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INVESTIGATION OF MACHINABILITY OF STAINLESS STEEL WITH CRYO-TREATED PVD CARBIDE INSERTS

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Abstract

The use of thermal treatments to enhance mechanical properties of metal components is an ancient art which is used until today. But lately focus of researchers shifted towards the concepts of sub-zero treatments. In the present investigation, PVD coated and uncoated carbide inserts were subjected to deep cryogenic treatment(-1960C) in order to investigate the machinability of stainless steel. Micro-structural study, elemental characterization and crystallographic phase orientations were studied with the help of scanning electron microscopy, energy dispersion X-ray spectroscopy and X-ray diffraction respectively. It was observed that cryo-treatment resulted in the formation of eta-phase in metal matrix. The turning tests were conducted at three different cutting speeds(50, 70 and 90m/min), feed rate(0.04, 0.05 and 0.06mm/min) and depth of cut (0.1, 0.2 and 0.3mm). The influence of cryo-treatments on carbide inserts in terms of flank wear of the cutting tool inserts, surface finish of the machined work-pieces and cutting forces has been investigated. It was observed that there was significant improvement of resistance to flank wear with enhancement of tool life. The surface finish obtained is better with deep cryo-genic treated carbide tools than untreated carbide tools. A comparative study on machinability was carried out between carbide insets cryo-treated at different conditions.

Keywords: Cryo-treatment, Tungsten-carbide turning, surface-finish, tool life

Nomenclature

ξ - Chip reduction co-efficient
CT - Cryo-treatment
F_C - Tangential Cutting Force
F_X - Feed force
F_y - Radial force
λ - Inclination angle

1. Introduction

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 the room temperature. But lately the focus of researchers shifted towards the concepts of sub-zero treatments. Cryo-genic treatments 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 also for centuries. For example, switch watch-makers use to store delicate components of time pieces for several years in mountain caves to stabilize them in order to obtain maximum performance and precision.

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The first attempts to perform sub-zero treatments were investigated at the beginning of 20th century, but the use of cryo-genic treatments to improve mechanical properties has been developed from the end of sixties. Cryo-treatment is a supplementary process to conventional heat treatment that involves deep freezing of materials at cryogenic temperature. The execution of CT on cutting tool materials increases wear resistance, hardness, dimensional stability, but at the same time, reducing the tool consumption and down time for the machine tool set-up. This leads to cost reductions. Cryogenically treated materials with some occasional heat-treatment generally improve hardness, toughness, stability, corrosion resistance and reduce friction. Cryo-treatment has been successfully applied to die, high speed steel, ferrous alloys and tungsten carbide.

A number of investigators have carried out cryo-treatment on different materials to improve the performance of the product. Hollies et al.(1961) studied the effect of cryo-genic cooling on the wear process of carbide-tipped tools while machining titanium. Barron(1982) showed that cryo-genic treatment had been successfully applied to die and high speed steel(HSS), ferrous alloys with enhancement of hardness and wear resistance. He subjected nineteen metals including 12 tool steels, 3 stainless steels and 4 other steels to cryo-genic treatment to determine the difference between -84^{0}C soak and -196^{0}C soak in improving wear resistance. The tool steels exhibited a significant increase in wear resistance after the soak at -196^{0}C soak in abrasive wear resistance. The tool steels exhibited a significant increase in wear resistance after the soak at -196^{0}C and a less dramatic increase after the -84^{0}C soak. Barron et al.(1990) studied the effect of cryogenic treatment on corrosion resistance.

In the present investigation, carbide inserts are cryo-treated with different cooling rates using liquid nitrogen to determine optimum condition. Investigation of machinability of AISI-304 stainless steel has been carried out using cryo-treated carbide inserts. Taguchi method has been used to determine the significant effect of input parameters for enhancing tool life, surface finish and reducing cutting forces. The influence of cryo-treatment on carbide inserts were evaluated in terms of different machinability criteria.

2. Experimental Investigation

The carbide inserts were cryo-treated in Kryo360-1.6 cryogenic set-up. The Kryo 360-1.6 is simple to programme and operate which incorporates all of the critical features from a high class biological freezer with the most advanced cryo-preservation technique (Fig.1).

