EXPERIMENTAL INVESTIGATION ON PERFORMANCE OF CRYO-TREATED TOOL BY TURNING OPERATION

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Abstract :

In the present investigation, PVD coated carbide inserts & uncoated carbide inserts were subjected to deep cryogenic treatment (-190°C) and machining studies were conducted on Stainless Steel using both untreated and deep cryogenic treated carbide cutting tool inserts. Micro-structural study, elemental characterization and crystallographic orientation were studied with the help of Scanning Electron Microscopy (SEM), Energy Dispersive X-ray Spectroscopy (EDS) and X-ray Diffraction (XRD) respectively. Micro-hardness of the same specimens was evaluated using Vickers micro-hardness. The results indicated that cryo-treatment resulted information of hard and wear resistant η-phase carbides along with the improvement of tungsten carbide distribution in cobalt binder phase in metal matrix. The turning tests were conducted at three different cutting speeds (50, 70, and 90 m/min), feed rate (0.04, 0.05, 0.06 mm/rev) and depth of cut (0.1, 0.2, 0.3 mm). The influence of cryo-treatment on carbide inserts were evaluated in terms of flank wear of the cutting tool inserts, surface finish of the machined work- pieces and cutting forces. The results showed that cryogenic treatment significantly improved the average flank wear. The surface finish produced on machining the work-piece is better with the deep cryogenic treated carbide tools than when compared with the untreated carbide tools. Cutting force for cryo-treated inserts appeared to be less than non-cryo-treated insert. Tool life test was also conducted and results favored cryo-treated inserts. Also, a comparative study was done between carbide inserts cryo-treated at different conditions. FEA analysis using ABAQUS software was carried out to investigate the stress and temperature distribution at tool-workpiece interface.

***Keywords- Cryo-treatment (CT), Carbide inserts,* Surface roughness, Cutting force, Flank wear.**

I. INTRODUCTION:

Machining is a term that is related to removal of unwanted material, usually in the form of chips, from a workpiece. This process is used to convert preformed blocks of metal into desired shape, size and finish specified, often to great precision in order to fulfil design requirements. Hence, machining processes are often the most expensive. Although the theoretical analysis of metal cutting process is complex, but the application of these processes in the industrial world is widespread. The study of metal cutting focuses on the behaviour of tool and work piece material that influence the efficiency and quality of cutting operations. The metal cutting process involves pressing of a cutting tool against the workpiece, with certain degree of force, resulting in removal of material from the workpiece, in the form of chips. This results in enormous heat generation at the tool chip interface. Hence, continuous use of cutting tool for machining, results in tool wear eventually leading to its failure.

With the advancement in metal machining operations, it is necessary to identify and quantify micro-structural changes of metal alloys used in metal cutting processes. There are number of treatment processes used for different metals which cause them to behave differently under different conditions. However, the mechanism of micro-structural changes in alloys under various treatments, are not yet fully understood.

The use of thermal treatments to improve mechanical properties of metal components is an ancient art and is used until today. Many of the developed processes apply treatments in a range of temperature higher than room temperature. But, lately focus of researchers shifted towards the concept of sub-zero treatments and this was introduced to check the effect on industrial field.

Cryogenic treatment also known as cold or sub-zero treatment is a very old process and is widely used for high precision parts. The use of extreme cold to strengthen metals has been used since long time ago for centuries. For example, Swiss watch-makers use to store delicate components of their time pieces for several years in mountain caves to stabilize them in order to obtain maximum performance and precision. In general, unlike surface treatments, the cryogenic treatments influence the core properties of the materials.

The first attempts to perform sub-zero treatments were investigated at the beginning of the 20th century, but the use of cryogenic treatment (CT) to improve mechanical properties of materials has been developed from the end of the Sixties. Various studies have demonstrated that, the life of cutting tools like high speed steel (HSS) and tungsten carbide (WC) can be increased by cryogenic treatment.

Cryo-Treatment:

Cryo-treatment (CT) is a supplementary process to conventional heat treatment, that involves deep freezing of materials at cryogenic temperatures (-190 °C) to enhance the mechanical and physical properties. The execution of CT on cutting tool materials increases wear resistance, hardness, dimensional stability, but at the same time, reduces tool consumption and down time for the machine tool set up, thus leading to cost reductions. The dry cryogenic process is precision controlled and the materials to be treated are not directly exposed to any cryogenic liquids. Overall, all the treated materials retain their size and shape. Cryogenically treated materials with some occasional heat treatment generally improve hardness, toughness, stability, corrosion resistance and reduce friction. Cryogenic treatment has been successfully applied to die and high speed steel (HSS), ferrous alloys and tungsten carbide.

Treatment Profiles:

A fundamental distinction among different CT processes is given by the parameters of the cooling-warming cycle, and especially on the minimum temperature reached during the cycle. These are categorized as:

Shallow Cryogenic Treatment (SCT) or Subzero Treatment: the samples are placed in a freezer at -80 °C and then they are exposed to room temperature;

Deep Cryogenic Treatment (DCT): the samples areslowly cooled to -196 °C, held-down for many hours and gradually warmed to room temperature.

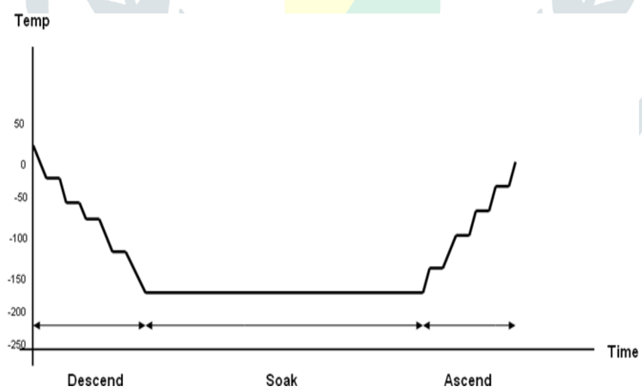


Fig. Cryogenic Treatment temperature profile Basic keynotes regarding cryo-treatment are listed below

In some cases, the actual Tmin could be higher than the nominal one because of thermal insulation limits;

- Each new material needs to be treated and tested at different temperature levels (i.e. -190 °C, -130 °C and -80 °C), in order to identify optimum treatment conditions and investigation of micro-structural changes;
- In most cases, Hold time of 24 hours are enough to obtain results and the same over 36 hours does not bring significant improvements;
- Cooling rate is one of the most critical parameter, which must not exceed 20-30 °C/h in order to prevent the rupture of the components because of the cooling stresses;

- Warming rate is not closely controllable and little importance to this parameter despite of some suggested literature about carbides precipitation during the warming phase.

II. Literature Survey:

Barron, (1982) showed that Cryogenic treatment has been successfully applied to die and high speed steel (HSS) ferrous alloys. The cryogenic process enhances the conversion from austenitic phase to martensite phase, which is a common change in ferrous metals as a result of heat treating and now cryogenic treating. The cryogenic treatment increases hardness and wear resistance of ferrous alloys.

Barron, (1982) subjected nineteen metals, including 12 tool steels, 3 stainless steels, and 4 other steels to cryogenic treatment to determine the difference between -84 ºC soak and

-196 ºC soak in improving the abrasive wear resistant. The tool steels exhibited a significant increase in wear resistant after the soak at -196 ºC and a less dramatic increase after the -84 ºC soak. There was an increase in the wear resistant after the cryogenic treatment for the stainless steels, but the difference between the two treatments was less than 10 %. The plain carbon steel and the cast iron showed no improvement after either cryogenic treatment.

