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Optimization of CNC face milling using cryogenic WC inserts with multi-layer coatings on EN24 STEEL

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Abstract - CNC machines have revolutionized the manufacturing industry by increasing production efficiency, accuracy, and repeatability while reducing costs. Coatings have been developed and used on cutting tools as part of the ongoing technological evolution of tool manufacture; these coatings serve in cutting by influencing tribological mechanisms. Much research has been published on various cryogenic treatments (CT) used to improve cutting tool performance and efficiency, but less has been done on coating deposition technology titanium aluminum nitride (TiAlN) and TiAlN – titanium nitride (TiN) on untreated and cryogenically treated Tungsten Carbide tools with face milling using CNC on EN24 steel substrate. The outcomes are demonstrated in comparison to those of untreated tools in terms of tool wear (TW), material removal rate (MRR), cutting temperature (T_c), and cutting forces (F_c) and results obtained after CT, higher MRR, lower T_c, and lower F_c, with approximately nil tool wear were detected.

Keywords* — CNC, *Cryogenic Treatment, Cutting force, Cutting Temperature, Material Removal Rate, Tool Wear Rate

I. INTRODUCTION

Computer Numerical Control (CNC) machines adopt automated machining procedures and are used in modern manufacturing processes to automate and control the movement of tools to create precisely cut and shaped parts. CNC machines have grown more popular due to their ability to increase flexibility and productivity, but the dimensional accuracy of the components they create depends on the quality of the machines using processes and methods. [1-2]. Tungsten carbide cutting tools were employed in industries that required high precision and accuracy with fast production in their machining operations. Tungsten carbide (WC) is a popular material for cutting tools due to its versatility in property adjustment via compositional changes and machining cost savings. Introducing multi-edged WC cutting inserts has increased the material's utility as a machining cutter even more. [3] For several reasons, including its great hardness, durability, and resistance to wear and tear, tungsten carbide cutting tools are in high demand across the industrial sector. When tungsten carbide particles are applied onto a substrate using various deposition processes, tungsten carbide coating is a high-performance surface treatment. This coating is excellent for cutting tools, mining equipment, and industrial machinery due to its great durability and resistance to wear. Tungsten carbide coatings can survive high temperatures, abrasion, corrosion, and wear because of their exceptional hardness and thermal conductivity [4]. CT, also known as cryo processing, has been studied extensively to enhance the tribological characteristics of both metallic and non-metallic components [5]. Two types of cryogenic treatment: shallow cryogenic treatment, which takes place at temperatures as low as -80 °C and is typically powered by solid carbon dioxide, and deep cryogenic treatment, which takes place at temperatures as low as -196 °C and is typically powered by liquid nitrogen (LN2). The rate at which a specimen is cooled to a specific temperature and returned to that temperature substantially impacts the properties it acquires throughout cry processing. Cryogenic therapy can achieve additional microstructural changes by employing liquid helium as the refrigerant and soaking at temperatures as low as -269°C [6]. In the CT method, the tools are gradually cooled to the cryogenic temperature, immersed for a set amount of time, and then heated back to room temperature [7]. Cryogenic treatment improves cutting tools' toughness, wear resistance, and fatigue resistance by changing their metallurgical properties. The low-temperature treatment approach is also environmentally safe, with no possibility of hazardous or explosive effects. This is a once-reasonable procedure since it may influence the whole side of the cutting tool [8,9]. The creation of more stable eta (η)-phase carbide particles, as well as the refinement of hard alpha (α)-phase particles with a corresponding decrease in beta (β)-phase cobalt binder content, are also credited with the improvement of the microstructure of WC tools. [10]. Carbide tools are more durable because of the transitions that increase their mechanical qualities. In addition, this results in lower cutting forces and a decrease in tool vibrations [11]. This paper reports on an experimental

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investigation into the extended durability of a coated WC insert treated with shallow cryogenic treatment for face milling of EN24 steel. To do so, the results of machining with both CT and non-cryo-treated (plain) WC-coated inserts were measured and compared to tool wear (Tw), material removal rate (MRR), cutting temperature (T_c), and cutting forces (F_c). Differences in outcome were examined regarding micro and macro-structural alterations following the cryogenic treatment.