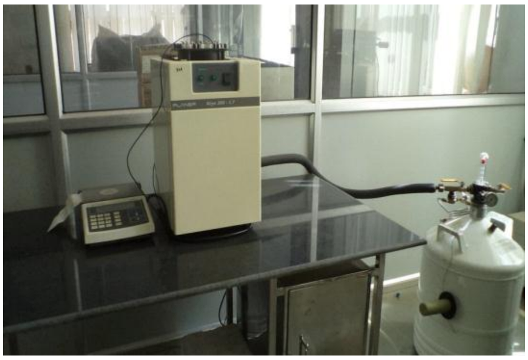


Fig. 1 Kryo 360-1.6 LIN cryogenic treatment set up

Cryogenic chamber was started and LIN was delivered at required pressure. All safety valves and pipe lines or transfer lines were checked properly if correctly sealed or not. Cooling rate was set-up by using computer controlled programme at 0.5^{0}C/min and temperature was set to move from 25^{0}C to -196^{0}C. Inserts were properly cleaned. The cryo-treatment at 0.5^{0}C/min cooling rate followed by tempering was carried out. A temperature of -196^{0}C was achieved in 8 hours. After cooling down, the material is soaked at the minimum temperature of 24 hours. It is again brought upto the room temperature in 8 hours as the warm up temperature. The total duration of the cryogenic treatment is about 40 hours. After cryogenic treatment, it is tempered to 200^{0}C in one hour. The material is brought back to room temperature in next 1 hour. The tempering is done to remove the residual stresses developed during cryo-genic cooling. The total duration of cryo-genic cooling is 45 hours(Fig,2).

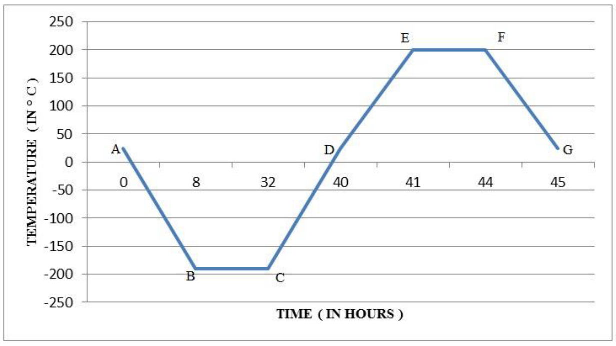


Fig. 2 Graph for Cryo-treated insert at 0.5 °C/min (Cryo-treated + tempered)

The various cryo-treatments carried out for cutting tools using the above procedure in order to study the effects have been given in Table1.

Table 1 Various CT procedures used for different **Cryo-treatment Conditions**

	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

In order to study the machinability using turning operation, the different experimental parameters used in the investigation has been given in Table2.

Table 2 Experimental Conditions for Turning

Lathe	NH 26 Precision Lathe
Work specimen material	AISI 304 Stainless Steel
Cutting tool	1. PVD coated Tungsten Carbide P 30 Insert 2. 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

Tungsten carbide inserts are used for machining AISI 304 austenitic stainless steel which are categorized as i)PVD coated Tungsten Carbide P30 insert and ii) uncoated Tungsten Carbide P30 insert. Insert designations are i)SNMG 120408 TN 400008(PVD coated Tungsten Carbide P30 insert coated with $TiCN+Al_2O_3+TiN$ ii)SNMG 120408 TTR(uncoated Tungsten Carbide P30 insert). Both inserts differ on the basis of coating, but have same tool geometry. The geometry of insert is given in Table3. PSBNR 2525M12 is used as a right hand tool holder. The experimental set up for turning operation has been given in Fig.3.

Fig. 3 Experimental set up for turning

To check the effect of CT, the inserts were subjected to turning operation and compared with non-CT insert. Using input parameters, a Taguchi L_9 experimental run was designed using DOE Minitab software and experiment was conducted for both type of inserts with each run having duration of 60 seconds. Surface roughness was measured using portable surtronic3+ Talysurf and the 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.

