A STUDY OF THE EFFECT OF A SURFACE TREATMENT ON THE PERFORMANCE OF CEMENTED CARBIDE INSERTS

A STUDY OF THE EFFECT OF A SURFACE TREATMENT ON THE PERFORMANCE OF CEMENTED CARBIDE INSERTS

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TITLE: **A STUDY OF THE EFFECT OF A SURFACE TREATMENT ON THE PERFORMANCE OF CEMENTED CARBIDE INSERTS**

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Abstract

The main objective of this research is to investigate the effect of wide peening and cleaning (WPC) also known as fine particle peening on the surface properties and cutting performance of cemented carbide inserts. In WPC, the surface of the material is bombarded with millions of high velocity fine shot generating a uniform layer of plastic deformation near the surface. The plastically deformed layer will have higher compressive residual stress levels, higher surface hardness, experience changes in surface morphology and changes in microstructure. Selecting suitable peening parameters is crucial for achieving proper results. In this study, tools are treated under different pressures varying between 0.2 to 0.4 MPa, and for different peening durations of 2.5 to 10 s.

The cutting performance of uncoated tools treated with WPC was examined while turning ductile cast iron and AISI 4140. To have a better understanding, the surface morphology, microstructure, surface roughness, cutting edge radius, residual stresses, and surface hardness were measured and discussed. The results are also compared with untreated tools. The compressive residual stresses were significantly higher after WPC. In addition, uncoated tools treated with WPC resulted in a 12-30% higher tool life over untreated tools.

Based on the findings outlined in this thesis, WPC can be recommended as a surface treatment on uncoated cemented carbide inserts for increasing tool life. Also, this study shows a significant potential for using WPC as a pre-coating treatment for improving coating adhesion on cemented carbide cutting inserts.

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I dedicate this thesis to my grandfather who was always very encouraging for my education. I also want to thank my lovely parents and my two little brothers for all their emotional support during the past 2 years.

Table of Contents

List of Figures

List of Tables

List of all Abbreviations and Symbols

AISI- American iron and steel institute

BEC- Backscattered electron composition

BUE- Built up edge

CBN- Cubic boron nitride

Co- Cobalt

CRS- Compressive residual stress

EDS- Energy dispersive spectroscopy

ISO- International standards organization

MMRI- McMaster manufacturing research institute

P- Pressure

R_a- Roughness average

R_q- Root-mean-square average roughness

S_a- Average height of selected area

S_p- Maximum peak height of selected area

S_q- Root-mean-square height of selected area

S_v- Maximum valley depth of selected area

S_z- Maximum height of selected area

SEM- Scanning electron microscopy

T- Duration Time

WC- Tungsten carbide

WPC- wide peening and cleaning (fine particle bombardment)

XRD- X-Ray diffraction

1 Introduction

1.1 Motivation

There is continuous demand for cost reduction in manufacturing. Cutting tools are an inherent part of the metal cutting process. Therefore, one way to reduce the cost of machining is to increase tool life. Having tools with higher tool life will lead to higher productivity, better geometrical tolerances, and less machine downtime. Many techniques have been introduced to improve the life of mechanical components, like cutting tools, such as surface engineering with coatings and mechanical surface treatments.

For components under cyclic stresses such as cutting tools, fatigue is one of the most important causes for failure. Fatigue failure happens faster in many machining operations due to the tensile residual stresses generated during these processes. Different micro shot peening treatments have been used to improve fatigue life and wear resistance of cutting tools.

Shot peening is a cold working process in which the metal surface is bombarded repeatedly by small particles called shot. The impact of each shot will generate a dimple on the surface. Below the dimple, there will be cold-worked material in a compressive state. The overlapping dimples lead to a large plastic deformation near the surface which changes the surface microstructure, topography, residual stress, and the work hardening state, depending on the material. All these changes can improve the fatigue strength of the surface.

