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Machinability investigation and cost estimation during finish dry hard turning of AISI 4340 steel with untreated and cryo treated cermet inserts

For higher tool life of cutting inserts cryogenic treatment is considered as the most prominent method but no substantial researches have been found concerning the impact of cryogenic treatment on cermet inserts especially in hard turning. Therefore, in the present experimental investigation, the comparative assessment of various responses such as cutting force, flank wear, crater wear, chip morphology and surface roughness were carried out during machining of hardened steel with both untreated and cryo treated cermet ins hard turning erts under dry cutting condition. Lastly, the input variables were optimized using Response surface methodology (RSM) to evaluate the tool life for the economic analysis. The experimental result demonstrated that the uncoated deep cryo treated with tempered cermet insert delivered better results in comparison to other cermet inserts. According to cost analysis, uncoated and deep cryo treated with tempered cermet insert was found to be the most economical among other cermet inserts at the optimum cutting condition.

Keywords: *hard turning, cryogenic treatment, machinability, cost analysis.*

INTRODUCTION

Quality, productivity and economic aspects of any machining process is influenced by tool life to a great extent. The cost of machining depends on one of the significant responses i.e. tool life and it is advisably influenced by the generation of high temperature at the tool-work and tool-chip interfaces during hard machining. In order to sustain at such high temperature hardness and wear resistance of the tool material must be high enough. Else, due to the softening of cutting edge and rapid progressive wear on the rake and flank surfaces, the machining characteristics may be severely hampered. Various methodologies have been proposed by number of researchers and scientists for the enhancement of tool life, such as coating, heat treatment, application of divergent coolants, use of different types of tool geometries and cryogenic treatment. However, over the last few years, cryogenic treatment has been put through extensively by various researchers in the field of metal machining. From the research outcomes, it was summarized that there was an improvement in the performances of cryo treated tools in comparison to the untreated tools. Therefore, the effects of both shallow and deep cryogenic treatment with tempering on the performances of uncoated cermets have been studied in this investigation.

Gill et al. [1] performed turning operation using cryogenically treated tungsten carbide inserts under dry and wet cutting conditions and better results were observed for cryogenically treated inserts in wet conditions, under both continuous and interrupted machining modes. While turning Ti–6Al–4V alloy, Dhananchezian et al. [2] compared the performance of modified cutting tool inserts in cryogenic machining and wet machining. It was observed that all the machining attributes, substantially reduced in cryogenic machining as compared to wet machining. Umbrello et al. [3] studied the effects of cryogenic cooling on surface integrity of hardened alloy steel. Better surface integrity aspects were observed while machining with cryogenic cooling in comparison to dry cutting. Kivak et al. [4] analysed the effect of cryogenic treatment on M42 HSS drills during machining Ti–6Al–4V alloy. Both wear resistance and tool life enhanced in cryogenic treatment under both dry and wet cutting conditions. Reddy et al. [5] carried out experiments on C45 steel with deep cryogenically treated tungsten carbide inserts and found that the machinability aspects of C45 steel were enhanced using deep cryo treated inserts compared to untreated inserts. Reddy et al. [6] compared the performances of untreated and deep cryogenic treated carbide inserts while turning AISI 1040 steel and found that the deep cryogenic treated insert outperformed untreated insert. Thornton et al. [7] studied the effects of deep cryogenic treatment on wear characteristics of carbide inserts while machining AISI 1045 steel. Results revealed that hardness of the insert was increased and flank wear was reduced. Gill et al. [8] performed experiments using three types of inserts and compared their performances. The results revealed that higher tool life, better surface finish and less machining forces were required for deep cryogenically treated and tempered tool. Gill et al. [9] also examined the wear behaviour of three types of carbide inserts while turning and studied the effect of cryogenic treatment on various machining characteristics. It was observed that shallow cryogenic treated and tempered insert performed superbly than other inserts. Hui-Bo He et al. [10] studied the performances of various tools while turning AISI 5140 steel under dry cutting condition. Deep cryogenic treated tool delivered an outstanding performance compared to the uncoated and untreated tool. Strano et al. [11] studied the wear behaviour of PVD coated and cryogenically treated tools during turning of Ti6Al–4V. The results revealed that deep cryogenic treated inserts outperformed untreated inserts at high cutting speed regarding flank wear due to the enhancement of wear resistance. Kumar et al. [12] differentiated the performances of three types of cutting inserts while turning EN-47 steel under dry cutting environment. The results revealed that cryogenically treated with double tempered insert performed superior to untreated and only cryo treated inserts. Akincioglu et al. [13] studied the effect of shallow and deep cryogenic treatment on carbide tools and found that deep cryogenic treated and tempered carbide tool performed better than shallow cryogenic treated and tempered tool in terms of surface roughness. Ozbek et al. [14] investigated the effects of different holding times during cryogenic treatment of carbide inserts regarding tool wear while machining AISI 316 stainless steel bars. The results showed that cryogenic treatment with holding time 24 hours performed superiorly compared to other holding times. Akincioglu et al. [15] reviewed different research publications on the cryogenic treatment of cutting tools and concluded that performance of the cutting tool can also be improved by optimizing cryogenic process parameters. Vadivel et al. [16] compared the performances of cryogenically treated and tempered coated inserts with untreated ones. Cryogenically treated and tempered inserts were found to have a better surface finish, less power consumption, less flank wear and higher wear resistance over untreated inserts. Dogra et al. [17] compared the performance of CBN insert with coated carbide, cryogenically treated and tempered carbide and untreated carbide. From the experimental results, it was discered that CBN outperformed all other inserts in terms of flank wear. The surface roughness achieved with carbide inserts was more or less compared to CBN inserts. Both microhardness and white layer were reduced with cryo treated and tempered carbide inserts compared to CBN. Deshpande et al. [18] investigated the effects of cryogenic treatment and microwave irradiation on carbide cutting tools while machining C45 steel. The results revealed that wear resistance, hardness and tool life of the inserts were improved due to cryogenic treatment and microwave irradiation.

Ozbek et al. [19] analyzed the effect of cryogenic treatment on uncoated carbide during dry turning of stainless steel. From the XRD analysis, it was observed that due to cryogenic treatment and tempering, both hardness and wear resistance were improved. Kalsi et al. [20] studied the effects of post-tempering cycles on cryo treated carbide inserts. The experimental results revealed that the wear resistance and microhardness of the insert were improved due to tempering and cryo treatment. Singh et al. [21] compared the performances of cryo treated and untreated carbide inserts regarding flank wear during turning of duplex stainless steel under dry cutting circumstances. It was concluded that cryo treated and tempered inserts performed superbly with less flank wear compared to untreated inserts. Cicek et al. [22] optimized drilling parameters while drilling AISI 304 steel using conventional heat treated, cryogenically treated and cryogenically treated and tempered HSS drills and observed that feed rate and cutting speed affected surface roughness and roundness more significantly. Cryogenically treated and tempered HSS drills performed better than other drills.

From the literature review, it was unveiled that, most of the research works have been performed using steel such as mild steel, low carbon steel, medium carbon steel, high carbon steel, stainless steel and tool steel,etc. Still, specific research on medium carbon low alloy steel (i.e. AISI 4340) has not been performed so far. Many researches have been carried out using both coated and uncoated inserts mostly carbide, ceramic, CBN and PCBN. However, the same study has not been carried out on cermet inserts. Most of the researchers have performed the machining activities with deep cryogenically treated inserts. But, very few have opted shallow cryo treatment process. Also, the cryogenic treatment with tempering has been proposed by very few researchers. In maximum cases, the temperature selected for the deep cryogenic treatment process was –196 °C and for shallow cryogenic treatment, the temperature, was –110 °C. Output responses like flank wear, surface roughness and cutting force have been analysed previously. However, substantial studies on chip morphology, crater wear and economic analysis have not been proposed by scientists and researchers using different untreated and cryo treated inserts in the hard turning experiment.

According to the above-mentioned research gap, the objective of the present work is focussed on studying the effect of both shallow and deep cryogenic treatment with tempering on output responses like flank wear, crater wear, surface roughness, cutting force and chip morphology while machining AISI 4340 alloy steel at 48 HRC using UCUT, UCSCT, UCSCTT, UCDCT and UCDCTT cermets. Further, the economic analysis has been performed using the above-mentioned cermet inserts.