3. Results and discussion

SEM analysis was carried out in order to study the microstructure of cryo-treated and non-cryotreated inserts for investing the effect of cryo-treatment. The SEM image of cryo-treated insert at 0.5^0C/min is given in Fig.4.

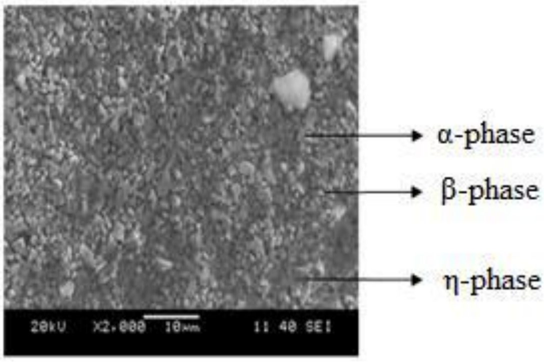


Fig. 4 SEM image for Cryo-treated insert at 0.5 °C/min (Cryo-treated + tempered)

The insert is tempered after cryo-treatment. It was observed that concentration of eta- phase of carbide increased and were uniformly distributed along the metal matrix. The concentration of α-phase consisting of WC increased along with Co binder. SEM image of non cryo-treated insert is shown in Fig.5.

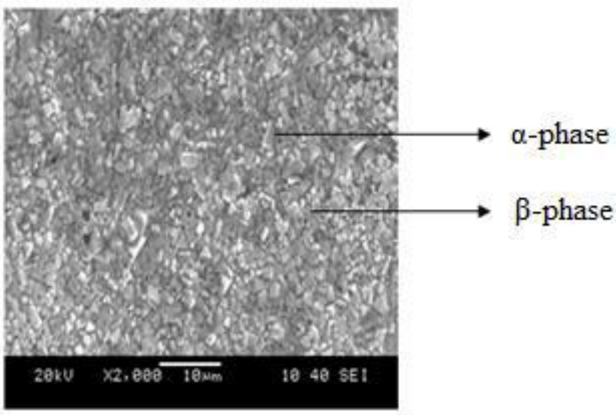
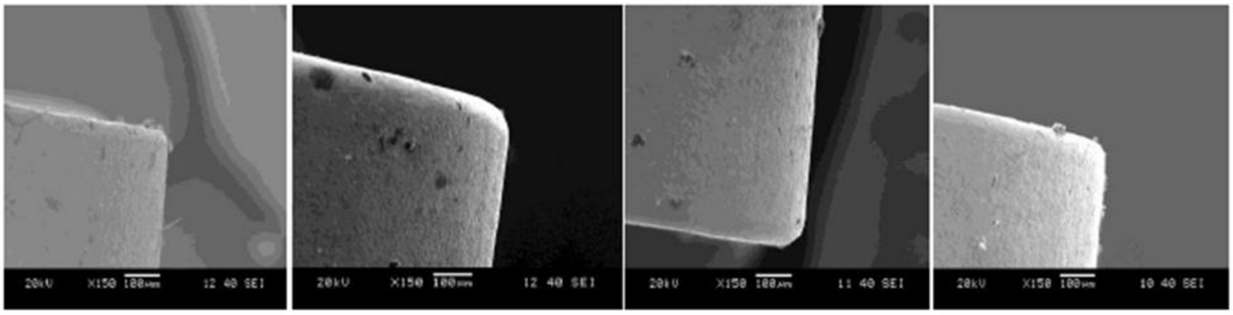