WPC (Wide Peening and Cleaning) also known as Fine Particle Peening is a relatively new peening process developed by Fuji Manufacturing Co., Ltd and Fuji Kihan Co., Ltd (Japan Patent No. 1594395) [1][2]. WPC uses extremely fine particles delivered with much higher velocity in comparison to conventional peening techniques. WPC can induce a higher amount of compressive residual stresses on the surface. Therefore, it can be more effective for harder materials such as cemented carbide. WPC is commonly used in the automotive and aerospace industry to induce compressive residual stress on the surface of a part. To this point, no study was found on the effect of WPC on cemented carbide turning inserts. Proposing this idea led to a collaboration between the MMRI and the Fuji Company.

1.2 Research Objectives

There are many studies on the effect of different peening processes such as shot peening, micro shot peening, shot blasting, micro shot blasting and WPC on components that experience fatigue loading. In all these processes, the surface of the part is bombarded with millions of small particles, generating overlapping dimples which leads to a layer of large plastic deformation near the surface.

WPC is mostly known in the automotive and aerospace industry but limited academic studies have been done on this treatment applied to tooling. Also, a detailed report on the performance and properties of turning inserts after WPC has not been found.

Fortunately, Fuji Company, the inventor of WPC agreed to collaborate through this research to investigate the effect of WPC and different process parameters on uncoated cemented carbide cutting inserts.

The main research objectives are the following:

1. To investigate the potential of using WPC as a surface treatment on uncoated cemented carbide inserts and as a pre coating treatment process.
2. To study the effect of WPC pressure on surface characteristics and cutting performance of cemented carbide inserts.

3. To investigate the effect WPC duration time on surface characteristics and cutting performance of cemented carbide inserts.

1.3 Organization of the Thesis

At the beginning of Chapter 2, different tool materials are introduced with a focus on cemented carbide. Metal cutting fundamentals and tool wear are then described. In Chapter 2.4, shot peening is introduced as a mechanical surface treatment method. Then the effect of different peening parameters on the peening treatment results is reported. Chapter 2.6 describes the effect of different peening processes on the properties and cutting performance of a cutting tool. Chapter 2 concludes with an introduction to the main features of WPC.

Chapter 3 covers the experimental procedure for examining the surface characterization and cutting performance of treated tools. Results and discussion are provided in Chapter 4 with 4.1 covering changes in surface morphology, microstructure, cutting edge radius, surface roughness, surface nano-hardness, and residual stress levels after WPC. The cutting performance of treated tools are examined and compared to untreated ones in Chapter 4.2. In Chapter 4.3, the relationship between the changes in surface characteristics and cutting performance is discussed.

Finally, the conclusion and some suggestions for future work are provided in Chapters 5 and 6 respectively.

2 Literature Review

Before studying WPC, it is important to outline metal cutting fundamentals and provide information on cutting tools. This chapter continues by explaining the main reasons for tool failure. Then it introduces mechanical surface treatment as a possible way of improving the cutting tools. The treatments considered are narrowed down to shot peening. The effective peening parameters and their results are explained. Next, the effect of micro shot peening and micro shot blasting on coated and uncoated carbide cutting tools is described. Finally, the WPC process itself is discussed.

2.1 Metal Cutting and Cutting Tools

Metal cutting is an important and commonly used subtractive process for manufacturing parts. It removes the swept volume of a tool from a workpiece using the prepared edge of a cutting tools. It is important to choose the tool materials and geometry based on the workpiece, the required tolerances, surface finish, and material removal rate [3]. Having a properly selected cutting tool not only helps to increase the machining efficiency but also, it can improve the product quality, enhance productivity and maintain the cost per component ratio.

Since there are many applications, there is also a wide range of different tool materials and compositions. Their resistance to high temperature, abrasion, and fracture is the three main properties that should be taken into consideration. Most common cutting tool materials are listed from the highest toughness to best thermal hardness: Carbon Steel, HSS, Cast Alloy, Tungsten carbide (uncoated and coated), Cermet, Titanium Carbides, Ceramic, Extra hard materials (Diamond and CBN) [3][4].