Cohen and Kamody, (1998) reported cryogenic treatment gradually reduces the tool temperature in an airtight refrigeration dry chamber to below −190 °C, after which the tool is slowly returned to room temperature.

III. EXPERIMENTAL LAYOUT:

Experimental Layout is divided into following steps:

- Cryo-treatment Procedure
- Pre- machining SEM, EDS, XRD Study
- Performance evaluation by turning operation
- Post- machining SEM study for tool wear
- Taguchi analysis
- Hardness test
- Conductivity test
- Cryo-treatment Procedure
- Cryogenic setup

The Kryo 360-1.6 is simple to programme and operate, which incorporates all of the critical features expected from a high class biological freezer with the most advanced cryopreservation techniques. The controlled rate of cooling and heating ensures sample integrity during transfer to storage. The high capacity LNP4 active nitrogen pump offers both faster cooling rates and a large reservoir, along with extended hold time. Compact design, controller displays demand, sample and chamber temperatures, programme stage and current temperature graphic are some of the unique features of the device.

Table: System Specifications of Kryo 360-1.6 cryogenic chamber

Operating Range	+40.0ºC to -180ºC
Heating rates	0.01ºC/min to 10ºC/min
Cooling rates	-0.01ºC/min to -50ºC/min
Chamber Capacity	1.7 lts
Chamber dimensions (mm)	Internal 200 x Ø150 External 450 high x 300 wide x 420 deep
PC Software	Delta TTM

Fig. cryogenic treatment set up

Experimentation:

Experiment was carried out in cryogenic treatment set up namely Kryo 360-1.6. LIN used for this purpose was stored in the transport storage tank. Cryogenic chamber was started and LIN was delivered at required pressure and all safety valves and pipelines or transfer lines were checked properly, if correctly sealed or not. Cooling rate was set up by using computer controlled program at 0.5 °C/min and temperature was set to move from 25 °C to -190 °C. Inserts were properly cleaned. As temperature of cryogenic chamber reached 25 °C, inserts were carefully kept inside and the chamber was closed. After 8 hrs., when temperature reached-190 °C, the thermocouple generated a signal to programmer to stop further cooling automatically through solenoid valve which controls LIN supply. It was left for soaking at -190 °C for 24 hrs. It was then brought to room temperature at the same rate (i.e. 0.5 C/min) by warming. This process of warming is called tempering. After being brought to room temperature, insert is kept in open environment before being transported to furnace regarding further tempering. Inserts were kept inside the furnace and machine was started. The temperature was set to move from 25 °C to 200 °C. This process exactly took 1 hr. Inserts were held at 200 °C for 3 hrs. and then slowly cooled down to room temperature in controlled environment. So, the total duration of cryogenic process is 45 hrs.

Similarly, cryogenic treatments was carried out for other set of inserts at 1.0 °C/min in order to check the effect of different rate of cryogenic cooling on micro-structure and performance of inserts and also compare with non-CT inserts. Cryo-treatment at 0.5 °C/min (Cryo-treated + tempered) The cool down time is 8 hours. A temperature of –190 °C is achieved in 8 hours. After cooling down, material is soaked at this minimum temperature for 24 hours. It is again brought up to the room temperature in 8 hours known as the warm up temperature. The total duration of the cryogenic treatment is about 40 hours. After the material is cryogenic treated, it is tempered to 200 °C and the same is achieved in 1 hour and it is kept at this temperature for 3 hours. Thematerial is brought back to room temperature in the next 1 hour. The total duration of tempering cycle is 5 hours. Tempering is done in order to remove the stresses developed during cryogenic cooling. The total duration of the Cryogenic-tempering cycle is 45 hours.

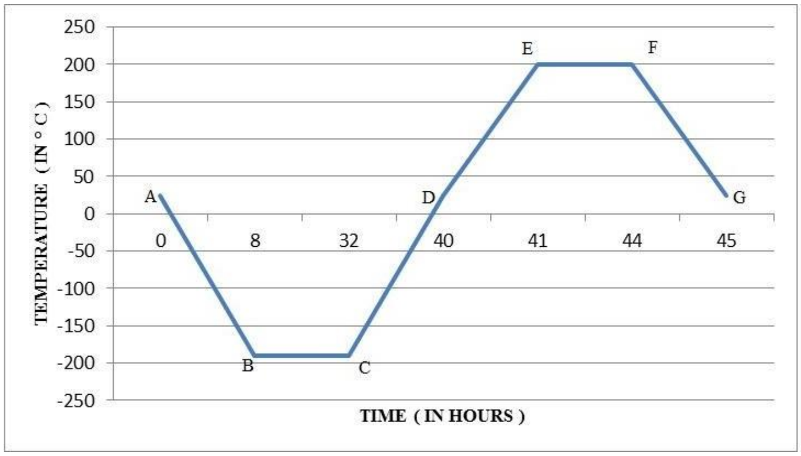


Fig. Graph for Cryo-treated insert at 0.5 °C/min (Cryo-treated + tempered)

Process A-B: Cooling phase (Chilling) Process B-C: Soaking phase Process C-D: Warming phase Process D-E: Tempering phase Process E-F: Holding phase Process G-H: Cooling phase Cryo-treatment at 1.0 °C/min (Cryo-treated + tempered) The cool down time is 4 hours. A temperature of –190 °C is achieved in 4 hours. After cooling down, material is soaked at this minimum temperature for 24 hours. It is again brought up to the room temperature in 4 hours known as the warm up temperature. The total duration of the

cryogenic treatment is about 32 hours. After the material is cryogenic treated, it is tempered to 200 °C and the same is achieved in 1 hour and it is kept at this temperature for 3 hours. The material is brought back to room temperature in the next 1 hour. The total duration of tempering cycle is 5 hours. Tempering is done in order to remove the stresses developed during cryogenic cooling. The total duration of the Cryogenic-tempering cycle is 37 hours.

Fig. Graph for Cryo-treated insert at 1.0 °C/min (Cryo-treated + tempered)

Cryo-treatment at 1.0 °C/min (Cryo-treated) The cool down time is 4 hours. A temperature of –190 °C is achieved in 4 hours. After cooling down, material is soaked at this minimum temperature for 24 hours. It is again brought up to the room temperature in 4 hours known as the warm up temperature. The total duration of the cryogenic treatment is about 32 hours. No tempering is done.