Fig. 5 SEM image for Non Cryo-treated insert

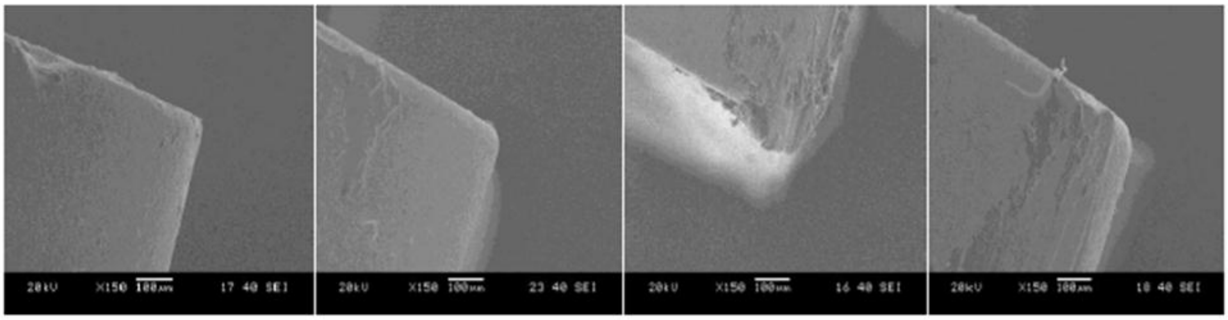
During cryogenic treatment, coarsely and randomly distributed eta phase particles are refined into the most stable form with presence of more fine eta-phase carbides. In case of untreated inserts, fewer and coarser eta-phase carbides were observed. Micro-structural analysis also reported densification of cobalt binder, which held the carbide particles more firmly in metal matrix, thereby, enhancing the wear resistance and hardness of the insert along with improvement in toughness properly.

The cutting tool 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 break-in wear caused by attrition and micro-chipping at the sharp cutting edges. Pre-turned SEM images of cryo-treated and non-cryotreated inserts is shown in Fig.6. Post –turned SEM images for cryo-treated insert is shown in Fig.7.



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

Fig. 6 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.



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

Fig. 7 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

It was found that less wear occurred in case of insert CT at 0.5^0C/min when followed by tempering. Appreciable wear occurred for insert CT at 1.0^0C along with tempering. Chipping of tool tip was observed for insert only CT at 1.0^0C/min. Tool wear was found to be more in case of non-CT inserts than CT inserts. Since the cryo-genic treatment improves the hardness of the coated inserts, it provides more wear resistance that reduces the flank wear.

In order to compare performance of various CT inserts with non-CT insert, a Taguchi L_9 experimental run was designed using cutting velocity, feed rate and depth of cut as input parameters. The flank wear of cutting insert, surface roughness of work-piece and cutting forces during machining operation are considered as the responses. The experimental run as per Taguchi L_9 analysis is given in Table4.

Table 4 Taguchi L9 experimental run

Run	**Cutting Velocity (m/min)**	**Feed Rate (mm/rev)**	**Depth of Cut (mm)**
1	50	0.04	0.1
2	50	0.05	0.2
3	50	0.06	0.3
4	70	0.04	0.2
5	70	0.05	0.3
6	70	0.06	0.1
7	90	0.04	0.3
8	90	0.05	0.1
9	90	0.06	0.2

Responses for PVD coated inserts is given in Table5 for cryo-treated at different conditions. Similarly responses are given in Table 6 for non-PVD coated insert.

Table 5 Response table for PVD coated inserts

Run	**PVD Coated Insert**																			
	0.5 °C/min (Cryo-treated + tempered)					**1.0 °C/min (Cryo-treated + tempered)**					**1.0 °C/min (Cryo-treated)**					**Non Cryo-treated PVD Coated insert**				
	R_a	FW	F_x	F_y	F_z	R_a	FW	F_x	F_y	F_z	R_a	FW	F_x	F_y	F_z	R_a	FW	F_x	F_y	F_z
1	1.05	0.090	74	19	197	1.13	0.112	95	31	210	1.35	0.143	118	75	255	1.31	0.127	140	51	238
2	3.27	0.115	120	55	208	3.40	0.127	145	62	221	3.56	0.151	161	117	262	3.54	0.141	185	95	245
3	4.21	0.147	195	368	232	4.46	0.175	220	372	245	4.64	0.200	247	430	288	4.51	0.192	264	431	271
4	0.90	0.108	100	40	212	1.06	0.132	128	52	226	1.30	0.154	147	97	269	1.28	0.153	170	81	252
5	2.90	0.160	100	65	225	3.20	0.182	130	81	239	3.45	0.209	157	119	280	3.31	0.197	181	98	262
6	3.81	0.151	92	9	230	4.03	0.174	119	21	243	4.20	0.198	139	69	288	4.07	0.190	165	51	275
7	0.85	0.170	67	52	156	1.00	0.198	89	64	169	1.20	0.227	115	110	211	1.11	0.214	138	95	195
8	2.12	0.182	77	3	145	2.30	0.207	101	16	157	2.84	0.220	128	65	200	2.38	0.222	151	46	182
9	2.82	0.200	62	31	140	3.00	0.230	90	45	151	3.19	0.263	111	90	192	3.08	0.245	134	78	175