II. Experimental and Methodology

In this investigation, the Machining experiments were conducted using CNC vertical milling machine (Make: HURCO, Model: VM10) in a dry cutting environment, Fig.1 shows the expemental machining process. For face milling, M.A. Tools (Mumbai, India) provided tungsten carbide cutting tools coated with TiAlN and TiAlN-TiN. The present study made use of TiAlN (single coating) and TiAlN-TiN (double coating) coated WC inserts shown in Fig.2 (a, b) and table 1 describes milling insert geometry, model numbers APKT 09T308R-EM TT9030 and APKT 09T308R-EM TT8080, manufactured by TaeguTec. For the milling, a tool holder with the model number 2S-TE90AP 220-20-09-L (TaeguTec ChaseMill) was employed.

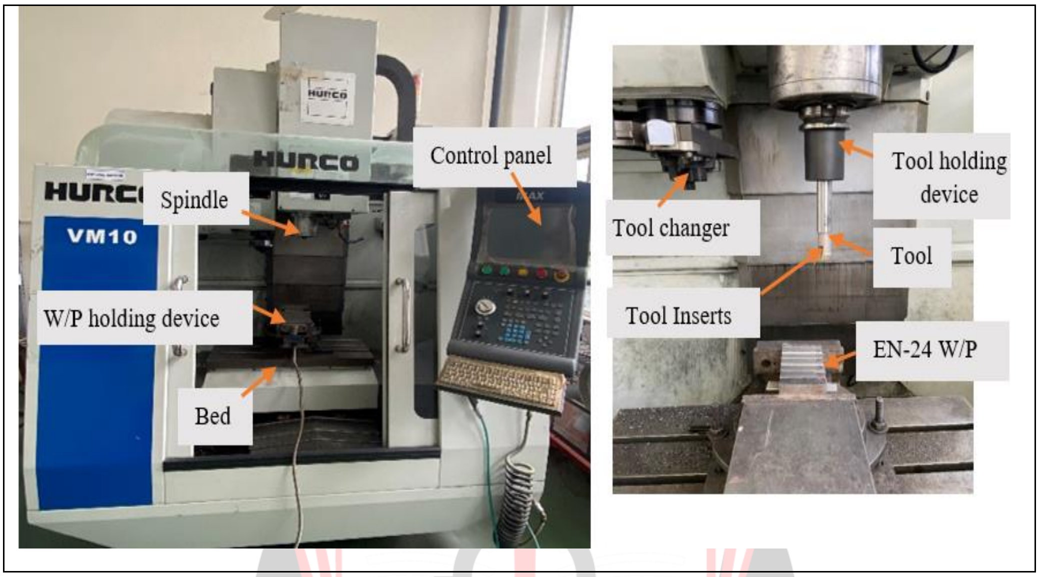

Fig.1 CNC Setup

Fig. 2 (a, b) shows TiAlN and TiAlN-TiN caoted Tungsten Carbide Inserts

Table 1 Milling Insert Geometry

S.no	Grade	Iso designation	Material	Coating	Edge length (l)	Thickness	Nose radius
1	TT9030	APKT09	TUNGSTEN CARBIDE	TiAlN	9.0 mm	3.970mm	0.80 mm
2	TT8080	APKT09	TUNGSTEN CARBIDE	TiAlN-TiN	9.0 mm	3.970 mm	0.80 mm

The research used the hot rolled EN24 steel shown in Fig. 2, the most popular alloy steel used in industries owing to its numerous useful properties for applications such as bolts, gears, etc. An EN24 steel workpiece measuring 32mm x 65mm x 120mm was subjected to dry face milling. The chemical composition of EN24 is shown in Table 2.