EXPERIMENTAL DETAILS

The materials employed in the present experimental work, measurement techniques and the detailed experimental procedures, including cryogenic treatment are illustrated in this section.

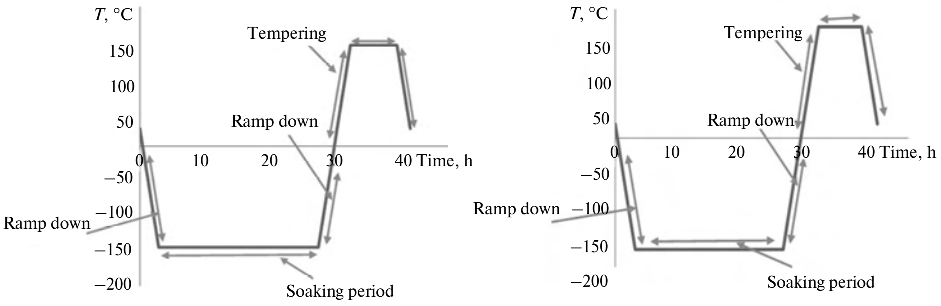
Shallow and deep cryogenic treatment of cermet inserts

In both shallow and deep cryogenic treatment, the inserts were kept in a plastic container before placing in the cryo chamber and the cryogenic dipstick as shown in Figs. 1, *a* and *b*, respectively. This was done to prevent the direct contact of inserts with the liquid nitrogen to circumvent the possibility of thermal damage. The tempering operation was performed after shallow and deep cryogenic treatment to alleviate the residual stress induced during cryogenic treatment. In the current research work, uncoated cermet inserts were shallow and deep cryo treated followed by tempering. The entire procedure adopted for the above thermal treatments were summarized in the following steps and the cryogenic cycle diagrams were shown in Figs. 2, *a* and *b* for both shallow and deep cryo treatment with tempering.

a *b*

Fig. 1. Experimental setup for shallow cryogenic treatment (*a*), and deep cryogenic treatment (*b*): *1* – cryo chamber; *2* – dipstick.

At first, the cermet samples were placed in the cryo chamber. For shallow cryogenic treatment using a cooling rate of 1 °C/min, the temperature was brought down to –145 °C from room temperature, i.e. 25 °C. After reaching the temperature mentioned above, for soaking the temperature was kept constant for 24 h. By the end of soaking period, the temperature was again raised to room temperature at the same rate. Tempering process was started after the final stage of the cryogenic cycle, where the inserts were kept in a furnace and heated to a temperature of 145 °C with a same rate. After attaining the temperature, it was kept constant for 7 h. Then finally, the temperature was brought down to the room temperature, at the same rate. For deep cryogenic treatment, the same procedure was adopted but the temperatures selected were 22°C (the room or initial temperature), –173 °C (final temperature) and 173 °C (temperature for tempering cycle). Also, in deep cryogenic treatment, cryo chamber was replaced by cryogenic dipstick, which was immersed in liquid nitrogen. The electronic temperature controller controlled the temperature. The tempering cycle adopted in deep cryo treatment was same as shallow cryogenic treatment.



a *b*

Fig. 2. Procedure followed for shallow (*a*), deep cryo treatment with tempering (*b*).

Experimental procedure

In the present experimental work, experimental runs were carried out according to L_9 orthogonal array, i.e. three factors with three levels for different uncoated inserts. Three factors such as cutting speed, feed and depth of cut were considered and their effects on the responses like cutting force, flank wear, crater wear, chip morphology and surface roughness were observed. Before the actual machining operation, the workpiece was first centered, and then the rust layer was removed from the outer surface of the workpiece for the alleviation of any end results of inconsistency on the responses. Each experimental run was carried out for a machining length of 200 mm. Taguchi's orthogonal array technique was used for better results with less cost and time.

Workpiece material

For the present experimental work, AISI 4340 steel was chosen as workpiece material having diameter 50 mm and length 600 mm (Round bar). Using Spectro metal analyser, the chemical composition of the specimen in wt % was examined and presented in Table 1. The steel utilized in this study was a medium carbon, low alloy and high strength steel. Due to high impact or shock resistance, wear and abrasive resistance, this material is preferred for manufacturing of different automobile as well as structural components. The material was heat treated with different heat treatment processes like austenitizing, quenching and tempering. After completion of the entire process, hardness of the specimen was enhanced to 48 HRC from 18 HRC.

Table 1. Constituents of the workpiece in wt %

Elements	C	Ni	Cr	Mo	Mn	Si	Fe
Weight percentage	0.397	1.55	0.9	0.275	0.77	0.339	95.762

Insert and tool holder

In the present experimental analysis, uncoated cermet insert was used. This insert was procured from Taegu Tec Company having grade CT3000 specified as SNMG 120408. The grade of chip breaker geometry associated with this insert was FG, preferred in finishing and semi-finishing operation. This particular insert was selected because of its superior wear resistance, toughness, thermal conductivity and low adhesion. The insert was mounted on a PSBNR2020K12 designated tool holder with the following cutting geometries as shown in Table 2.

Table 2. Tool holder geometry

Tool holder signature	Clearance angle	Back rake angle	Entering angle	Point angle	Nose radius, mm	Side rake angle
Angle recommended	0	–6°	75°	90°	0.8	–6°

Machine tool and measuring instruments

Straight turning operation was carried out in dry cutting condition on a highly rigid and precision lathe (HMT India Ltd.) having a maximum spindle speed of 2040 rpm and power of 11 kW. To measure the machining forces along three perpendicular directions, Kistler three-dimensional dynamometer was used. The width of flank wear after each experimental run was measured using advanced optical microscopy of model 100HD-3D (Carl Zeiss) with a range of magnification from 10X to 50X. Whereas, the morphological study of the flank surface was accomplished using SEM (JEOL JSM-6084 LV). Chip morphological study was accomplished using SEM and the identifications of wear patterns on the rake surface of the inserts were also accomplished by the SEM. The surface roughness parameter *Ra* was measured using a Mitutoyo roughness tester. A simplistic view of the present experimental investigation was shown in Fig. 3.