Table 6 Response table for Non PVD coated inserts

Run	Non PVD Coated Insert																			
	0.5 °C/min (Cryo-treated + tempered)					1.0 °C/min (Cryo-treated + tempered)					1.0 °C/min (Cryo-treated)					Non Cryo-treated Non PVD Coatedinsert				
	R_a	FW	F_x	F_y	F_z	R_a	FW	F_x	F_y	F_z	R_a	FW	F_x	F_y	F_z	R_a	FW	F_x	F_y	F_z
1	1.26	0.152	129	61	266	1.35	0.168	148	79	278	1.62	0.215	211	128	315	1.40	0.179	189	103	299
2	3.46	0.171	181	121	276	3.59	0.189	199	134	286	3.92	0.231	255	187	327	3.74	0.221	228	174	305
3	4.46	0.210	251	457	298	4.60	0.229	263	487	312	4.95	0.261	340	532	350	4.71	0.241	306	503	335
4	1.06	0.181	162	101	281	1.20	0.211	188	119	295	1.54	0.211	228	171	333	1.37	0.218	225	153	316
5	3.20	0.223	177	121	292	3.31	0.247	191	138	308	3.77	0.261	242	182	343	3.60	0.260	235	150	330
6	4.03	0.216	153	67	295	4.13	0.234	179	81	311	4.49	0.258	231	131	348	4.25	0.250	221	132	333
7	1.00	0.230	114	118	220	1.14	0.256	145	135	232	1.49	0.288	211	182	272	1.31	0.273	183	178	251
8	2.30	0.245	128	62	216	2.41	0.244	157	75	228	2.90	0.275	229	121	269	2.60	0.265	198	96	245
9	3.00	0.262	111	90	214	3.13	0.271	146	103	224	3.70	0.310	199	150	263	3.31	0.288	183	141	239

From Taguchi analysis, cutting velocity affects cutting forces more than feed and depth of cut for all cases. The feed rate has significant effect on surface roughness. The cutting velocity has also significant effect on flank wear. The 0.5^{0}C/min(cryo-treated +tempered) insets showed desirable significant effect on output responses than other category of inserts. Flank wear versus time for PVD coated inserts is shown in Fig.8. Similarly flank wear for non-PVD coated inserts is shown in Fig.9.