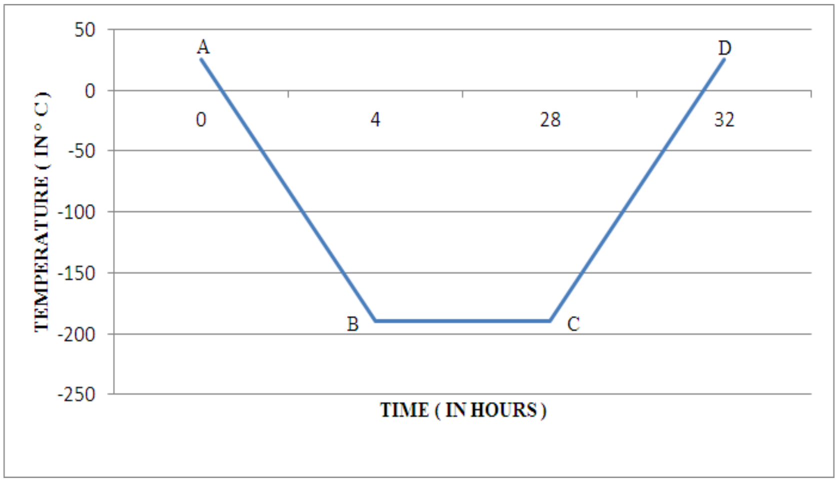


Fig. Graph for Cryo-treated insert at 1.0 °C/min (Cryo-treated)

Fig. Tempering Machine

Cryo-treatment Condition	**Cool Down Time(in hrs)**	**Soaking Time (in hrs)**	**Warming Time (in hrs)**	**Tempering Time (in hrs)**	**Holding Time (in hrs)**	**Cooling Time (in hrs)**	**Total Treatment Time**
0.5 °C/min	8	24	8	1	3	1	45
1.0 °C/min	4	24	4	1	3	1	37
1.0 °C/min	4	24	4	-	-	-	32

Table: Various CT procedures used

Physical Characterization:

Scanning electron microscopy (SEM)

SEM is used to examine surface features, textures and particles that are too small to see with standard optical microscopes. The JSM-6480LV is a high-performance, scanning electron microscope with a high resolution of 3.0 nm. The fully automatic low vacuum system allows observation of specimens which cannot be viewed at high vacuum due to excessive water content or due to a non-conductive surface. Its asynchronous five-axis stage rotation and tilt can accommodate a specimen of up to 8-inches in diameter. Standard automated features include auto focus, auto gun and automatic contrast and brightness, which provide fast and unattended data acquisition.

Fig. JEOL JSM-6480LV Scanning Electron Microscopy

All samples are analyzed using a JEOL JSM-6480LV SEM with an Oxford INCA X-sight EDXA (Energy Dispersive X-Ray Analysis system). Energy Dispersive X-ray Spectroscopy (EDS) Energy Dispersive X-ray Spectroscopy (EDS) provides micro-chemical information from a sample inside a Scanning Electron Microscope (SEM). A sample with unknown chemistry is analysed and spectra, elemental distribution maps and quantified chemistry is produced. Electron Backscatter Diffraction (EBSD) provides micro-structural information from a sample inside an SEM. A sample of known chemistry is analysed and maps of micro-structure, plots of orientation frequency, phase % and grain size are produced using Point and Shoot Phase Identification.

X-ray diffraction (XRD):

X-ray diffraction (XRD) is a versatile, non-destructive technique that reveals detailed information about the chemical composition and crystallographic structure materials. When a monochromatic X-ray beam with wavelength lambda is projected onto a crystalline material at an angle theta, diffraction occurs. Based on the principle of X-ray diffraction and the concept of Bragg's Law conditions, the structural, physical and chemical information about the material investigated can be obtained.

Fig. X-ray Diffraction Machine

Performance Evaluation by Turning Operation:

In order to check which tool is best, inserts were machined with AISI 304 Stainless Steel by turning operation. Regression equation was used to correlate input parameters as speed, feed and depth of cut with output parameters, namely surface roughness, flank wear and cutting force.

Table: Experimental Conditions for Turning

Lathe	NH 26 Precision Lathe
Work specimen material	AISI 304 Stainless Steel
Cutting tool	PVD coated Tungsten Carbide P 30 Insert Uncoated Tungsten Carbide P 30 Insert
Insert Designation	SNMG 120408
Tool Holder	PSBNR 2525 M12
Tool Geometry	-6°, -6°, 6°, 6°, 15°, 75°, 0.8
Cutting Velocity	50, 70, and 90 m/min
Feed	0.04, 0.05, 0.06 mm/rev
Depth of cut	0.1,0.2,0.3 mm
Type	Dry cutting
Force Measuring Dynamometer	Kistler Type 9272 SN 1634808
Surface Roughness Measurement	Taylor Hobson Pneumo Surtronic 3+
Flank Wear Measurement	Optical Microscope

Lathe:

NH 26 Precision Lathe is used for turning AISI 304 Stainless Steel with Tungsten Carbide Insert as tool. Its rigid rectangular section with wide bed along with short spindle and shaft for maximum drive rigidity power provides precision and versatility for achieving unmatched capabilities in precision turning.

Table: Specification of NH 26 Precision Lathe

Distance between centers	3000 mm
Spindle Speed range	16 from 40-2040 forward 7 from 60-1430 reverse
Spindle power	11 kW
Feed range (longitudinal)	0.04-2.24 mm/rev
Main motor power	7.5 kW

Work Specimen Material:

Chemical Composition:

Element	C	Cr	Ni	Fe	Mn	P	S	Si	N
Content (%)	0.08	18-20	8-10.5	66.354-74	2	0.045	0.03	1	0.1

Table: Chemical Composition of AISI 304 grade austenitic stainless steel

Physical Properties:

Table: Physical Properties of AISI 304 grade austenitic stainless steel

Density	8 gm/cm3
Hardness	29 HRC

Mechanical Properties:

Table 8 Mechanical Properties of AISI 304 grade austenitic stainless steel

Elastic Modulus	197 GPa
Elongation % (Break Point)	70% (upto 50 mm)
Shear Modulus	86 GPa

Cutting Tool:

Tungsten carbide inserts are used for machining AISI 304 austenitic stainless steel, which are categorized below:

PVD coated Tungsten Carbide P 30 Insert

Uncoated Tungsten Carbide P 30 Insert

Insert Designation

SNMG 120408 TN 4000 08 (PVD coated Tungsten Carbide P 30 Insert coated with TiCN + Al_2O_3 + TiN),

SNMG 120408 TTR 08 (Uncoated Tungsten Carbide P 30 Insert)

Tool Geometry

Both inserts differ only on the basis of coating, but have same tool geometry. Table 9 Tool Geometry of insert

Inclination angle	-6˚
Orthogonal rake angle	-6˚

End clearance angle	6˚
Side clearance angle	6˚
Auxiliary cutting edge angle	15˚
Principal cutting edge angle	75˚
Nose radius	0.8 mm

Tool Holder:

PSBNR 2525 M12 is a right hand tool holder used to turning operation.

Surface Roughness Measurement:

The Taylor Hobson Pneumo Surtronic 3+ Talysurf is ideal instrument for measurement of surface roughness of various types of components, even if they are inaccessible or difficult to move. Features like portable and flexible; simple menu structure; long traverse length andextended pick-up reach; powerful software option; comprehensive range of accessory & pick-up reach along with good mechanical rigidity, makes it a unique device for surface finish measurement

Table: Specification of Taylor Hobson Pneumo Surtronic 3+Talysurf

Traverse length	120 mm
Straightness of traverse	1.0 micron
Traverse speeds	1.0 mm / sec and 0.5 mm/sec (+/- 5%)
Column traverse	450 mm
Stylus range	6 mm
Stylus tip radius	1.5 - 2.5 micron

Force Measuring Dynamometer:

Four-component Kistler Type 9272 SN 1634808 Dynamometer is used for measuring torque and the three orthogonal components of a force. The dynamometer has a great rigidity and consequently a high natural frequency. Its high resolution enables the smallest dynamic changes in large forces and torques to be measured. The dynamometer is rustproof and protected against penetration of splash water and cooling agents.