Generally, tungsten carbide tools are cheaper than Diamond and Cubic Born Nitride (CBN) tools, therefore, they are more commonly used in mass production. 80-90% of all cutting tool inserts currently used are coated cemented carbide [5].

2.2 Tungsten Carbide Tools

In most machining processes, the tool experiences extreme pressures (>1600MPa) and temperatures (750°C) during machining which make the selection of tool material very important [6].

Cemented Carbide is one of the most successful composite engineering materials which is mainly made of tungsten carbide particles bonded together with cobalt. The physical and chemical properties of the cemented carbide particles can vary so that maximum resistance to wear, fracture, corrosion, and oxidation can be obtained. Cemented carbide tools are manufactured using powder metallurgy techniques which allows the production of various shapes and sizes [7].

The amount of cobalt (grade of the tool) is usually between 3-20% and has a major effect on the properties of carbide tools. By increasing the amount of cobalt, the toughness of the tool will increase while decreasing the hardness and thus decreasing the strength of the tool [8].

2.3 Tool Wear

Tool wear is an important issue in metal cutting since it directly affects productivity and product quality. Harsh conditions such as high temperatures, destructive chemical conditions, or repetitive impacts of hard materials are some examples of the initial concerns for tool life and the part surface quality.

2.3.1 Types of Tool Wear

On a single point cutting insert, there are multiple common wear types (ISO standard 3685):

2.3.1.1 Flank wear

Abrasion is usually the cause of flank wear which happens on the cutting edge's flank [6]. Flank wear can be used as a reference for measuring tool life, however, in practice, the end of tool life is often determined based on achieving the desired size, tolerances, and surface finish of the part.

2.3.1.2 Crater wear

Crater wear happens on the rake face due to a combination of abrasion and diffusion wear mechanisms. When crater wear grows, it can also change the effective edge geometry (rake angle), weaken the cutting edge, and consequently result in tool breakage [6].

2.3.1.3 Plastic deformation

Tool undergoes high pressure and temperature during cutting, especially when high speeds and feeds are used. Therefore, the tool material must have the required mechanical properties to resist plastic deformation while cutting [6].

2.3.1.4 Notch wear

Notch wear can happen on both the flank and rake face close to the tool nose or/and at the depth of the cut lines [9]. The mechanism of notch wear is mainly adhesion between the tool and the chip.

2.3.1.5 Thermal and Mechanical Fatigue cracking

In machining processes, the tool undergoes thermal cycling. Thermal cracking can be the result of fatigue caused by thermal cycling. These cracks usually happen perpendicular to the cutting direction [6]. Continues and extreme fluctuations in loads due to high feed rates can also result in mechanically induced fatigue cracking.

Fatigue is the main cause of failure in components experiencing cyclic stresses. Usually, fatigue cracks initiate on or very near the surface of the component since these stresses are maximum at the surface. With time, these cracks continue growing and cause in loss of resistance in the component. Eventually, the component loses the ability to withstand the cutting forces and that is when the fracture failure happens [10].

One of the parameters which strongly affects the fatigue behavior of a component is residual stresses. Residual stresses can also affect the corrosion resistance and crack growth. Residual stresses are the internal stresses that remain within the elastic body of the component without the application of any external load due to mechanical or thermal plastic deformations [11]. Its distribution near the surface of a mechanical component can determine how the component is going to perform [12][13].

The effect of residual stresses on the component depends on the magnitude, sign, and the distribution of the stresses. The fatigue cracks initiate where tensile stresses are present. Hence, the tensile residual stresses are detrimental and will reduce the fatigue life of the part since they work to open and grow cracks. Fatigue failure happens faster in many standard machining processes such as grinding, milling and turning due to the generated residual tensile stresses during these processes. However, compressive residual stresses (CRS) tend to prevent the cracks from changing from a stage I shear crack to a stage II tensile opening mode crack [14]. Compressive residual stress can be induced in a part using different surface treatment methods.