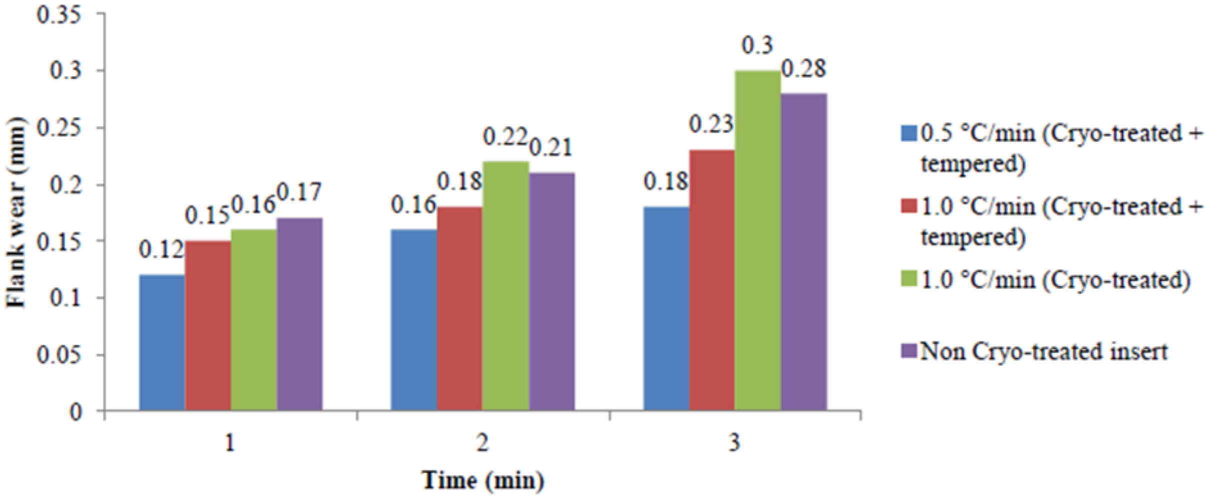


Fig. 8 Variations of flank wear vs. time for PVD coated inserts

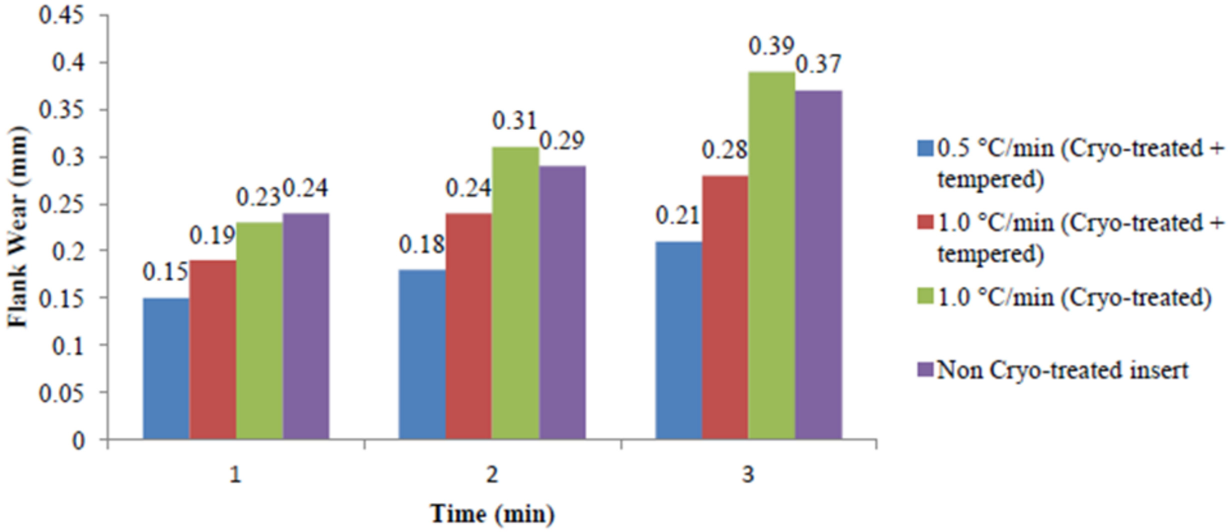


Fig. 9 Variation of flank wear vs. time for Non PVD coated inserts

Graphical analysis for variation of flank wear in tool along with increase in cutting velocity showed that minimum flank wear was observed in case of 0.5^0C/min(cryo-treated + tempered) and maximum flank wear was reported for non-cryotreated insert both for PVD coated and non-PVD coated carbide insert.

4. Conclusion

1) SEM analysis of CT inserts treated at 0.5^0C/min showed the presence of fine particles of eta-phase carbides along with WC uniformly in metal matrix along with Co binder phase densification.
2) Cutting velocity affects cutting forces more than feed and depth of cut. Feed rate has significant effect on surface roughness.
3) Tool life analysis was based on flank wear study which proved that CT inserts provided long run than non-CT inserts. This was mainly due to Co-binder densification which developed ductility.
4) CT when accompanied with tempering resulted in improved tool life. It is a single step process which need not to be done again and again as in case of coating process.

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