Table 2 Chemical composition of hot-rolled EN24 steel

Element	Si	Mn	Ni	Cr	C	Mo
%	0.32	0.68	1.4	0.99	0.35	0.27

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The pilot study consisted of Twenty tests, all of which were planned using the Central Composite Design of the Response Surface Methodology. Extensive experiments were run for each set, and the results were assessed after every 70 mm of cut in terms of cutting temperature, tool wear, and cutting forces. Analysis of variance was used to do statistical analysis of the data, after which a mathematical model was developed to accommodate the results. The model was refined until it produced the expected results. Speed 140 m/min, Feed rate 0.2 mm/tooth, and depth of cut 1.0 are optimum input values. Finally, these ideal characteristics were taken into account for face milling using cryogenically treated tools, and the results were compared to those produced with untreated carbide inserts. The cutting forces were determined with the use of a Kistler 9257B Data Acquisition System piezoelectric multicomponent dynamometer shown in Fig. 3 (a). Force components Fx, Fy, and Fz were measured in the X, Y, and Z directions, respectively; torque component Mz was measured in the Z direction. In this study, forces were calculated in the direction of the cut. Microhardness tests were accomplished with a Vickers hardness tester (model: VM50; maximum capacity: 50 kg) to account for the forces acting on the spindle, Shown in Fig.3d


Fig.3 (a) Dynamometer setup

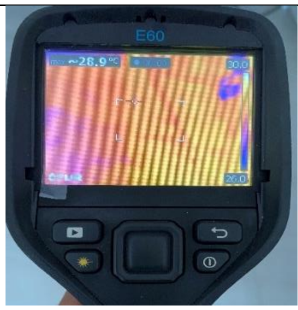

Fig.3 (b)Thermal Camera


Fig.3(c) Weighing Machine


Fig.3 (d) Micro hardness tester

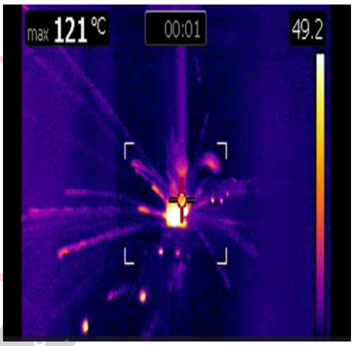

Fig. 3 (e) Temperature During Machining

Measurements were taken with a 0.5 kg weight and a dwell time period (10 sec), the indenter's face angle was 136° 0'; and it was a well-polished, square-based pyramidal diamond, as shown in Figure 3. The present investigation made use of high-resolution images obtained with a JEOL (JSM-IT100) SEM, which is equipped with secondary and backscattered electron detectors. A SEM equipped with EDS (X-act; Oxford Instruments) could identify everything from boron to uranium. Maximum machining temperature was captured using a model FLIR E60 thermal camera at the chip-tool contact as shown in Fig. This non-contact tool operates on the basis of infrared radiation Eagle Silver 3 precision weighing machine was used to determine the difference in weight between the unmachined and machined components. The MRR was calculated by comparing the weight of the workpiece before and after machining shown in Fig 3(c).

MRR = Wi – Wf/T×ρ

where:

Wi–weight before machining of the workpiece [g],

Wf –weight after machining of the workpiece [g],

ρ – density of work material [g/cm³],

T – time to machining [min].

III. Cryogenic treatment

Cutting inserts WC (TT8080 and TT9030) were subjected to a shallow cryogenic treatment at a temperature of -110°C using liquid nitrogen as the refrigerant. The freezing rate was set at 0.5°C/min, with a controlled temperature drop from 25°C to -110°C. Before the operation, the WC inserts were cleaned with acetone and placed in the cryogenic treatment chamber for the

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allotted period of time. As can be seen in Fig.3(e), and maintained a steady temperature for 6 hours to facilitate soaking, and then gradually returned the temperature to room temperature (at a rate of 0.5 degrees per minute). To alleviate the tensions introduced by the cryogenic treatment, a tempering cycle was carried out, which included heating the material to 200 °C for two hours before cooling it down to ambient temperature shown in Figure 4.