2.3.1.6 Chipping

Chipping is when a crack propagates to a critical length weakening a region so that a relatively large part of the tool is removed quickly rather than by gradual wear such as that associated with abrasion. It can be said that chipping is a kind of fatigue failure as it is often induced by the cyclic stresses generated during machining [6].

2.3.1.7 Fracture

Fracture can be extremely harmful to the insert and the machined part. Fracture happens when a bulk of cutting tool material is removed from the tool.

2.3.1.8 Built Up Edge (BUE)

Built up edge (BUE) happens when the workpiece material adheres to the cutting edge and changes the edge geometry. BUE is very unstable and it breaks when reaching a critical size and it often breaks or chips a part of the tool off as well [6].

2.3.2 Tool Wear Mechanism

Wear is defined as material removal from a surface as a result of mechanical action [15]. There are several types of wear mechanisms such as adhesion, abrasion, fatigue, oxidation, and corrosion. However, it should be noted that wear does not happen through only one mechanism. Also, the dominant mechanisms changes during the part's life for many reasons like changes in surface material properties and its dynamic responses [16].

According to Yen et al., tool wear can be affected by 4 groups of parameters: The mechanical and thermal properties of the workpiece material, the interface between the chip and tool, the properties of the tool such as substrate material, coating and geometry, and the machine tool's dynamic characteristics [17].

Generally, cutting tools fail due to sudden mechanical breakage or plastic deformation due to excessive stresses and temperature or when failure happens gradually due to wear on the flank or rake face. Sudden failure can be very harmful to the process, workpiece and the cutting machine. In general, it can be prevented by selecting a suitable tool in terms of material and geometry relative to the cutting conditions and the workpiece. Ultimately tool wear is inevitable but there are ways to reduce its rate and thus enhance tool life and process performance.

Tool wear mechanisms can be listed as follow [3]:

- **Adhesion**: Adhesive wear generally happens at the cutting edge and along the rake and flank faces. High friction between the tool and the workpiece causes the softer material (chip) to stick to the harder material, which is the tool.
- **Abrasion**: Depending on the workpiece materials there can be hard abrasive particles in the workpiece material such as sand particles from casting or carbide inclusions in steel for example. As the tool moves through the workpiece it will collide with these particles while cutting which will lead to a much higher wear volume rate. Abrasive wear is the most common type of wear and generally leads to a consistent wear rate when machining.
- **Diffusion:** Diffusion is important in many applications in metal cutting. Diffusion occurs when atoms in a metallic crystal lattice move from a region of high concentration to low concentration. This process is very dependent on the materials present in the cutting zone and increases exponentially with temperature.

- **Corrosion:** corrosion happens when significant amounts of chemical or electrochemical interactions take place in the cutting zone. Corrosion is greatly increased due to the high loads and temperatures associated with the cutting process.
- **Fracture:** fracture happens due to either excessive mechanical or thermal loads and can occur over time due to fatigue loading and thermal fluctuation.
- **Delamination:** delamination happens when the micro cracks on the subsurface join each other and undermine a surface treatment like a coating.