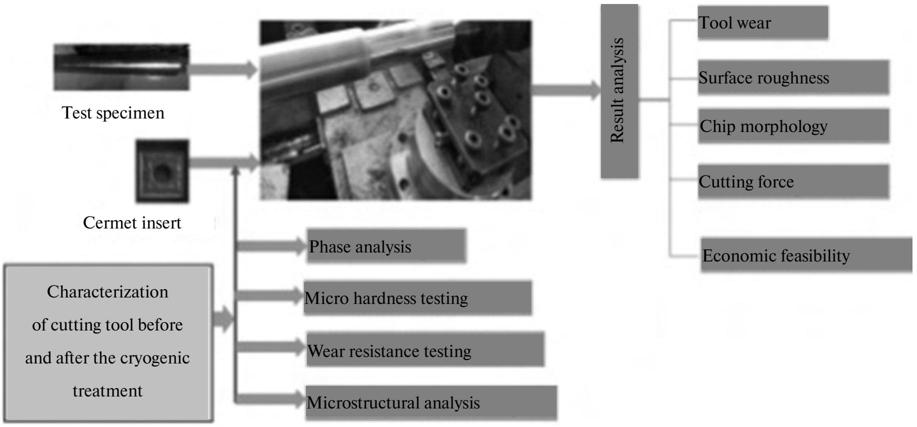
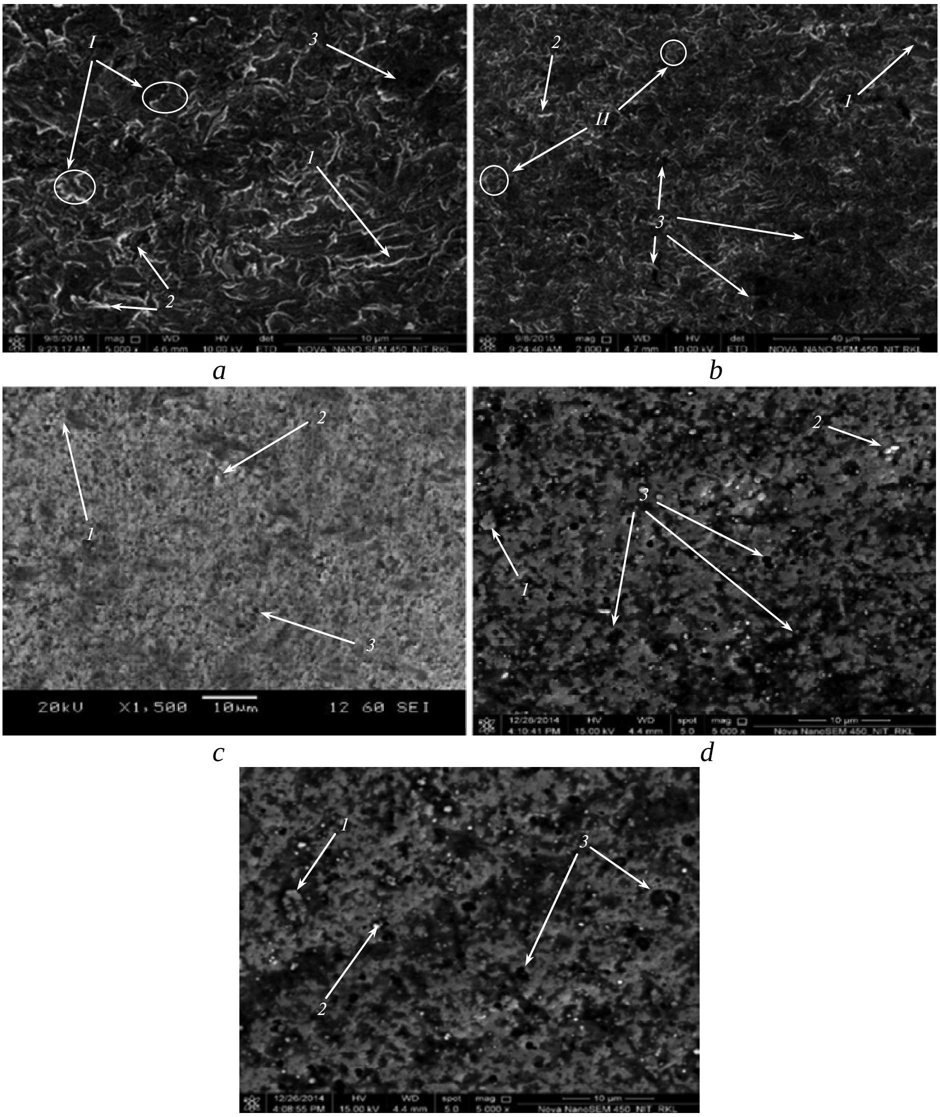


Fig. 3. Simplistic layout of the present experimental setup.

RESULTS AND DISCUSSION

Microstructural analysis of untreated, cryo treated and cryo treated with tempered inserts

From Fig. 4, *a* it was found that the volume of η phase carbides present was lower than that of α phase carbides. Due to non-cryogenic treatment secondary carbide particles were not formed. The uniformly distributed coarse grain structure (larger components) was also found. From Fig. 4, *b* it was discovered that secondary particles precipitated uniformly in the substrate and they formed on a large scale. In cryo treated inserts, fine grain structure (smaller components) was observed when compared to untreated inserts. The hardness and wear resistance of inserts were improved because of formation of η phase carbides. The SEM image of UCSCTT shown in Fig. 4, *c*, revealed that better precipitation and uniform distribution of η phase carbide particles was due to tempering. However, due to tempering the volume of that particular phase of carbide was diminished as compared to cryo treated inserts. Same results were observed in case of UCDCT & UCDCTT cermet inserts shown in Figs. 4, *d* and *e*.



a *b*

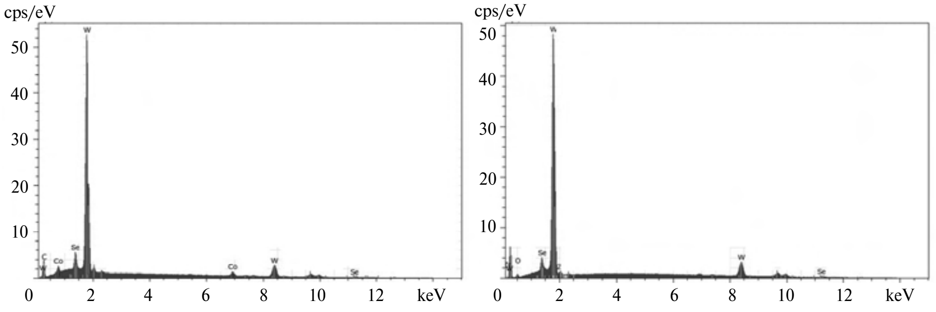
c *d*

e

Fig. 4. SEM images of cermet inserts: UCUT (*a*), UCSCT (*b*), UCSCTT (*c*), UCDCT (*d*), and UCDCTT (*e*): larger (*I*) and smaller (*II*) components; α (*1*), β (*2*), and η (*3*) phase carbides.

EDX analysis

Hardness and wear resistance of cermet inserts were improved after cryogenic treatment. This was due to the diminution and compaction of cobalt or binder phase as well as the increment of carbon percentage both in weight and atomic scale. This was evident from the EDX analysis of uncoated cermet, before the cryogenic treatment, the weight percentage and atomic percentage of cobalt were 5.40 and 6.10, but after the cryogenic treatment, the weight and atomic percentage were diminished to 1.01 and 3.08 respectively as shown in Figs. 5, *a*, *b*, and was mentioned in Table 3 as given below. During cryogenic treatment, different carbide particles or carbide fillers of various phases such as α, β, γ and η phase carbides are normally formed. This was due to the alteration of carbon percentage after the cryogenic treatment, as observed from the EDX graph. It was observed after cryogenic treatment, the weight and atomic percentage of carbon was enhanced from 11.52 to 18.66 and 63.84 to 75.64 percentage respectively. However, after tempering the weight and atomic percentage of cobalt increased and weight and atomic percentage of carbon reduced. The variations in weight and atomic percentage of carbon and cobalt for different cermet inserts were tabulated below in Table 3.



a *b*

Fig. 5. Elemental analysis of uncoated cermet: before (*a*) and after (*b*) cryogenic treatment.

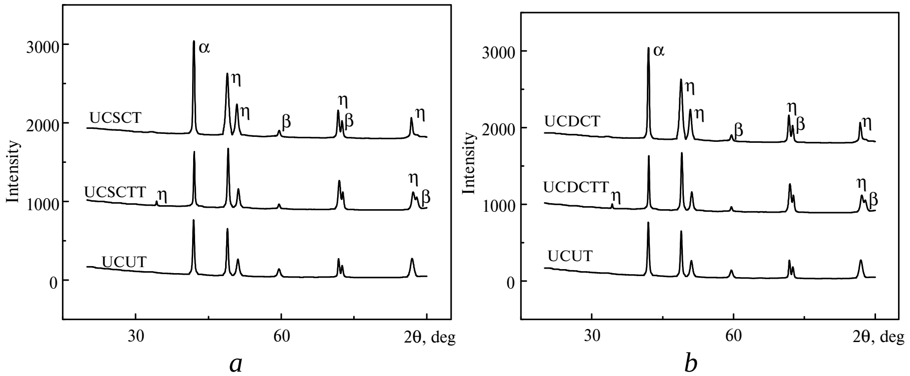
Table 3. Constitute elements of different cermet inserts before and after cryo treatment

Elements	Before cryogenic treatment		After cryogenic treatment		Shallow cryogenic treatment with tempering		Deep cryogenic treatment		Deep cryogenic treatment with tempering	
	normalized C, wt %	atomic C, at %	normalized C, wt %	atomic C, wt %	normalized C, wt %	atomic C, at %	normalized C, wt %	atomic C, at %	normalized C, wt %	atomic C, at %
W	83.01	30.06	80.33	21.27	81.39	27.11	71.38	17.78	76.394	19.62
C	11.52	63.84	18.66	75.64	16.69	72.32	27.33	91.02	24.49	84.631
Co	5.40	6.10	1.01	3.08	2.47	4.19	0.56	1.91	0.93	2.17
Se	0	0	0	0	0	0	0	0	0	0

XRD analysis

Before and after the cryogenic treatment, with the help of XRD texture measurement machine XRD analysis was done to ensure whether there were any physical changes occurred or not, in all three cases, i.e. untreated, cryo treated (both shallow and deep) and cryo treated with tempering. There were three phases of carbides like α, β and η phase present. A phase consists of Tungsten carbide

(WC), β phase consists of binder phase and η phase consists of multiple carbides (one phase from the binder and another phase from Tungsten). In cryogenically treated inserts (both shallow and deepcryo treatment), α, β and η phase carbides were present with high intensities compared to untreated and cryo treated with tempered inserts. And the high volume of η phase carbide was present in cryo treated inserts as compared to treated with tempered one, whereas the minimum volume of η phase carbide was present in untreated inserts as shown in Figs. 6, *a*, *b*. As the selected grade contains cobalt and tungsten, γ phase carbide was considered to be insignificant. The elements like TiC, TiN, and TaC were found absent according to EDX analysis.



a *b*

Fig. 6. XRD analysis of cermet inserts: UCUT, UCSCT, UCSCTT (*a*); UCUT, UCDCT, UCDCTT (*b*).