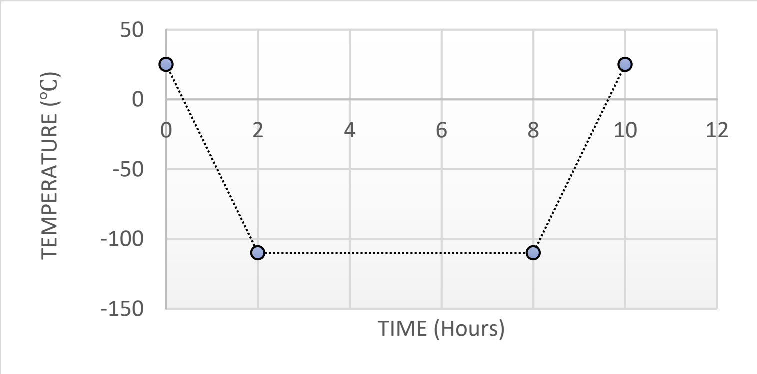

Fig.4. MRR for plain and cryogenically treated WC inserts.

Table 4, there is a description of the specimen nomenclature for the various types of tools that were employed in the experimental investigation. The inserts that were not subjected to cryogenic treatment are shown by the Untreated name.

TABLE 3. Description of WC Inserts used in Experimentation

Nomenclature	Description
Type A	9030 untreated (single coated)
Type B	9030 SCT (single coated)
Type C	8080 untreated (double coated)
Type D	8080 (double coated)

IV. Result and Discussion

The material removal rate for shallow CT inserts showed better results as related to untreated inserts. This happened due to the less force required to cut the workpiece, as a result, the time taken for machining was also decreased, by the enhancement in the microstructure of the cryo-treated inserts due to the creation of finer η-phase particles which makes the matrix tougher shown in Fig. 4. The values of MRR for machining of the workpiece by every insert shows in Fig.5. Type D inserts shows an MRR of 7783 mm^3/min which were followed by Type B whose MRR value was 7037 and Type A and C showed 5775 and 5886 mm^3/min. Fig.6 showed that the cutting temperature of Type A inserts were maximum, which was followed by Type C, Type B and Type D inserts respectively. The cutting temperature of Type D inserts was lowest due to the smaller chips produced while machining. As a result, most of the thermal energy was taken by the smaller chips, which were swiftly removed from the cutting area due to the enhanced microstructure and cutting efficiency of SCT inserts. Cutting temperatures for Type D inserts were recorded at 112 ℃, Type B at 115 ℃, Type C at 121 ℃and Type A at 125 ℃, respectively. In comparison to normal WC inserts, the micro hardness value of the SCT inserts increased after controlled cryo processing. An average of three readings were collected from various locations on the insert's surface to determine its micro hardness using a Vickers scale, a 0.5 kg force, and a 10-second dwell period with a diamond indenter. A significant amount of research reports revealed that cryogenically treated cutting tools have increased micro hardness. It was noted that the tungsten carbide cutting tool, hardness increased somewhat as an outcome of the cryogenic treatment used in this investigation. When compared to all types of inserts Type D insert showed larger hardness and Type A has the least hardness shown in Fig.7. Densification of the softer β-phase, and decreased content as free cobalt, via precipitation into stiff η-phase particles, was responsible for the rise in micro hardness. In addition, the main carbides were displaced by the much finer η-phase particles, which filled the spaces between the bigger particles to make the matrix denser and tougher. Micro hardness testing revealed that types A, B, C, and D of inserts had values of 1341 HV, 1584 HV, 1475 HV, and 1734 HV, respectively. Cryogenic treatment resulted in the precipitation of secondary carbides in the microstructure, which increased the micro hardness.