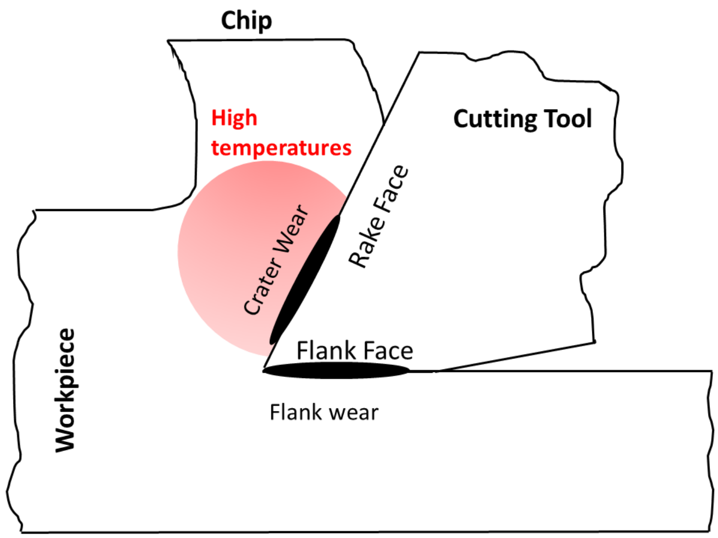


Figure 1- general image of cutting edge, flank and crater wear.

Carbide tools are well suited to many applications in metal cutting. However there are many ways to still improve their properties and performance. Methods include carefully choosing the substrate metal, optimizing the coating deposition parameters, and applying surface treatment prior to and post coating deposition. Surface treatment is a potential way of improving the properties and performance of the cutting tools. There are three types of surface treatments such as thermal treatments, mechanical treatments, and plasma treatments [1]. In this research, the main focus will be on mechanical surface treatments.

2.4 Mechanical Surface Treatments

Mechanical treatments are commonly used for enhancing the performance of cutting tools [2]. Some examples of mechanical treatments include polishing and peening.

Generally, polishing processes are used to improve surface finish and peening processes are used to induce compressive residual stresses on the surface. Polishing is used to reduce adhesion of workpiece material by reducing sites for mechanical interlock and peening processes are used to improve the fatigue resistance of the part. Many peening processes have been developed such as micro shot peening, sandblasting, micro blasting, water jet peening and WPC [4].

2.5 Shot Peening Process

Shot peening is a cold working process in which a surface is bombarded repeatedly by small particles called shot. Usually, spherical particles are used in shot peening and they are often of cast steel, stainless steel, glass, and ceramic beads [18].

The impact of each shot generates a dimple on the surface (Figure 2). The kinetic energy of the shot is responsible for impact intensity with the total energy that is transferred to the material defined as the difference between the incoming and the returning kinetic energy. In addition to velocity of the particle the returning energy also includes vibration, heat and shot plastic deformation. The impact efficiency for spherical shot is estimated between 0.8 to 0.9 [19].

The impact of the shot will create a dimple on the surface. Below the dimple, there will be a local plastic deformation (Figure 2). The material below the deformation tries to push the surface back to its original shape. This generates a cold-worked region that is in compression. By continuing the peening process, a large number of individual shots impact the surface, generating a uniform layer of plastic deformation near the surface. This changes the surface microstructure, topography, residual stress, and the work hardening state with the final amount of change depending on the material properties. All these changes can be organized to improve fatigue strength or if applied incorrectly can damage a surface.

The main changes induced by shot peening are:

- Formation of the residual stress field
- Changes in surface roughness
- Changes in hardness
- Changes in the microstructure of the surface [20].