Micro hardness analysis

In this present experimental investigation, micro hardness of cutting inserts, an indispensable mechanical property, was evaluated and studied in details. Micro hardness normally get influenced by the phase change and microstructural alteration of a material. Micro hardness of the inserts was measured with Vickers micro hardness tester. Fig. 7 illustrated the micro hardness of different cermet inserts. Because of shallow and deep cryogenic treatment, there was an increment in the hardness of 8.92 and 13.09 % respectively [7 and 20] whereas tempering reduced the hardness of both shallow and deep cryo treated inserts about 4.46 and 2.48 % respectively.

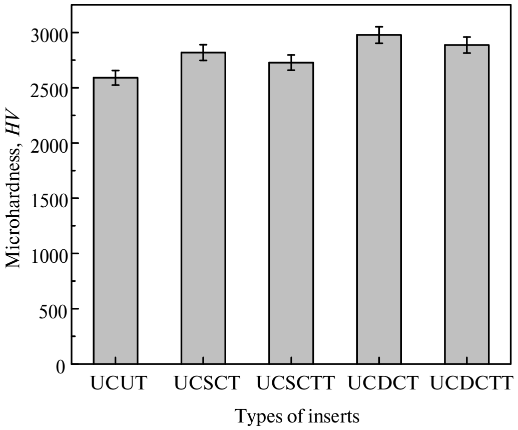


Fig. 7. Micro hardness of cermet inserts.

Wear resistance test

To study the potential of cermet inserts regarding their wear resistance, wear resistance test was accomplished on pin on disc apparatus. Figure 8 demonstrated the wear behaviour of five types of cermet inserts. From the figure, it was concluded that highest or maximum wear was found for UCUT insert whereas minimum wear was found for UCDCTT insert. Because of less hardness and wear resistance, the maximum wear was observed for UCUT cermet insert. It was also noticed from the wear graph that cryogenically treated and tempered inserts performed well as compared to only cryogenically treated inserts. Because, both hardness and brittleness of the inserts were simultaneously increased to a higher range in case of both shallow and deep cryo treated inserts. Tempering enhanced the performances of the inserts resulting diminishment of extreme hardness and rise of both wear resistance and toughness [7, 16 and 20].

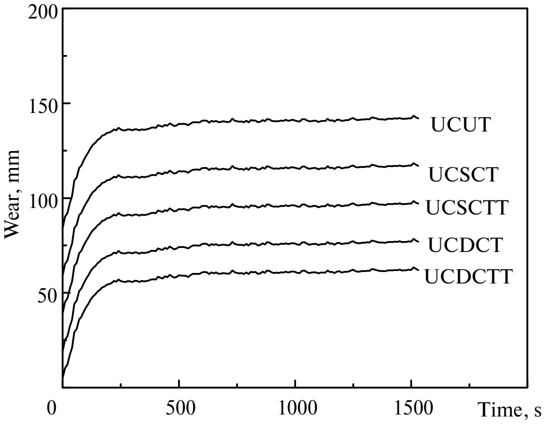


Fig. 8. Wear resistance of cermet inserts.

Effects of machining parameters on the responses

Cutting force increased with the increment of cutting speed. The highest value of cutting force was observed for UCUT insert, while the least cutting force appeared in case of UCDCTT insert. The tool geometry highly influenced both the flank wear and machining force. In the current study, square inserts having point angle 90° and entering or approach angle 75° were considered. Due to high magnitude of point angle, the larger contact area between cutting edge and workpiece was established. Therefore, high cutting force was exerted by these inserts. Similarly, due to the entering angle, vibration was developed during machining, for which both cutting force and flank wear increased. When flank wear was increased, cutting force was greatly affected and changed drastically as a result of temperature rise. UCUT inserts exhibited highest flank wear and therefore maximum cutting force was developed as compared to other inserts as shown in Fig. 9, *a*. Surface roughness increased with the increment of cutting speed because there was an enhancement of cutting force with speed for all inserts. The higher cutting force was observed at high cutting speed because of maximum vibrating force. As a result, surface roughness increased almost for all types of inserts. There was a mixed relationship between the depth of cut and surface roughness, whereas with feed, surface roughness increased. Flank wear grew rapidly as cutting speed increased, because, with cutting speed, temperature increased simultaneously, which was responsible for tool wear and plastic deformation. At high cutting speed, high temperature was developed near the cutting edges of the inserts, but because of lower thermal conductivity for UCUT insert, the tool strength was reduced drastically compared to cryo treated inserts. So more flank wear was observed in case of UCUT insert in comparison to other inserts as shown in Fig. 9, *b*. The surface roughness of the specimen was also affected with the increment of flank wear for all cermet inserts. Due to maximum flank wear, the highest value of roughness was obtained for UCUT insert and lowest value was for UCDCTT insert [8, 13, 16] as shown in Fig. 9, *c*.

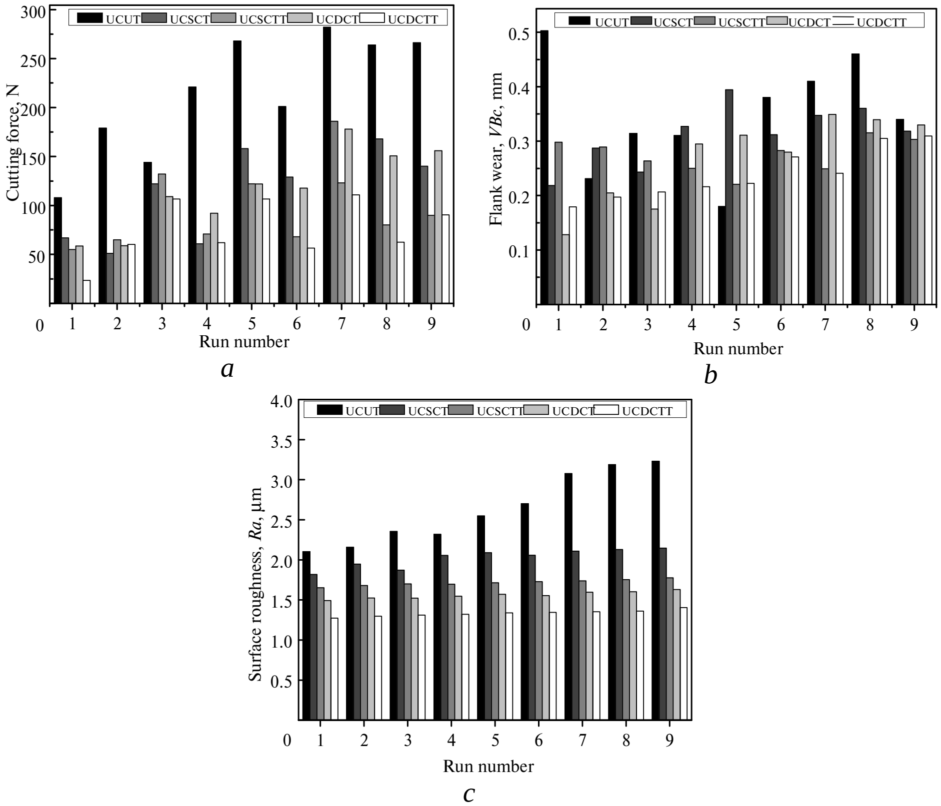


Fig. 9. Development as well as growth of cutting force (*a*), flank wear (*b*) and surface roughness (*c*) using various cermet inserts.