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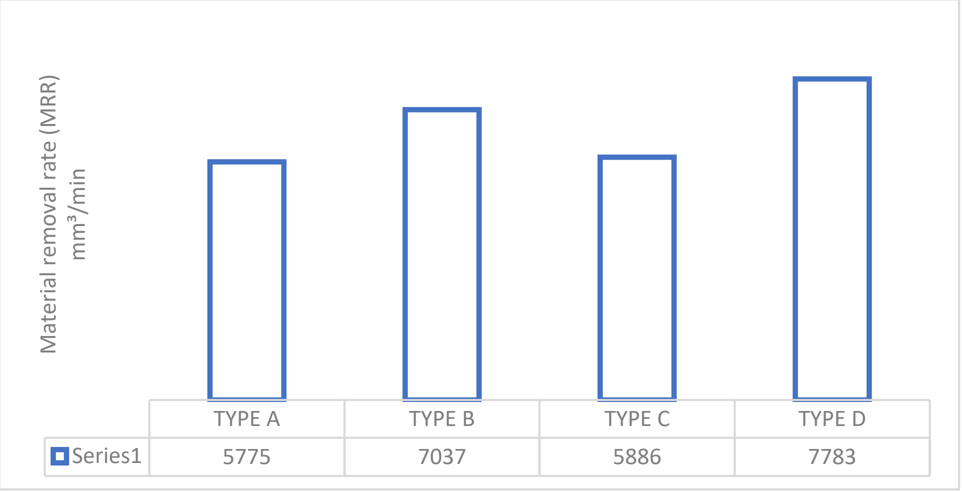

Fig.5. MRR for plain and cryogenically treated WC inserts.

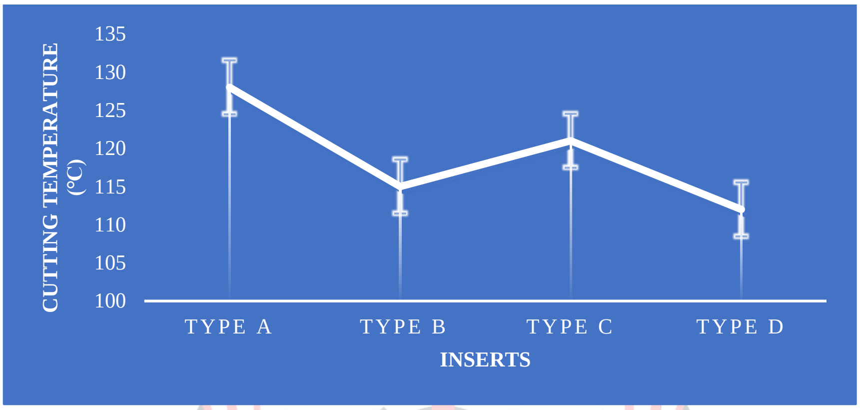

Fig.6 cutting temperature of all inserts.