Table: Specification of Kistler Type 9272 SN 1634808 Dynamometer

Measuring range	Fx, Fy: 5kN Fz: 20kN
Operating temperature range	0-70°C
Height	70 mm
Diameter	100 mm
Sealing	Welded/epoxy (IP67) with connecting cable types 1677A5, 1679A5
Mass	4.2kg

Turning Operation:

To check the effect of CT, inserts were subjected to turning operation and compared with non- CT insert. Workpiece was taken as AISI 304 Stainless steel and turning operation was carried out on NH 26 Precision Lathe. Machining parameters like cutting speed, feed rate and depth of cut were taken as input and performance of different inserts were analyzed on basis of flank wear of insert, surface roughness of machined workpiece and cutting forces generated during machining. Using input parameters a Taguchi L9 experimental run was designed using DOE Minitab software and experiment was conducted for both types of inserts, each run having duration of 60 seconds. Consecutively, dynamometer was fixed on the tool post and cutting forces were recorded. Also, surface roughness was measured using Talysurf and flank wear was measured using optical microscope. The results were analyzed using Taguchi DOE in order to find out the individual effect of input parameters on various output responses.

Mechanical Characterization:

Hardness Test:

The Vickers hardness test method consists of indenting the test material with a diamond indenter, in the form of a pyramid with a square base and an angle of 136 degrees between opposite faces subjected to a test force of between 1gf and 100kgf. The full load is normally applied for 10 to 15 seconds. The two diagonals of the indentation left in the surface of the material after removal of the load are measured using a microscope and their average calculated. The area of the sloping surfaces of the indentation is calculated. The Vickers hardness is the quotient obtained by dividing the kgf load by the square mm area of indentation.

The Vickers number (HV) is calculated using the following formula:

HV = 1.854(F/D2),

where F is the applied load (in kgf) and D2 the area of the indentation (in sq. mm).

Conductivity Test:

The four point probe is a simple apparatus for measuring the resistivity of samples at various temperatures with a high degree of accuracy. Because of the use of pressure contacts, this arrangement is specifically useful for quick measurement. It includes the four probes arrangement, PID controlled oven, constant current source, and DC micro-voltmeter. The four point probe contains four thin collinearly placed tungsten wires probes, which are made to contact the sample under test. Current is made to flow through two outer probes, and voltage is measured between the two inner probes, ideally without drawing any current, hence, allows the measurement of the substrate resistivity. After obtaining resistivity, conductivity is calculated for the specimen.

IV. RESULTS AND DISCUSSION :

SEM Analysis:

SEM analysis was carried out in order to study the micro-structure of Cryo-treated and non Cryo-treated inserts in order to check the effect of Cryo-treatment.

SEM analysis include

Micro-structural analysis

Tool wear analysis

Micro-structural Analysis

Microstructure analysis is carried out to understand the micro-structural changes that provide the information about improvement in properties such as hardness and wear resistance. According to the procedure specified in ASTM standards B657 ‗Standard method for metallographic determination of microstructure in cemented tungsten carbides', metallographic microstructure was determined. The following phases are generally present in the metallographic microstructure of cemented tungsten carbides:

Alpha (α-phase): Tungsten carbide (WC),

Beta (β-phase): Cobalt binder,

Gamma (γ-phase): Carbides of cubic lattice (TaC, TiC, NbC, WCetc.) and

Eta (η-phase): multiple carbides tungsten and at least one metal binder ((Co_3W_3C (M_6C), Co_6W_6C ($M_{12}C$))

The α-phase comprises of tungsten carbide grains which is gray angular shaped grains. The β-phase consists of white vein like regions which is cobalt binder phase, and this imparts toughness to the cutting insert. The eta η-phase carbide appears as dark gray specksand are formed during the long exposure to critical temperatures, which occupies the volume formerly occupied by cobalt. Eta η-phase is a carbon deficient form of tungsten carbide, which results in a harder, more brittle cemented carbide part. These fine η-phases in addition to the larger carbide particles present before thermal treatment, along with homogeneously distributed Co binder, form a denser, uniform and tougher metal matrix.

i. Cryo-treated insert at 0.5 °C/min (Cryo-treated + tempered)

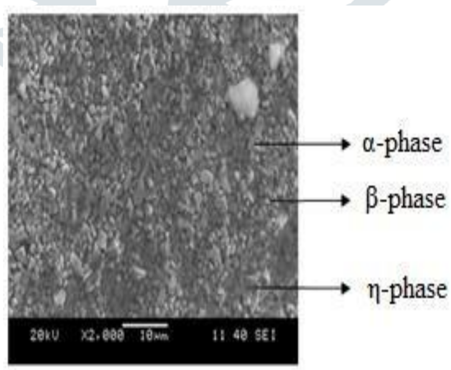


Fig. SEM image for Cryo-treated insert at 0.5 °C/min (Cryo-treated + tempered)

After SEM analysis of above insert, it was found that, due to CT and tempering, the concentration of η-phase of carbide increased and were uniformly distributed along the metal matrix. Also, the concentration of α-phase consisting of WC increased along with Co binder. This proved that, after CT and tempering, the hardness of insert increased due to η-phase and toughness is increased due to Co binder densification.

ii. Cryo-treated insert at 1.0 °C/min (Cryo-treated + tempered)

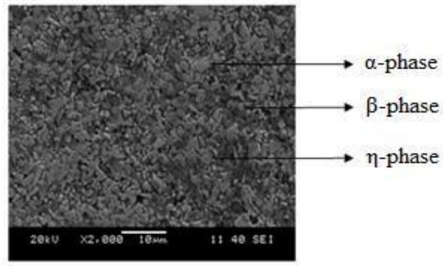


Fig. SEM image for Cryo-treated insert at 1.0 °C/min (Cryo-treated + tempered)

Since, treatment at 1˚C/min disobeys CT laws, but still, it was found that, CT caused an increase in concentration of WC while causing simultaneous decrease in concentration of Co binder. Both these concentration are less than that of above CT condition (i.e. 0.5 ˚C/min). Also, SEM study showed non-uniform distribution of almost all phases like WC, Co binder, γ-phase and η-phase as micro-structural grain refinement could not take place even after tempering.

iii. Cryo-treated insert at 1.0 °C/min (Cryo-treated)

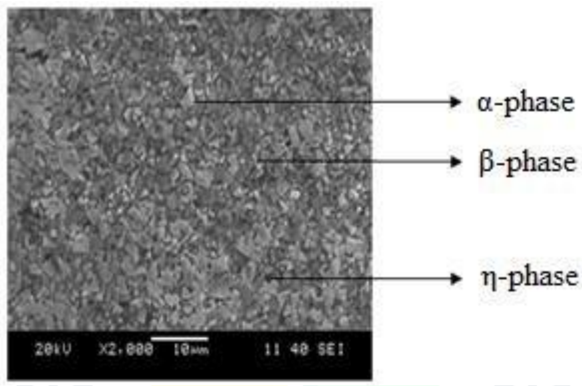


Fig. SEM image for Cryo-treated insert at 1.0 °C/min (Cryo-treated)

SEM study showed an abrupt increase in concentration of WC, but also simultaneous decrease in Co binder phase, which clearly indicates that, only CT of insert is not sufficient to improve the toughness. The insert hardness might have increased and could possibly make it prone to chipping during machining. The decrease in Co binder phase and its non-uniform distribution along metal matrix is due to only CT and without tempering. Some traces of η-phase carbide were found, but acceptable grain refinement had not taken place.