Flank wear analysis of cermet inserts using SEM

Various types of wear patterns were observed in case of UCUT insert as shown in Fig. 10, *a* i.e. chipping or breakage of cutting edge, nose wear, abrasion, adhesion and notch. Because of non-cryogenic treatment, the hardness and wear resistance of the insert could not be improved. This might be the main reason for the types of wear mechanisms quoted above. The notch was formed due to plastic deformation of the cutting edge. Due to excessive mechanical loading during machining, edge chipping occurred. Deep abrasion marks were observed on the flank face because of the presence of hard constituents in the specimen due to heat treatment. At the nose surface, plastic deformation was noticed because of thermal softening. This might be due to low thermal conductivity. Chip materials were adhered to both the rake and flank face of the insert due to its tenacious nature. Due to this tenacious nature, wear with higher depth was observed at the tool rake face.

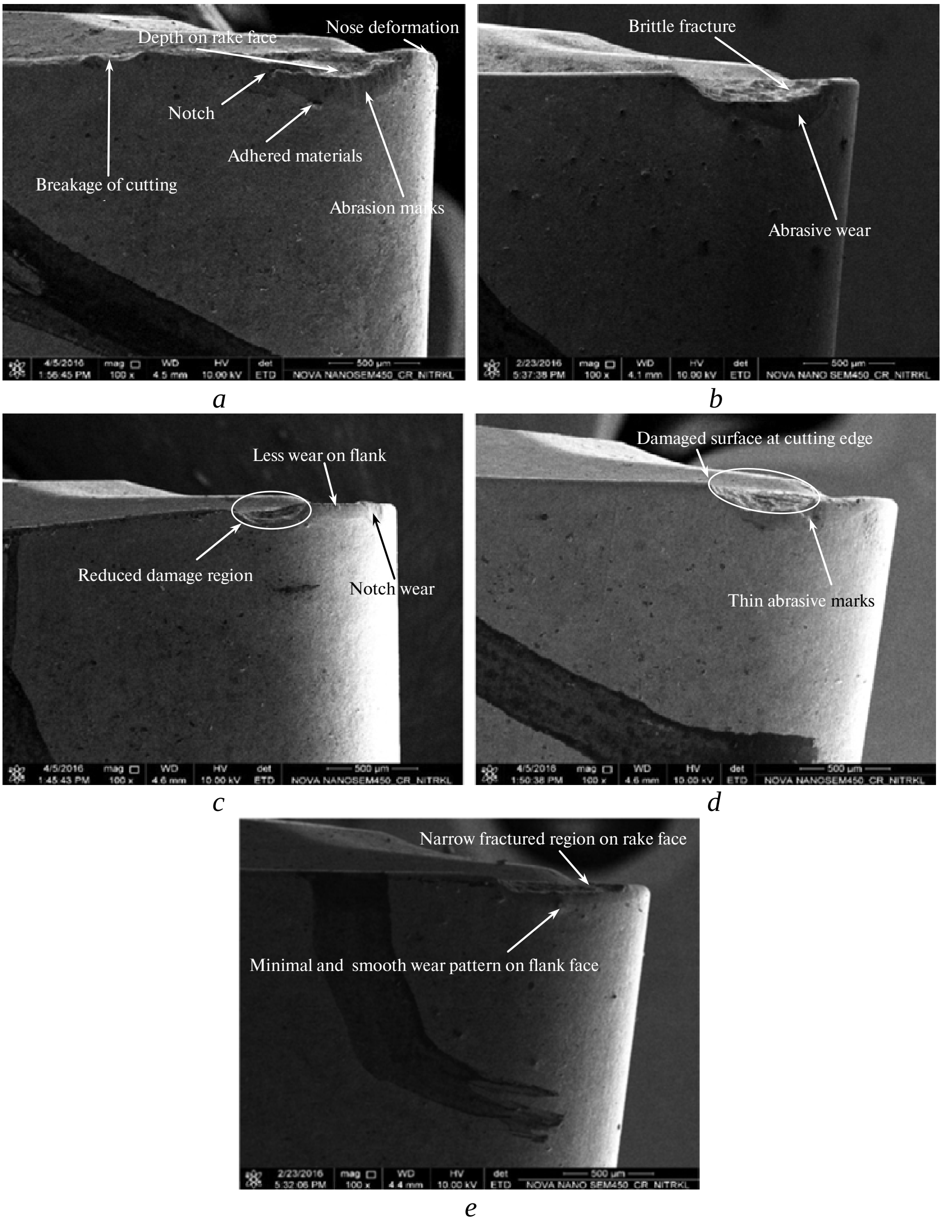


Fig. 10. Flank wear of cermet inserts: UCUT (*a*), UCSCT (*b*), UCSCTT (*c*), UCDCT (*d*), and UCDCTT (*e*).

In case of UCSCT cermet insert, hardness, wear resistance and toughness were improved due to shallow cryogenic treatment. As a result, less flank wear with thin abrasion marks were observed as shown in Fig. 10, *b*. However, at the region of the main cutting edge, brittle or catastrophic failure was observed. Because of the disruption of various phases of carbide particles from the tool substrate, the other wear mechanisms such as a notch, plastic deformation was not found in case of the shallow cryo treated insert.

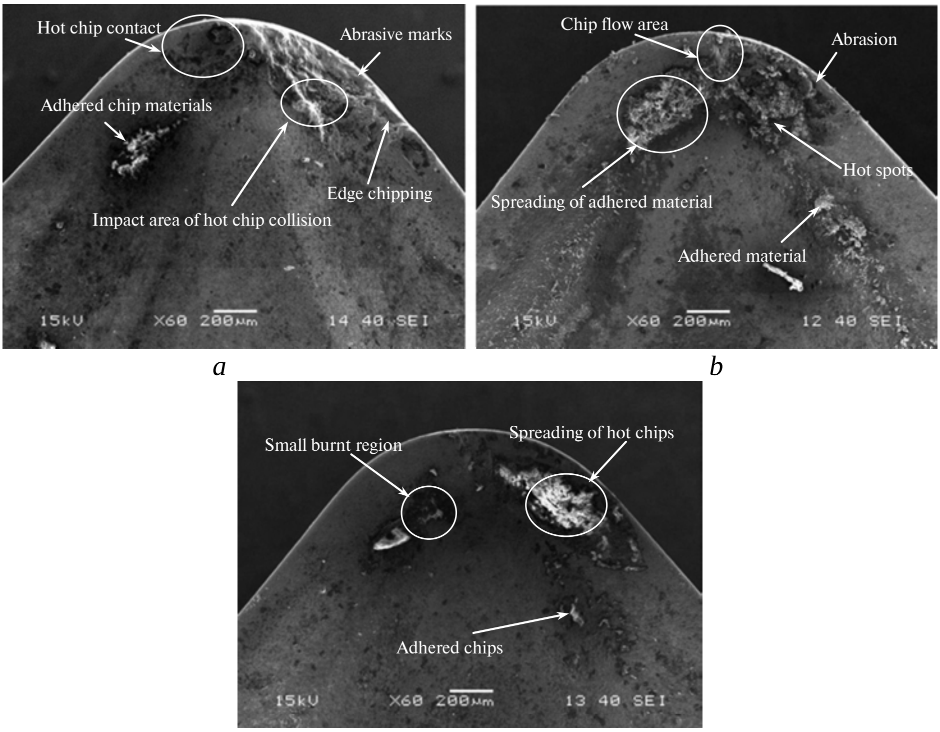
On account of tempering, appropriate precipitation and better distribution of η phase carbides were noticed in the SEM image of UCSCTT cermet insert (see Fig. 4, *c*), for which the excessive hardness of the insert was reduced but toughness and wear resistance were improved. As a result, very less flank wear and reduction of damaged surface appeared at the main cutting edge as shown in Fig. 10, *c*. Whereas, due to the decrement of hardness, plastic deformation occurred at the nose region, which can be referred, as notch wear. The decrement of damaged region was observed due to less residual stress concentration and vibration. In addition, due to the reduction of excessive hardness and increment of wear resistance and toughness, the impact of chip hammering was substantially diminished.