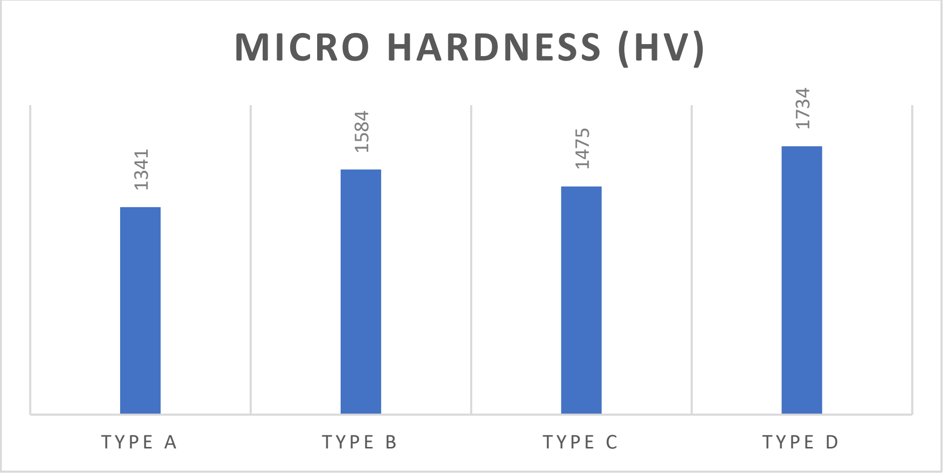

Fig.7s micro hardness of all inserts.

Tool wear of every insert after run was checked on the SEM. The results were showed in Figure 8. from which it can be seen that there was approximately nil tool wear shown for the inserts, when machining was done on EN24 steel with this tungsten carbide tool for selected input parameters. Some researchers have reported the tool wear of tungsten carbide inserts with SCT and DCT on different workpieces materials [7-9], despite the fact that in the tested carbide inserts, this phenomenon was not seen. This happened due to the huge difference in the hardness of inserts as compared to workpiece, and the coatings on inserts increase the machinability, as a result better performance was observed.

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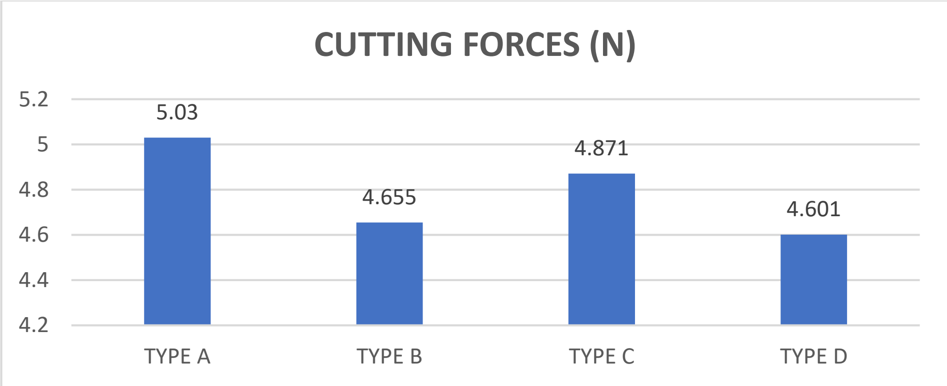

Fig. 8. Cutting forces during machining.

From the experiment, the microstructure result was analyzed from the SEM images and it has been found that The stable form of WC is a combination of three phases, which are denoted by the notations α-phase, β-phase, and η-phase respectively. The α-phase is the hard carbide phase that is dispersed evenly and may be characterized by the grey WC particles that have an angular shape. The β-phase, which corresponds to cobalt and has a structure resembling white veins, serves as the binder for WC and gives the cermet its hardness. The 'eta phase carbides' represent the larger carbides and create the more solid and compact carbide structure as shown in Fig. 4 (Type (a, b, c, d)) compared. The production of this phase takes place when a WC tool is exposed to critical temperatures for lengthy periods of time. The ultimate consequence of this process is a denser, more uniform particle dispersion as well as a more robust, rigid, and sharp cemented carbide. As a result, the microstructure of the SCT WC inserts has undergone substantial modification. This has resulted in the hard α-phase carbides becoming more refined and bigger as a result of spheroidization, β-phase densification, and the deposition of eta-phase particles. The microstructure has been shown to have changed, as evidenced by the fact that the η-phase in carbides used for SCT inserts is now present throughout the cermet, while in the case of regular inserts, it was nearly totally missing in the past. As can be seen in figure 4, the densification of the cobalt and the presence of the eta phase both contributed to a higher increase in the hardness and the toughness of the SCT inserts. The findings of the EDS analysis also revealed a higher concentration of carbide and nitrogen in the SCT inserts, which led to a surge in the stiffness of the WC tool. Additionally, a rise in carbon % was seen for SCT inserts, which may be interpreted as a representation of the conversion of originally existent predominant carbides into η-phase carbides. The nitrogen percentage of Type A, Type B, Type C, and Type D inserts were 23.58, 27.25, 30.89, and 35.06 respectively. Change of percentage in nitrogen demonstrates the CT operations undergoes with liquid nitrogen.