iv. Non Cryo-treated insert

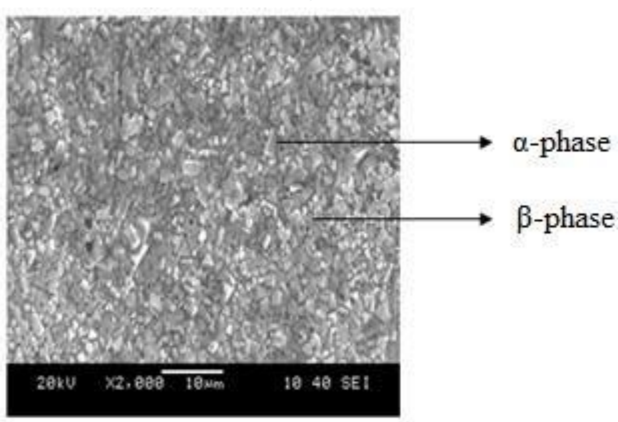


Fig. SEM image for Non Cryo-treated insert

Since, this carbide insert was used as comparison to other above inserts treated at different cryogenic condition, we can conclude from SEM analysis that, WC, Co binder and Carbides of cubic lattice (TaC, TiC, NbC, WC etc.) were uniformly distributed in non Cryo-treated insert.

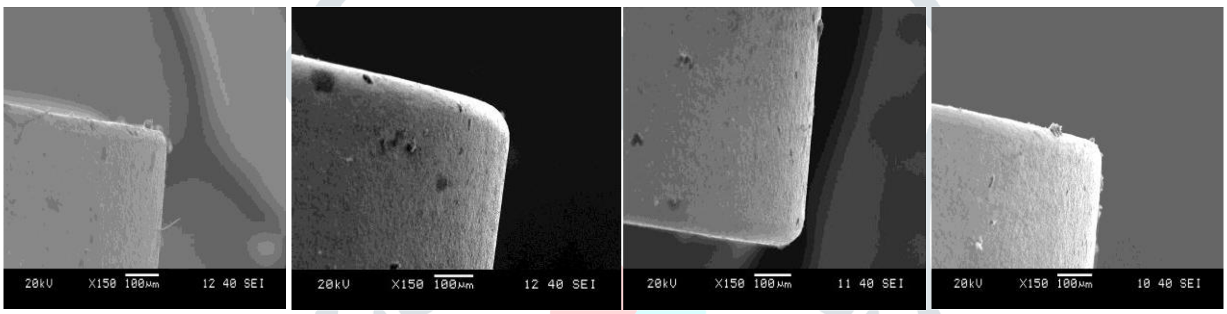
It is seen clear that due to CT, some physical changes had takenplace. During cryogenic treatment, coarser and randomly distributed η phaseparticles are refined into the most stable form presence of more and fine η-phase carbides, while in case of untreated inserts, fewer and coarser η-phase carbides was observed. Micro-structural analysis also reported densification of cobalt binder, which holds the carbide particles more firmly in metal matrix

thereby, enhancing the wear resistance and hardness of the insert, along with improvement in toughness property. The micro-stresses in the cutting inserts are also relieved, which increase the tool life.

Tool Wear Analysis:

The cutting tools while machining, particularly in continuous chip formation processes like turning, generally fail by gradual wear by abrasion, adhesion, diffusion, chemical erosion, galvanic action etc., depending upon the tool-workpiece and machining condition. Tool wear initially starts with a relatively faster rate due to a break-in wear caused by attrition and micro- chipping at the sharp cutting edges. In this work, SEM analysis is carried out to understand the flank wear forcryogenically treated and untreated tool inserts for one setof cutting conditions.

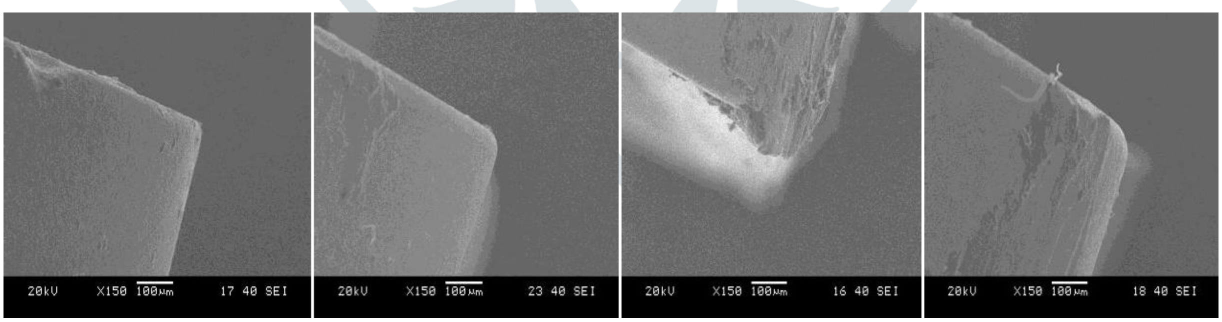
i. **Pre-Turning Tool Wear Study:**



(a) (b) (c) (d)

Fig. Pre-Turned SEM image for Cryo-treated insert at (a) 0.5 °C/min (Cryo-treated + tempered), (b) 1.0 °C/min (Cryo-treated + tempered), (c) 1.0 °C/min (Cryo-treated), (d) Non Cryo-treated insert.

ii. **Post-Turning Tool Wear Study:**



(a) (b) (c) (d)

Fig. Post-Turned SEM image for Cryo-treated insert at (a) 0.5 °C/min (Cryo-treated + tempered), (b) 1.0 °C/min (Cryo-treated + tempered), (c) 1.0 °C/min (Cryo-treated), (d) Non Cryo-treated insert

When comparison of tool wear was made before and after turning with AISI 304 stainless steel for various insert, it was found that,

- Less wear occurred in case of insert CT at 0.5 °C/min, when followed by tempering;
- Appreciable wear occurred for insert CT at 1.0 °C/min along with tempering;
- Chipping of tool tip was observed for insert only CT at 1.0 °C/min;
- Tool wear found to be more in case in non-CT inserts than CT inserts.

Since the cryogenic treatment improves the hardness of the coated inserts, it provides more wear resistance that reduces the flank wear.

To support the above conclusion, it was necessary to cross check the results with EDS analysis which would provide the weight percentage of various phases present in the carbide inserts and would aid to reach an agreeable conclusion with SEM results.