From the experimental data, it was observed that hardness and wear resistance of cermet insert were substantially increased due to deep cryogenic treatment because of the formation of η phase carbide particles. As a result, very less wear was observed on the flank surface of UCDCT cermet insert as shown in Fig. 10, *d*. In addition, due to the improvement in thermal conductivity, thermal cracks, damages and softening of cutting edge were not detected. Whereas, there was a damaged region found at the main cutting edge due to the enhancement of excessive hardness and brittleness for deep cryogenic treatment. As the high volume of η phase carbide was precipitated along the tool substrate owing to deep cryogenic treatment, the compressive residual stress was formed. This local stress concentration might be hampered the tool performance during machining in terms of edge breakage. Another reason for the damaged region at the cutting edge was due to clashing of hard chips with the cutting edge that formed during machining, called chip hammering.

As seen from the SEM image of UCDCTT insert (see Fig. 4, *e*), there was a decrement in the volume of η phase carbides due to tempering. The hardness of the insert was reduced, but wear resistance and toughness were significantly improved [4, 11 and 19]. Minimum wear rate for this particular insert was observed in the friction wear test as shown in Fig. 8. Due to high wear resistance and toughness, smooth wear pattern could be seen at the flank surface of the insert as shown in Fig. 10, *e*. Also, because of better wear resistance of UCDCTT insert, a very narrow fractured region on the rake face was noticed and abrasive wear due to hard chip flow on the rake surface was minimized. The other wear mechanisms such as plastic deformation, notch wear, thermal softening and chipping were not found for the increment of thermal conductivity, high hot hardness and reduction of residual stress concentration due to tempering.

Analysis on crater wear

Minimum wear on the rake surface was observed for uncoated and cryo treated with tempered insert compared to untreated and cryo treated insert, which was shown in Figs. 11, *a–c*. The crater wear mainly occurred due to diffusion or chemical reaction between the workpiece and tool material. At the rake face of the uncoated and untreated cermet insert, thick abrasion marks due to hard chip flow and adhered chip materials were noticed along with edge chipping. Due to the sliding action of hot chips, black spots were observed at the contact area as shown in Fig. 11, *a*. Further, it was observed from the SEM image, that because of hot chip collision the respective area was deteriorated. This happened mainly because of low thermal conductivity, less hardness and wear resistance of UCUT cermet insert. Similarly, for uncoated and cryo treated cermet insert, thin abrasion marks and adhered workpiece materials were observed along with very few hot spots on the rake face. Nevertheless, one interesting phenomenon called spreading of adhered material was detected on the rake face of the insert as shown in Fig. 11, *b*. Throughout the continuous turning operation, hot chips were produced, but these hot chips could not damage the rake surface of the cryo treated insert due to high thermal conductivity and better hot hardness. Whereas, due to segregation of high volume of hot chips and generation of high temperature at the tool-chip contact zone, melting of chips occurred on the rake face resulting spreading of materials. The same phenomenon was also observed for cryo treated and tempered insert and a very small burnt region was found. Chipping and fracture were not observed for this insert because of high wear resistance and increment of toughness.



a *b*

c

Fig. 11. Crater wear of cermet inserts: uncoated & untreated cermet (*a*), uncoated and cryo treated cermet (*b*), and uncoated and cryo treated with tempered cermet (*c*).

When machining hardened steel under high cutting speed, very high cutting zone temperature occurred, and the cutting tool was subjected to ultra-high frequency and strong impact thermal-mechanical loads. The chips burned under high cutting temperature; meanwhile, the cutting edge was submerged in the extremely hot environment, leading to the reduction of strength and hardness. The tool failed to maintain its shape integrity in a few seconds, exhibiting large area flaking in the rake face. At lower cutting speeds, the workpiece material exhibited the brittle behavior with little effect of either strain rate or temperature. Higher cutting speeds lead to the increase in material ductility and higher cutting temperatures. When the cutting speed was further increased, the cutting temperature at localized region of chips became high enough to cause the burning of thin chips, giving rise to the difficulty in the collecting of chips. This should obviously be ascribed to the higher strain rates and temperature variation under very high cutting speeds, and the process was more complex during chip formation. Moreover, the highest content alloying element of workpiece material is Fe. As the cutting speed increases, the percentage of oxygen atomicity increases, and also promotes the reaction between O element and Fe element for oxidation. Because of high temperatures that was generated at the tool-chip and tool-work interfaces during machining, the migration of atoms occurs from the workpiece and tool material. The generated chip is not the melt of the AISI 4340 steel but the oxidation (Fe_3O_4) of it. Figure 12 details the SEM photographs of this chip and the EDS result of point 1 on the chip. As can be seen from the result, there is melted chip material on the chip back surface, and the existence of oxygen element in the melted chip reveals that the melted material was burned or oxidized under high temperature. For some small chips, the oxidation may be very intense and chip maybe burn. This is due to the large amount of heat liberation confirmed by the sparks appeared at higher cutting speed. The heat released during the oxidation melts the chip. The adhesion of workpiece material in the form of hot molten chip on the tool rake face was observed for untreated, cryo treated and cryo treated with tempered inserts.

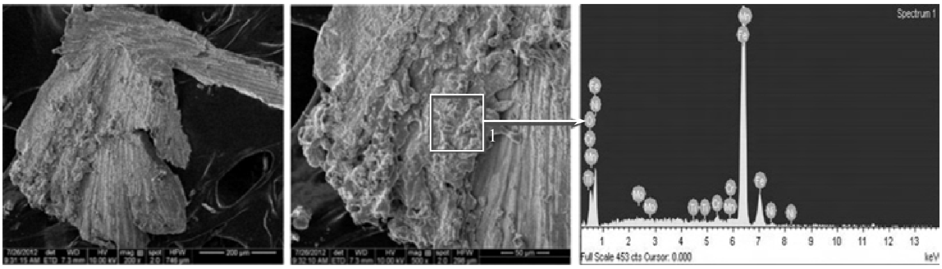
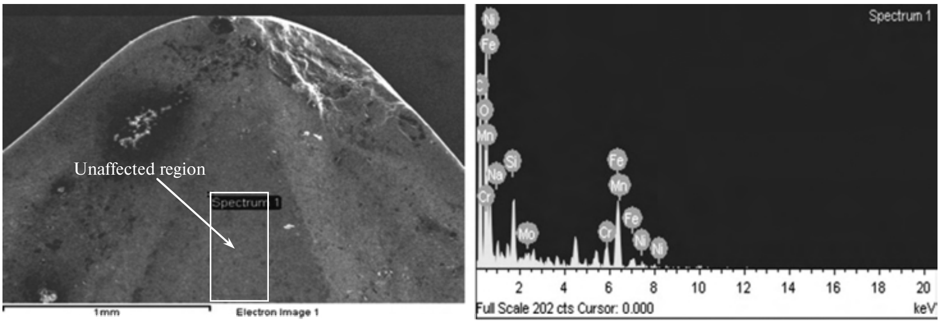


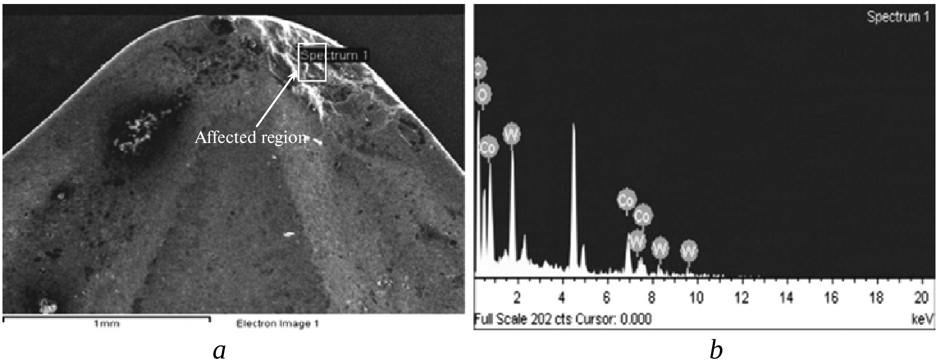
Fig. 12. SEM photographs of the chip and its EDS result of point 1 on the chip.