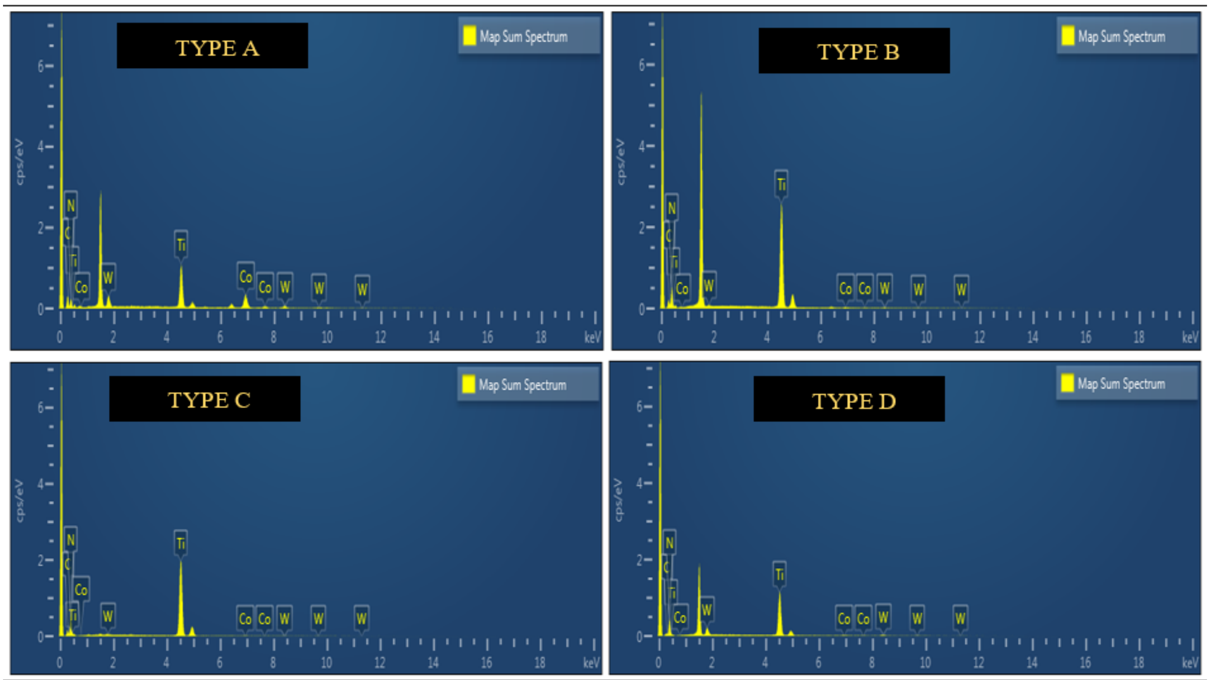

Fig.9. EDS outcomes for (a) plain (A and C) and (b) SCT WC (B and D) inserts.

Figure 9 also reveals that free cobalt's peaks are lower than expected, suggesting that the element was interacting with WC to produce eta-phase carbides.

