over the rake surface. The increase in temperature is seen in UT insert would increase in wear rate. The performance of UT insert is not satisfactory. The results indicated that with a raise in cutting speed the cutting temperature raises for both the cases. However, the entire CT cutting inserts performed better in contrast with UT insert due to improvement in the mechanical properties and similar results are observed in [23]. Other researches also claimed that the increase cryogenic effect reduces the cutting temperature [16, 17].

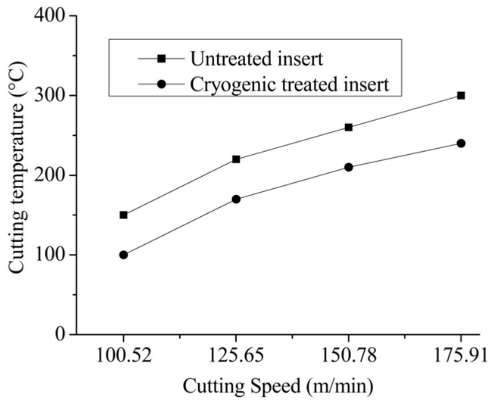


Figure 12. Development of cutting temperature at different cutting speed.

Effects of Cutting Speed on Surface Roughness

The enhancement of surface quality of the working material is also equally important in addition to increase the machinability of the working piece. There are many factors that cause the surface quality of the specimen such as feed, speed, vibration, environmental factor and cutting temperature. The surface roughness has been carried out for both inserts. The typical average value of the surface roughness is shown in Figure 13. It is clear that, CT insert exhibited a better surface finish and more stable reading is obtained than UT insert. The unstable reading has been reported for UT insert due to the excessive generation of chips on the tool rake surface. This may cause to increase in the level of friction and produce residual stresses over the surface which leads to poor surface finish. Whereas surface quality has been shown good in case of CT and found to be around 18% over UT insert. It is revealed that the surface quality improves for all the cutting speed tested in the current study. This is due to higher wear resistance, minimized cutting temperature and lesser distortion of cutting edge. Also the lower cutting temperature due to CT improves thermal conductivity which leads to better heat dissipation and in turn helps to obtain good surface roughness. It is found that the surface roughness is being reduced with raise in cutting speed and for both the inserts. The built-up edge formation and vibration further worsen the surface roughness. Previous researcher also claimed that CT insert improves the surface roughness [36].

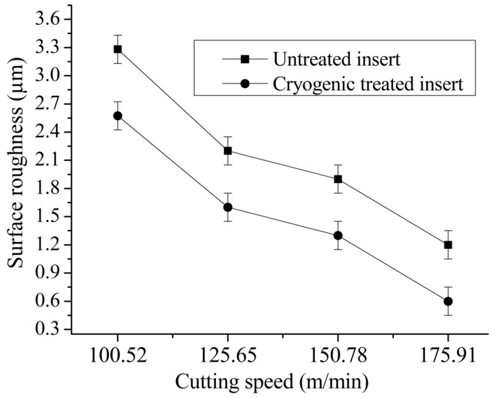


Figure 13. Development of surface roughness at different cutting speed.

CONCLUSION

In the present experimental investigation, machining of AISI304 austenite stainless steel is carried out with cryogenic treated (CT) cutting insert and the results are compared with untreated (UT) insert one. Different types of wear mechanism, cutting temperature, chip morphology and surface roughness has been assessed and compared.

i. The CT cutting insert resists wear more effectively than untreated cutting tool. The enhanced in the micro-hardness due to CT enabled to withstand wear resistance at high speed up to certain extent, but it decreases with further increase in speed. However, the cryogenic treated cutting insert reported least flank wear in comparison with untreated cutting insert.
ii. The CT inserts account for the reduction in temperature with increase in speed compared to UT insert. This attributed to the fact that the CT cutting insert improved mechanical properties and heat dissipation over the rake surface. The rise in temperature is seen in untreated insert would adversely affects the hardness and wear rate.
iii. After CT, the fine η carbides improved the hardness without significantly affecting the toughness. While the α phase of the CT cutting tool is seen in more stable condition The stable form of α phase might have supported to enhance wear resistance of CT cutting tool.
iv. The reduction in tool temperature due to increase in the thermal conductivity, which reduced the tool wear under CT condition in contrast with UT.
v. The highest percentage of reduction in surface roughness during cryogenic machining is 82% in contrast with UT insert.
vi. The results clearly depicts that, both the cutting tools produce ser-rated chips while lower serrations with CT cutting inserts were seen. The high stress, shear force and excess amount of heat generation in the UT cutting insert would have produced large serrated chips.
vii. The results revealed that the reduction in cutting temperature in case of cryogenic treated insert found 36% in comparison with untreated cutting insert. The difference between CT and UT insert is 27% when the cutting speed increase from 100.52m/min to 125.66m/min followed by 20% for further increase in speed from 125.66m/min to 150.79m/min. At 175.92m/min speed, the difference is found to be 10%.

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