The migration of atoms from work to tool material was observed in the EDS spectrum analysis as shown in Fig. 13 and Fig. 14. Similar phenomena were obtained when material transformation occurred from tool to work. From the EDS



a *b*

Fig. 13. SEM image (*a*), and EDS spectrum (*b*) of unaffected region for UCUT cermet.



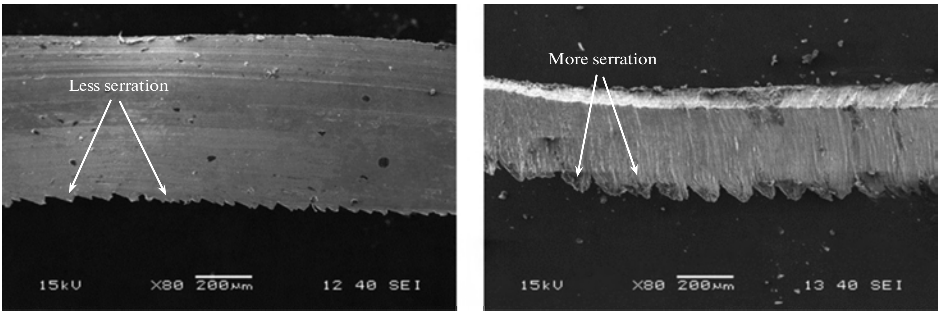
a *b*

Fig. 14. SEM image (*a*), and EDS spectrum (*b*) of affected region for UCUT cermet.

spectrum of uncoated and untreated cermet, different elements were observed like C, O, Co and W at the unaffected region, whereas in the EDS spectrum of affected region, various elements that are associated with the workpiece material such as C, O, Ni, Fe, Mo, Mn, Cr and Si were observed. Therefore, from this EDS spectrum, it was cleared that the components of workpiece material were migrated on to the tool substrate. So due to the migration of materials from the tool and workpiece, substantial wear on the rake face was observed. More adhesion was observed for UCUT insert compared to other inserts. Moreover, as the cutting speed increased during machining, the cutting forces measured increased rapidly due to the larger cutting loads and cutting energy to remove the workpiece material from the substrate. And at the same time, the vibration as well as cutting temperature increased because of the more severe friction between the cutting edge and noncutting surface of workpiece, except for the cyclic thermal shock which would weaken the mechanical properties of cutting tool material, the tool wear accelerated sharply into the abrupt tool wear stage. The main wear mechanism for UCUT cermet tool was chipping by brittle fracture due to its low toughness and high impact regime for the tribological system evaluated caused by the presence of ultra-hard particles on workpiece material.

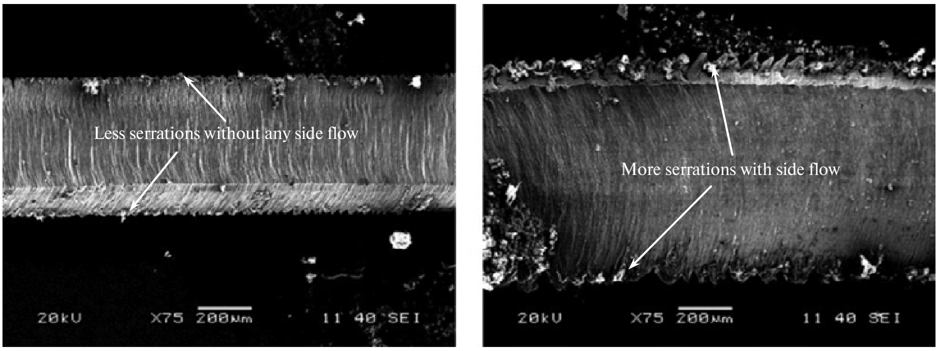
Chip morphology

Chip morphology plays an important role in hard machining. Both the surface quality and the tool life highly depend upon the chip morphology. At inflated feed rate, the chip was entwined and the structure of the chip was changed, i.e. impression of saw tooth formed on the chip surface, which was mainly due to shear deformation at primary and secondary shear zones. Also, due to higher feed, the increase in the contact length between chip and tool resulted in high heat generation due to which microstructural alteration and thermal deformation occurred. This was the main reason for the formation of saw tooth chip. Highest flank wear was observed for UCUT cermet while lowest flank wear was observed for UCDCTT cermet insert because of good strength, enhancement of micro hardness, increment in toughness and wear resistance resulted smaller saw tooth on the chip surface as shown in Fig. 15. Due to maximum flank wear, more heat was generated that contributes to wider saw tooth chip for UCUT insert illustrated in Fig. 15. Another important attribute of chip morphology was discerned during this present experimental investigation called side flow of chips. With UCDCTT insert, no side flow of chip was observed, whereas with UCUT insert severe material side flow was observed, which was shown in Fig. 15. A notable improvement in micro hardness, wear resistance and toughness for UCDCTT insert after cryogenic treatment and tempering might be contributed to this.



a *b*

Fig. 15. Images of chips procured by FESEM after machining hardened alloy steel with cryo treated and tempered tools (*a*, *c*), and uncoated and untreated tools (*b*, *d*).



c *d*

Fig. 15. (Contd.)

Economic feasibility in hard turning using various types of uncoated cermet inserts

The fundamental venture of any manufacturing process is to produce a component at the minimum cost possible. Nowadays, with increased burden on cost management and profitability, manufacturers have aimed to regulate the overall cost for machining operations in order to confirm consistency and establish cost benchmarks for recommendation in coming times. The total machining cost has three major constituents: machining cost, cutting tool changing cost (idle time cost) and cutting tool cost. Longer tool life results high machining cost because of the cost of using the machine and operator for an extrapolated machining time while, a shorter tool life leads to high production cost because of frequent tool replacement (tool cost and tool changing cost). Therefore, a detailed economic analysis is needed in order to maintain a balance in the aforementioned trends. Concerning for economical estimation and cost consciousness, the selection of process parameters appropriate to an optimum range leads to a paradoxical enhancement in tool life. In addition, to investigate whether a cryogenic treatment could be an economically feasible process for hard turning operation using various cermet inserts at optimal setting of cutting parameters, tool life evaluation is mandatory. Hence, in the present work, desirability function analysis of Response surface methodology (RSM) is performed to obtain the optimum cutting condition for tool life evaluation. Figure 16 exhibits the optimization results, which presented the optimal solution for minimum tools flank wear (VB) value at cutting speed = 80 m/min, feed = 0.05 mm/rev and doc = 0.10 mm. Finally, some additional experiments are conducted under the precited optimal parametric condition, which reported the life of the different uncoated cermet inserts such as UCUT, UCSCT, UCSCTT, UCDCT and UCDCTT are about 22, 28 33, 41, and 47 min respec-