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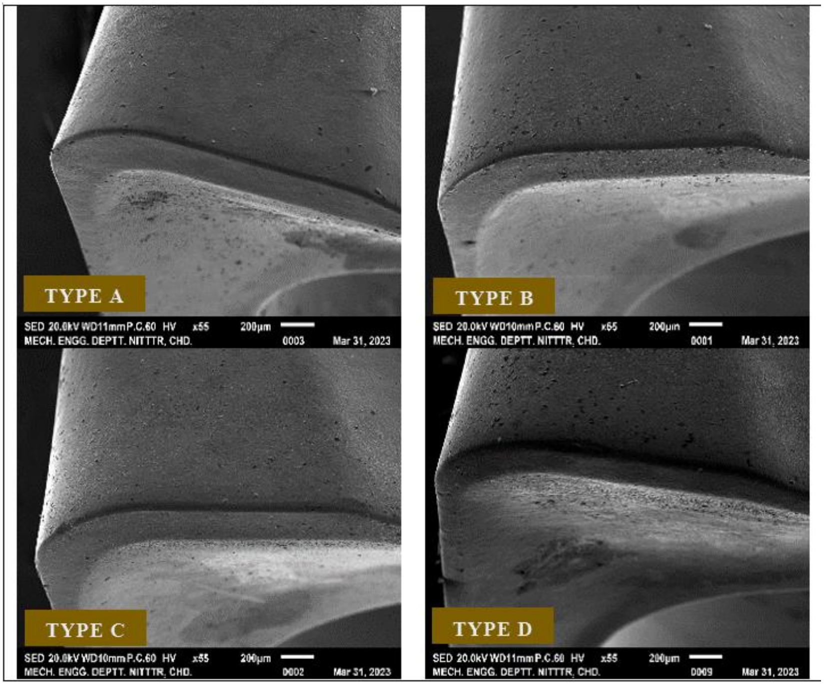

Fig. 10. Sem images of inserts at Vc=140(m/min), f=0.2(mm/min), d=1.0mm

Figure 10. showed a graphical depiction with a comparison of the cutting forces, measured for 65mm length in the x-direction (direction of cut). The initial cutting forces were found to be lowest for Type D inserts, then Type B, then Type C, and highest for Type A inserts. The force had a reading of 5.030 N for Type A inserts, 4.655 N for Type B inserts, 4.871 kN for Type C inserts, and 4.601 N for Type D inserts. Therefore, cutting forces were lowered by 8.908% using Type D inserts when compared to Type A inserts. Improved microstructure in Type D inserts was responsible for their increased stability and rigidity, which leads to a significantly smoother cut during face milling. During machining, SCT inserts create shorter chips than standard WC inserts, requiring less force to cut.

V. CONCLUSIONS

Dry face milling of EN24 steel alloy was studied; using coated WC inserts undergoes cryogenic treatment. The outcomes demonstrate the enhancement in microstructure, cutting temperature and cutting forces, but no tool wear was observed for this length of cut. The data collected for SCT inserts were shown and compared to those collected for untreated inserts to see how the two sets of results differed. Some of the study's results are as follows:

- In contrast to untreated inserts, where η-phase carbides were essentially negligible, SCT inserts revealed a formation of η-phase carbides in the microstructural characterization.
- Due to the formation of η-phase carbides, hardness of SCT inserts showed a remarkable difference. Hardness was found to vary by 16.3% between double coated CT (8080) and cryogenic untreated CT (8080), and by 16.2% between single coated CT (9030) and cryogenic untreated CT (9030).
- By comparison to inserts that were not subjected to cryogenic treatment, the values for cutting temperature (Ct) and cutting forces (Fx) measured with cryotreated inserts were lower. cutting temperature and cutting forces were found to be lowest for shallow cryogenically treated TiAlN-TiN inserts.
- Cryogenically treated inserts showed higher values for material removal rate, with both inserts showing greater values than their untreated ones. When compared to other cutting tools, Type D inserts removed the most material from the workpiece.
- Tool wear for every insert showed no results because of the better machinability of coating tools and greater hardness difference in workpiece and tool material.
- Cryogenic treatment is superior to other methods of surface modification because it entirely improves the tool's microstructure, enabling it to be reused after grinding and leading to greater machining efficiency.

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