I. EDS Analysis

EDS analysis is carried out in order to support the conclusion drawn from micro-structural image of carbide insert using SEM.

i. Cryo-treated insert at 0.5 °C/min (Cryo-treated + tempered)

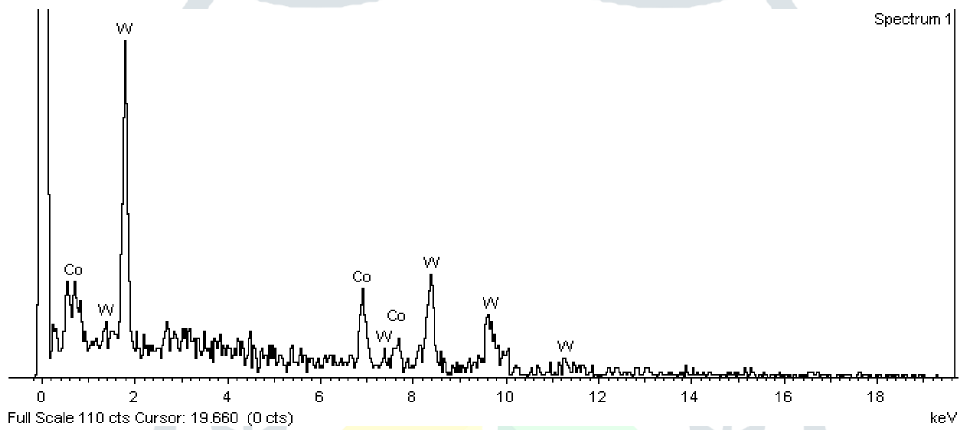


Fig. EDS for Cryo-treated insert at 0.5 °C/min (Cryo-treated + tempered)

Above EDS analysis showed a greater increase in concentration in carbide (i.e. η-phase) which proved an increase in hardness of insert. Also, concentration of Co binder phase increased, which concludes that, CT and tempering increases the toughness and conductivity. It is also observed that, no carbon percentage in present, which could possibly be due to conversion of all primary carbides into η-phase carbides.

ii. Cryo-treated insert at 1.0 °C/min (Cryo-treated + tempered)

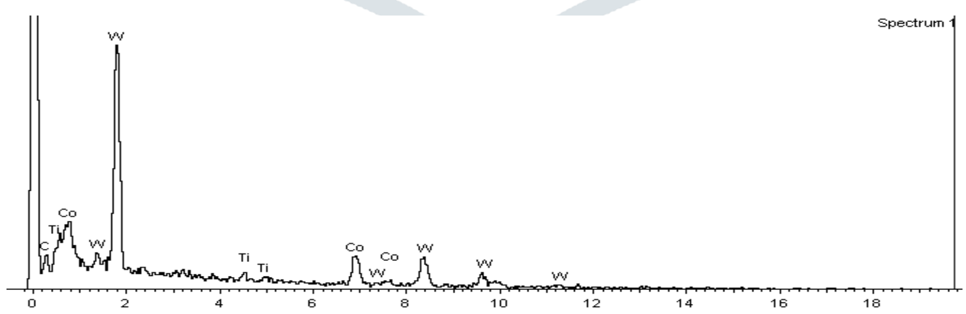


Fig. EDS for Cryo-treated insert at 1.0 °C/min (Cryo-treated + tempered)

Less amount of tungsten carbide and Co phase was observed after EDS analysis. This might be attributed to as inability of precipitation due to high rate of CT (i.e. 1.0 ˚C/min). Also, Carbon weight percentage is high, which proves less conversion of primary carbides into secondary phase carbides had occurred. Proper densification of Co binder phase could not take place.

iii. Cryo-treated insert at 1.0 °C/min (Cryo-treated)

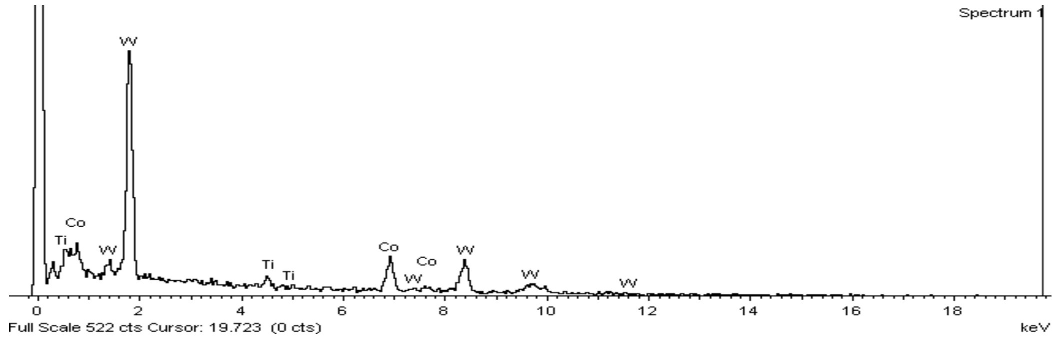


Fig. EDS for Cryo-treated insert at 1.0 °C/min (Cryo-treated)

EDS analysis for this insert showed an increase in carbide phase, but also simultaneous decrease in Co binder phase, which conclude that, toughness of this insert might be decreased due to less grain refinement of Co phase in metal matrix, which could have been avoided, if CT would have been followed by tempering. Due to high content of WC % and low Co %, insert becomes brittle and is prone to fracture.

iv. Non Cryo-treated insert

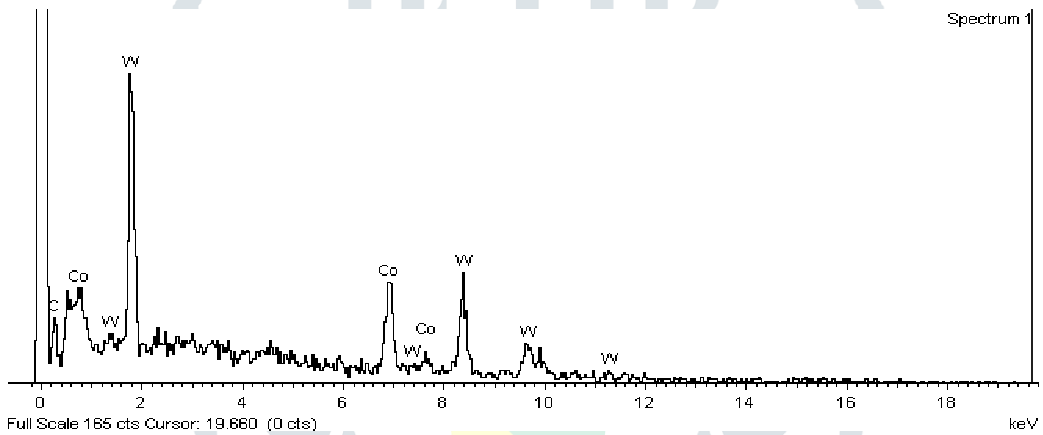


Fig. EDS for Non Cryo-treated insert

Since, this category of insert is non-CT and not tempered, it is taken as basis for comparison with other CT inserts. As usual, its EDS analysis showed a uniform distribution of WC in Co binder along with some traces of primary carbide particle.

Comparison Study

Table Composition of various elements present in different insert type

Cryo-treatment Condition	WC (Weight %)	Co (Weight %)	Carbide (Weight%)
0.5 °C/min (CT+T)	72	28	-
1.0 °C/min (CT+T)	64	14	21
1.0 °C/min (CT)	80	17	-
Non CT	47	23	31

II. XRD Analysis

Tungsten carbide inserts were examined to understand whether any structural changes have taken place or not after treating WC inserts using X-ray diffraction method. Cryogenic treated inserts showed almost same trend as that of an untreated insert because due to cryogenic treatment only physical changes takes place. Densification of the cobalt metal binder might have taken place.

i. Cryo-treated insert at 0.5 °C/min (Cryo-treated + tempered)