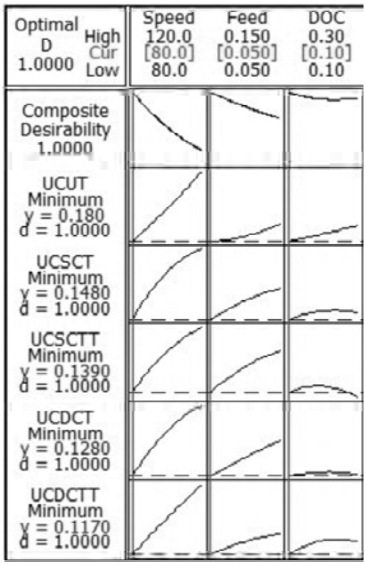
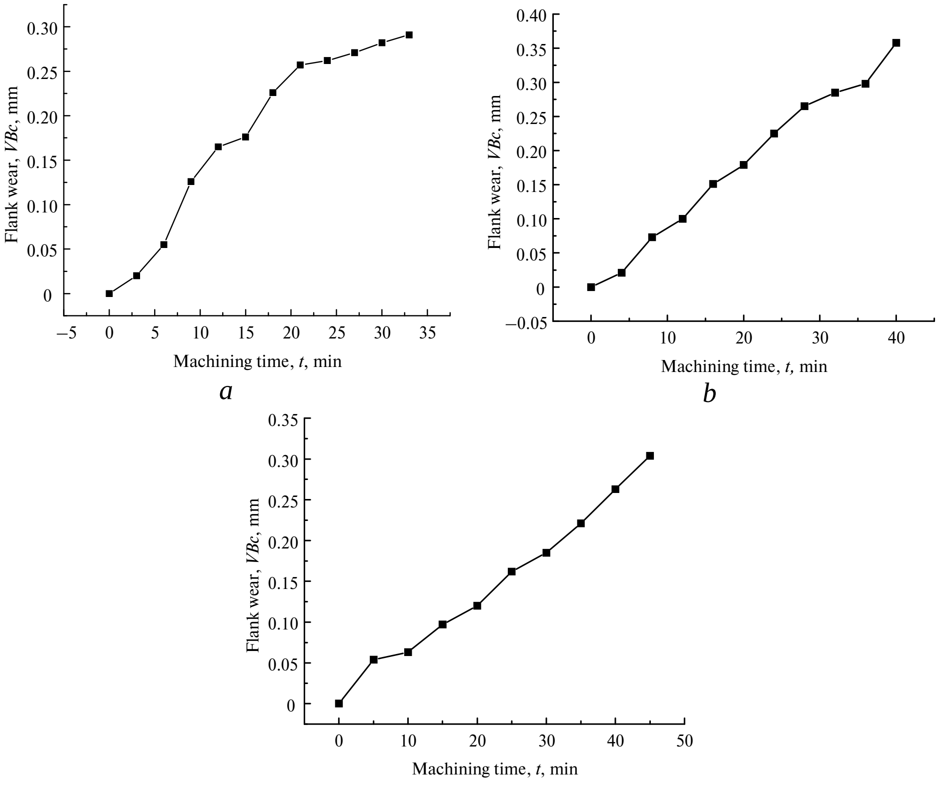


Fig. 16. Optimization plot of flank wear using RSM for different cermet inserts.

tively, keeping in mind of tool life criterion (VB ≤ 0.3 mm) during HT process. The progression of flank wear of various cermet inserts (UCUT, UCSCT, UCSCTT, UCDCT, and UCDCTT) w.r.t machining time are illustrated in Fig. 17. In considering the life of coated ceramic tool being evaluated, a cost analysis has been proposed according to Gilbert's strategy of machining economics [23–26]. A general procedure of estimating the total cost per piece for proposed work material and different uncoated cermet tool inserts in FDHT condition is described in Table 4. On the basis of single cutting edge, the approximate total machining cost per part using different uncoated cermet inserts are Rs. 51.39 for UCUT, Rs. 51.59 for UCSCT, Rs. 49.33 for UCSCTT, Rs. 49.15 for UCDCT, and Rs. 47.40 in case of UCDCTT. So, from the above cost analysis, it was observed that UCDCTT cermet insert was the most economical one compared to other cermets due to its higher tool life for which down time reduced. So the above analysis clearly indicated that it was beneficial to carry out the hard turning operation with UCDCTT cermet insert at the optimal combination of machining variables. Moreover, deep cryogenic treatment with tempering was a better alternative for the tool life enhancement.



a *b*

c

Fig. 17. Development of flank wear of different cermet inserts with machining time at optimum cutting conditions.

CONCLUSIONS

In this present experimental investigation, hard turning was performed on 4340 alloy steel at 48 HRC using UCUT, UCSCT, UCSCTT, UCDCT and UCDCTT cermet inserts and the performances of these inserts in terms of cutting force, flank wear, crater wear, chip morphology and surface roughness were studied. Moreover, economic feasibility for the current study was also accomplished using these inserts. Following remarkable conclusions were drawn from the current experimental work.

Table 4. Comparisons of machining cost in hard turning of AISI 4340 steel with different cermet tools

No.	Costs	UCUT	UCSCT	UCSCTT	UCDCT	UCDCTT
1	Cost associated with machine and operator, Rs. 550/h (x)	Rs. 9.17/min	Rs. 9.17/min	Rs. 9.17/min	Rs. 9.17/min	Rs. 9.17/min
2	Machining cost per piece (xT_m)	Rs. 28.79	Rs. 28.79	Rs. 28.79	Rs. 28.79	Rs. 28.79
3	Tool changing cost per piece [$xT_d(T_m/T)$]	Rs. 6.54	Rs. 5.14	Rs. 4.36	Rs. 3.51	Rs. 3.06
4	Cutting insert cost per piece	Rs. 450	Rs. 450	Rs. 450	Rs. 450	Rs. 450
5	Cost associated with surface treatments of tool substrate	Rs. 0	Rs. 180	Rs. 230	Rs. 430	Rs. 470
6	Average value of single cutting edge (y)	Rs. 112.5	Rs. 157.5	Rs. 170	Rs. 220	Rs. 230
7	Machining cost per piece over tool life [$y(T_m/T)$]	Rs. 16.06	Rs. 17.66	Rs. 16.18	Rs. 16.85	Rs. 15.37
8	Total machining cost per piece (No. 2 + No. 3 + No. 7)	Rs. 51.39	Rs. 51.59	Rs. 49.33	Rs. 49.15	Rs. 47.40

Note. Machining length $L = 100$ mm, uncut w/p diameter $D = 40$ mm, machining time per piece $T_m = \dfrac{\pi DL}{1000vf} = 3.14$ min, machine downtime $T_d = 5$ min.

All the machining characteristics such as cutting force, flank wear, crater wear and surface roughness were found to be minimum in case of UCDCTT cermet insert compared to other four inserts.

Chip formation process was greatly affected by cryogenic treatment. Serrations and material side flow were the two primary properties of chips found. With deep cryo treated and tempered inserts, very less serrations and no side flow were observed compared to untreated inserts.

Hardness enhanced substantially for cryo treated insert compared to untreated one and with tempering excessive hardness was reduced also.

The total machining cost for UCDCTT insert was found to be the least i.e. Rs. 47.40 among all other inserts.

In the wear test, least wear was observed for UCDCTT insert because of better wear resistance and toughness compared to other inserts.

Machining with optimal input parameters reduced the cost effectively.

Для збільшення тривалості роботи ріжучих пластин кріогенна обробка є найвідомішим методом, але ґрунтовних досліджень щодо впливу кріогенної обробки на металокерамічні вставки не виявлено, особливо при точінні твердих сплавів. Тому в даному експериментальному дослідженні порівняльну оцінку різних характеристик, таких як сила різання, знос по задній поверхні, знос у вигляді кратерів, морфологія стружки і шорсткість поверхні, проведено при механічній обробці загартованої сталі як з необробленими, так і з кріообробленими металокерамічними вставками в умовах сухого різання. Нарешті, вхідні змінні параметри було оптимізовано з використанням методології реакції поверхні, щоб оцінити тривалість роботи інструменту для економічного обґрунтування. Експериментальний результат показав, що глибока кріообробка без покриття загартованої металокерамічної вставки дає кращі результати порівняно з іншими металокерамічними вставками. Відповідно до аналізу витрат, виявлено, що загартована ме-

талокерамічна вставка без покриття та з глибокою кріообробкою є найбільш економічною серед інших металокерамічних вставок за оптимального режиму різання.

***Ключові слова**: токарна обробка, кріогенна обробка, оброблюваність, аналіз витрат.*

Для увеличения срока службы режущих пластин криогенная обработка считается наиболее известным методом, но фундаментальных исследований, касающихся воздействия криогенной обработки на металлокерамические вставки не было найдено, особенно при точении твердых сплавов. Поэтому в настоящем экспериментальном исследовании сравнительная оценка различных характеристик, таких как сила резания, износ по задней поверхности, износ в виде кратеров, морфология стружки и шероховатость поверхности, была проведена при обработке закаленной стали с необработанной и криообработанной металлокерамической вставкой в условиях сухой резки. Наконец, входные переменные были оптимизированы с использованием методологии реакции поверхности, чтобы оценить срок службы инструмента для экономического анализа. Результаты эксперимента показали, что глубокая криообработка без покрытия обработанной закаленной вставки из кермета дает лучшие результаты по сравнению с другими вставками из кермета. Согласно анализу затрат, было обнаружено, что закаленная вставка из кермета без покрытия с глубокой криообработкой является наиболее экономичной среди других вставок из кермета при оптимальных условиях резания.

***Ключевые слова**: токарная обработка, криогенная обработка, обрабатываемость, анализ затрат.*

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