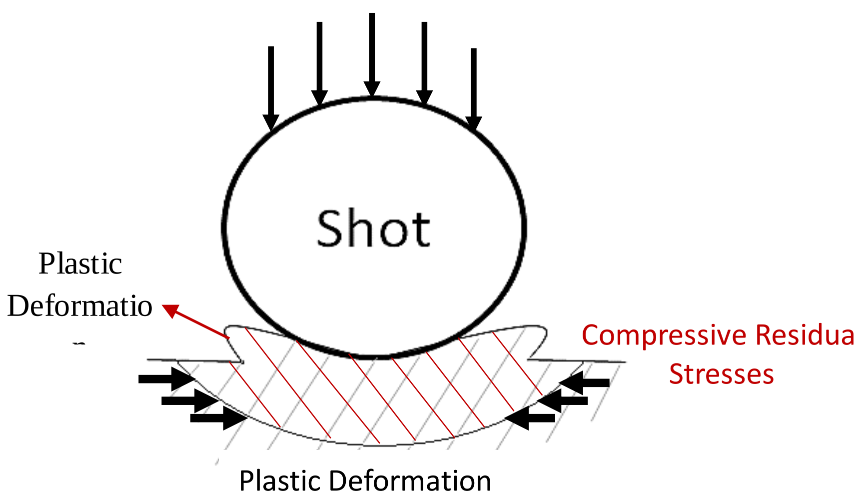


Figure 2- Shot impact, Plastic deformation, and the residual stress (based on [21]**).**

Controlling the peening parameters is essential for achieving good results. Shot peening parameters can be divided into 2 groups, intensity and coverage. Intensity consists of parameters such as velocity, which is controlled by changing the process pressure, shot size, shot shape, material and hardness of the shot while coverage consists of exposure time, the angle of impact, and shot flow rate [22].

2.5.1 Peening Effects

As was mentioned before, peening process can improve the surface characteristics. The energy of shot impact is referred to as the peening intensity which will be absorbed in four ways:

1. plastic deformation,
2. elastic deformation,
3. the rebound velocity of the shot and
4. heat generation.

However, most of the energy goes into 1 and 2 which is within the peened material [10][19].

The main factors that can be modified by the peening process are listed in Table 1.

Table 1- Effects of Peening Process

Metallurgical effects	Microstructure, Hardness
Mechanical effects	Residual stress, Depth of plastic deformation layer
Geometrical effects	Roughness

It is important to know that it is almost impossible to change only one parameter through a peening process as they are very coupled in nature. If one parameter is changed there is going to be some alteration to the others as well.

2.5.1.1 Residual Stress

As mentioned earlier, the impact of the shots will generate localized plastic deformation. Since the material is bonded together, underneath this plastic deformation the material tries to push the plastically elongated layer to its original shape. This is the cause of compressive residual stress (CRS) in the plastically deformed layer. In order to have a balanced system, underneath the layer of CRS, there is going to be a distribution of tensile residual stresses. However, the tensile stresses below the surface would not affect the fatigue life since fatigue cracks usually start at or very near the surface [21].

Inducing compressive residual stresses on the surface of a part can dramatically increase its fatigue resistance. The following parameters can affect the depth and the maximum level of induced residual stress [23]:

- the nature of the shot material,
- shot size,
- projection velocity and
- peened material.

By increasing the shot diameter and velocity, the depth of the residual stress layer will increase [20]. Harada et al. indicated that the depth of the plastically deformed layer is about 70% of the shot diameter [24]. A more uniform layer of compressive residual stress is generated when using finer shot particles. Achieving a uniform layer has been observed to have a significant effect on the fatigue life of the peened part [25].

Surface residual stress values are dependent on both the mechanical properties of the peened part and the peening process parameters [11]. The shot hardness, size, and peening pressure will determine the overall energy available to be absorbed by the material and the mechanical properties such as yield strength, ultimate yield strength, and hardness of the peened material will determine the maximum compressive residual stress that can be induced [26]. It is obvious that workpiece materials with higher hardness will have less plastically deformed depth under the same peening conditions. Consequently, harder materials are less sensitive to projection pressure. However, harder materials can have a higher amount of maximum residual stress while the effective depth tends to increase in softer materials [12].

2.5.1.2 Surface Topography

The most effective peening parameters on surface topography are:

- shot size and
- peening pressure (velocity).

Various peening pressures and shot sizes can create different impressions on the surface of the material, which can affect the surface roughness [23]. Some other parameters also affect surface roughness. For instance, decreasing the angle of impact (90° being the highest), tends to decrease roughness.

2.5.1.3 Hardness

It should be mentioned that strain hardening and residual stresses have the most significant effect on the fatigue resistance of a peened part. Conversely, surface hardness becomes very important when high wear resistance is required rather than high strength in a part [27]. Surface hardness is mostly affected by peening pressure and shot size.