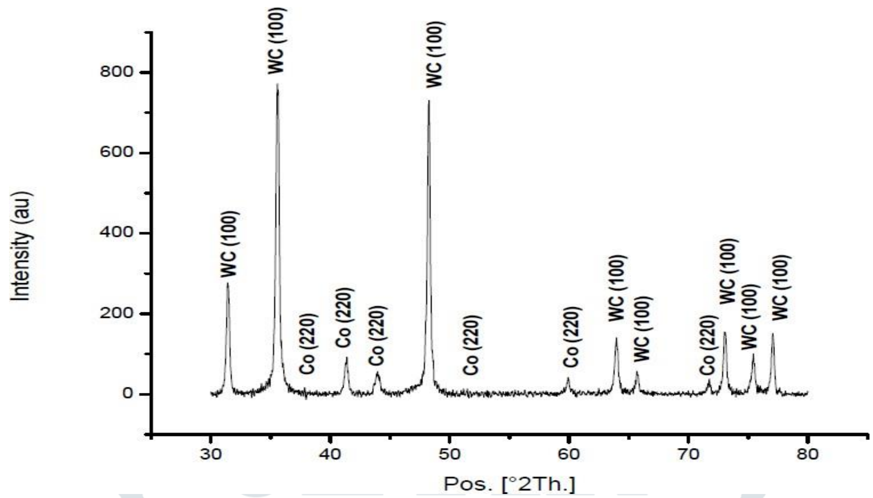


Fig. XRD Profile for Cryo-treated insert at 0.5 °C/min (Cryo-treated + tempered)

This CT insert when analyzed by XRD showed presence of WC crystal along with Co uniformly distributed in metal matrix. Also, on further analysis, presence of other forms of carbides were found to be low as compared to others, which concludes that due to CT and tempering, most of primary carbides are converted to secondary η-phase carbides, which improves the tool life due to increase in hardness along with toughness.

ii. Cryo-treated insert at 1.0 °C/min (Cryo-treated + tempered)

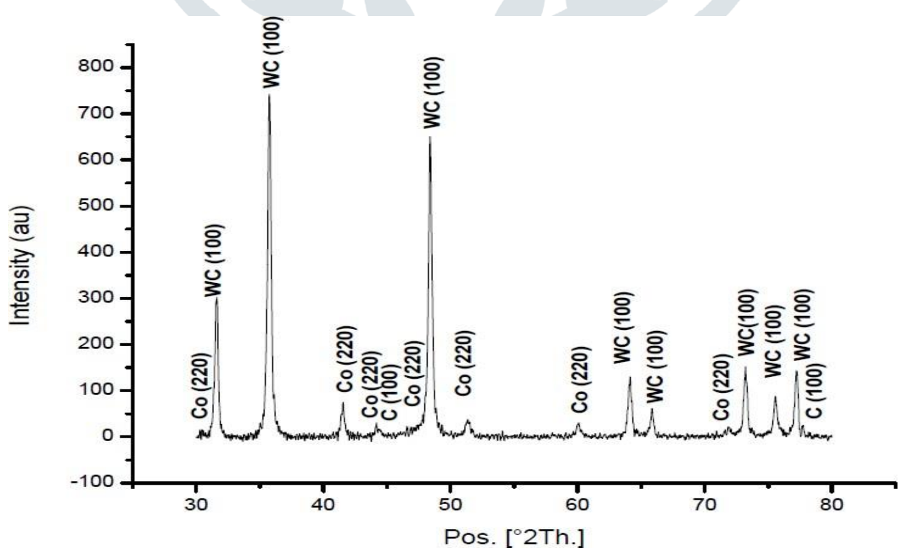


Fig. XRD Profile for Cryo-treated insert at 1.0 °C/min (Cryo-treated + tempered)

XRD analysis of this insert showed presence of primary carbide, which points to the direction that, less η-phase are formed. This is due to high cooling rate, which led to non-homogeneous grain refinement of carbide particles. Although, Co binder densification reduced, but insert might have acceptable harness property due to presence of

WC, which is solely due to tempering performed after CT.

iii. Cryo-treated insert at 1.0 °C/min (Cryo-treated)

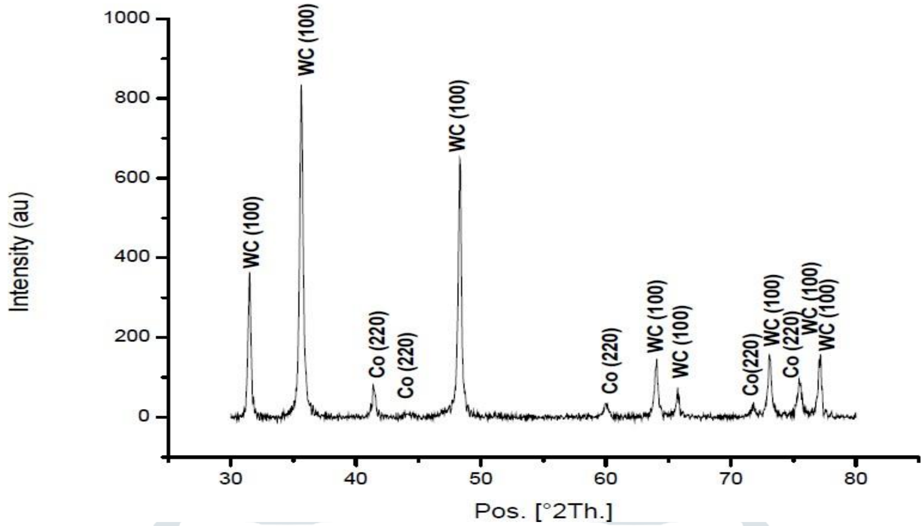


Fig. XRD Profile for Cryo-treated insert at 1.0 °C/min (Cryo-treated)

XRD analysis of this insert showed presence of WC crystal but simultaneous decrease in quantity of Co and increase in quantity of primary carbides, which leads to conclusion that, due to only CT and no tempering being done, conversion of primary carbide to secondary carbide could not take place and also, this affected uniformity of Co binder and resulted in non-uniform metal matrix.

iv. Non Cryo-treated insert

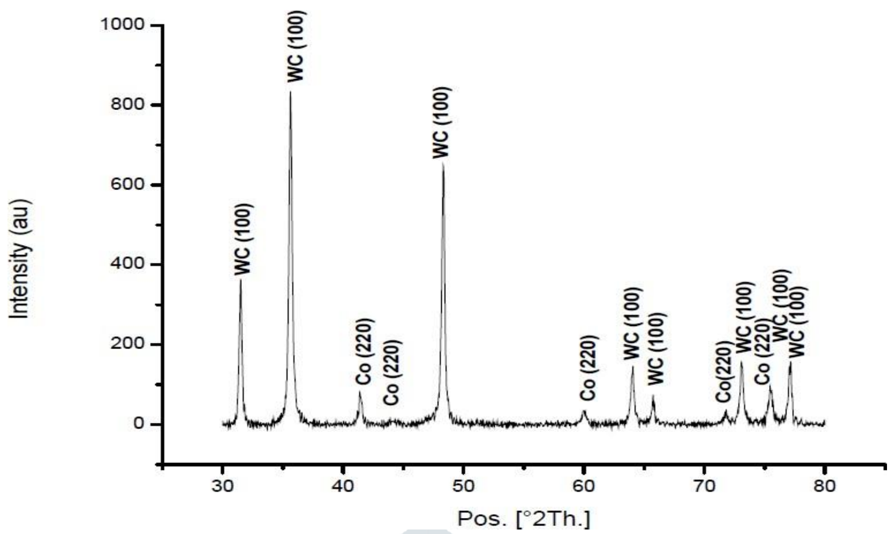


Fig. XRD Profile for Non Cryo-treated insert

As this insert was taken as reference, XRD of the same showed uniform presence of WC crystal along with Co binder phase. Also, presences of some primary carbide were reported.

III. Hardness Test Analysis

Since, due to subsequent cooling and heating of inserts, the thermal stresses are generated in WC–Co alloys as a result of the large difference between the coefficients of thermal expansion of the WC and Co-phases. The carbide phase is subjected to compressive stresses while the binder to tensile ones. The magnitude of the stresses in the cementing phase increases with decreasing cobalt content due to quenching. This causes decrease in ductility of the insert. The rapid cooling of these alloys causes compression of tungsten carbide from all sides, and an increase of compressive stresses would lead to an increase in the strength of the carbide matrix. Therefore, the strength of low-cobalt alloys as awhole gets slightly increased. There is a slight increase in the micro-hardness along with toughness due to the controlled cryogenic treatment compared to untreated WC–Co sample.

To check the effect of CT on hardness property of PVD coated and Non PVD coated insert, Vickers micro-hardness test was conducted. A load of 50 kgf was impressed on surface of insert using pyramidal diamond indenter for dwell time of 10 seconds and hardness values were tabulated as shown below.

Fig. Vickers Hardness Tester

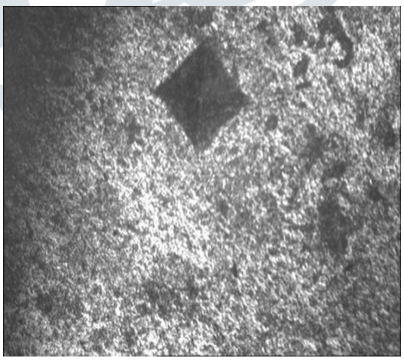


Fig. Impression made by indenter on surface of insert

Table: Vickers Hardness Value for PVD Coated Inserts

Insert Type	Vickers Hardness Value
0.5 °C/min (Cryo-treated + tempered)	2332 HV 50
1.0 °C/min (Cryo-treated + tempered)	2234 HV 50
1.0 °C/min (Cryo-treated)	2284 HV 50
Non Cryo-treated insert	2170 HV 50

Table: Vickers Hardness Value for Non PVD Coated Inserts

Insert Type	Vickers Hardness Value
0.5 °C/min (Cryo-treated + tempered)	3595 HV 50
1.0 °C/min (Cryo-treated + tempered)	3320 HV 50
1.0 °C/min (Cryo-treated)	3494 HV 50
Non Cryo-treated insert	3239 HV 50

It was found that, when inserts were CT, hardness is increased as compared to Non CT inserts. But, it was also reported that, CT insert at 0.5 °C/min and when followed by tempering provided better improvement in hardness as compared to 1.0 °C/min (Cryo-treated + tempered) and 1.0 °C/min (Cryo-treated).

V. CONCLUSION:

- The concept of cryogenic treatment (i.e. treatment at -190 °C) of inserts was being extended by subjecting the inserts to different cooling and warming rates (i.e. 0.5 °C/min (Cryo-treated
- + tempered), 1.0 °C/min (Cryo-treated + tempered), 1.0 °C/min (Cryo-treated)) and evaluate the performance by comparing with non-CT inserts using turning operation. Some of the major conclusion that was drawn after various analyses is as follows:
- SEM, EDS and XRD analysis of CT inserts treated at 0.5 °C/min showed the presence of fine precipitates of η-phase carbides along with WC uniformity in metal matrix along with Co binder phase densification; when compared to inserts treated at other cooling rates and non-CT insert. This proves that CT and tempering at 0.5 °C/min (20-30 °C/hr.) improves hardness along with improvement in toughness of inserts.
- Treatment at 1.0 °C/min or above and followed by tempering showed that inserts develop brittleness and hardness, with decrease in toughness as % of Co binder phase decreases due to high rate of cooling and warming. This also affects the precipitation of η-phase.
- Only CT of inserts at 0.5 °C/min or above produces catastrophic results as tool becomes fragile and is easily prone to chipping as WC % increases and Co % decreases with no or less η-phase grain refinement.
- After all set of inserts were being turned using AISI 304 Stainless steel and output responses were recorded in the form of cutting forces, flank wear and surface roughness;
- it was found that, CT inserts at 0.5 °C/min and followed by tempering, proved better than other category of inserts.
- Taguchi analysis was used to check the significant effect of input parameters on responses and ANOVA table was created, which showed that:

1. Cutting velocity affects cutting forces more than feed and depth of cut;

2. Feed rate has significant effect on surface roughness;
3. Feed force was mostly affected by cutting velocity, followed by depth of cut and feed rate;
4. In the case of thrust force, depth of cut was found to have significant effect followed by cutting velocity and then feed rate;

- Cutting velocity has also significant effect on flank wear. This was also validated with tool life analysis experiment which supported Taguchi result.
- Conductivity test showed an increase in electrical conductivity from untreated to deep cryo-treated inserts. Thus, there is an increase in thermal conductivity from untreated to deep cryo-treated inserts, which protect the tool tip from high temperature and increases its working life.
- Hardness test proved that, when inserts were CT, hardness is increased as compared to Non CT inserts. But, it was also reported that, CT insert at 0.5 °C/min and when followed by tempering provided better improvement in hardness as compared to 1.0 °C/min (Cryo- treated + tempered) and 1.0 °C/min (Cryo-treated).
- Chip morphology study reported continuous chip formation for 0.5 °C/min (Cryo-treated
- + tempered) insert and 1.0 °C/min (Cryo-treated + tempered); continuous chip with built up edge for non CT insert, while 1.0 °C/min (Cryo-treated) produced discontinuous chip.
- CT when combined with tempering process results in releases of residual stress and improve the ductility of inserts which directly increases toughness property. Hence, CT should be followed by tempering in order to avoid brittle fracture of cutting insert
- Tool life analysis was based on flank wear study, which proved that CT inserts provide long run than non-CT inserts, which is mainly due to Co binder densification which develops ductility and conductivity nature and this causes heat generated at tool chip interface to be easily carried away without affecting the inserts tip and improves tool life.
- CT inserts provide better surface finish, lower cutting forces and less flank wear in comparison with non-CT inserts, which can be attributed to the reason that, micro- structural grain rearrangement and refinement takes place due to CT and tempering respectively.
- Carbide population increases when exposed to critical temperature and they form into fine particles which are homogeneously distributed. This fine carbide improves wear resistance and have low co-efficient of friction. This phenomenon only occurs only when inserts are subjected to tempering after CT is over. Hence, CT inserts have added advantage of both hardness and toughness over non CT inserts.
- At last but not the least, since CT when accompanied with tempering results in improved tool life and is single step process, which need not to be done again and again as in case of coating process; the CT tool can be used again and again after successive regrinding and hence, is a cost effective and time saving process. This leads to increase in productivity run and is a promising technique for eco-friendly machining in industrial arena and further research in this area holds brighter results.

VI. FUTURE WORK:

Many useful benefits of CT have been reported by the researchers, but due to complexity of the process, change in mechanism is still unpredictable. Further investigation requires a critical study of parameters like cooling rate, soaking duration, warming rate and tempering cycle in order to optimize the process for various materials. Effect of CT on the thermo-mechanical fatigue behaviour of different material could be an interesting research field. CT should be applied to non ferrous alloys like polymers and composites in order to study changes in their mechanical properties. FEA modeling and simulation of orthogonal cutting can be extended for determination of cutting forces in order to validate with experimental results. For sustainable production, concept of cryogenic machining should be implemented to shop floor level.

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