When the shot material has hardness equal or less than the peened surface, peening will have more effect on material deformation with negligible effect on the abrasion resistance of a surface [28].

Increasing the peening pressure can increase surface hardness since it will cause more intense plastic deformation. Also, using bigger shot particles can result in a higher work-hardened layer depth compared to fine shot particles operating under the same peening conditions [29].

2.5.2 Peening Parameters

Peening parameters such as peening pressure, exposure time and percentage of coverage, shot dimension, shape, and hardness, and the projection angle have significant effects on the peening performance [23]. Using unsuitable peening parameters can easily damage the part and reduce its fatigue performance. Therefore, the peening parameters should be carefully selected and controlled [14].

2.5.2.1 Shot Material

Different materials can be used as shot media such as cast iron, steel, aluminium oxide, ceramics, glass, corundum and plastic.

2.5.2.2 Peening Intensity and Shot Size

Peening intensity depends on shot mass, velocity (pressure), shot hardness, and the angle of impact. Peening intensity generally refers to the kinetic energy of peening at the instance of impact.

The diameter of the shot particles can vary from 10 µm to 10 mm based on the peening application. Mostly, finer shots with a diameter smaller than 0.5 mm (500 µm) are used for inducing compressive residual stress especially when the surfaces being treated have fine geometric features and surface finishes.

2.5.2.3 Percentage of coverage

Percentage of coverage usually varies between 100% and 400% [30]. 100% peening coverage means that the surface of the peened part has been totally exposed to shot peening. Coverage percentage of more than 100% is done to ensure a uniform treatment and improve the integrity of the plastically deformed layer.

2.6 Micro blasting/Micro shot peening WC Tools

Basically, micro shot peening, micro shot blasting, and WPC have the same process principals. In all these processes, the surface of the part is bombarded with many individual shots and are used to generate a compressive residual stress in the workpiece surface. The difference is in the amount of damage done to fine surface features, residual stress, depth, and the material removal effect of these processes. Many researchers have studied the effect of micro shot peening and micro shot blasting on properties and performance of cemented carbide tools. Applying these treatments before and/or after coating deposition will have different influences on the surface. In the following, the effect of micro shot peening and blasting on cemented carbide tools before and after coating deposition is investigated.

2.6.1 Peening prior to coating deposition

Many researchers investigated the effect of peening processes on uncoated tools. Tönshoff et al. investigated the effect of different surface integrities on coating adhesion and the wear behavior of cemented carbide tools. The results showed that water peening the substrate can increase the surface roughness. Consequently, the interface area between the coating and the substrate increased which improved the coating adhesion if it is of the right scale and structure. Also, by increasing the duration time of water peening, the surface roughness can be reduced since it may remove some binder material around the cemented carbide at the surface of a tool. This means that the roughness would be the actual grain size of the material. He also mentioned that there were some areas with a molten binder phase after applying water peening. Also, the binder phase was observed to completely disappear from the surface when a high peening duration time was used. By depositing the coating on treated substrates, the roughness values were significantly reduced. In addition, after depositing the coating on the treated substrate, the value of compressive residual stress decreased. The measurement of residual stress was also influenced by the depth of penetration of the X-Ray typically used to measure residual stress [31].

Bouzakis et al. indicated that micro blasting the carbide tool reduced the high roughness peaks since it removed some of the carbide grains from the surface while revealing many small peaks. It also reduced the amount of cobalt binder since cobalt is more brittle than WC grains. All the mentioned aspects led to better mechanical locking between the coating and the substrate provided the scale of the surface roughening is appropriate. The cutting performance of the tools pre-treated before coating with high and low micro blasting pressure was examined using a milling process. Coated tools with a micro blasted substrate performed under higher pressures were observed to have the best cutting performance. Although the tools with an untreated substrate and micro blasted with lower pressures had good coating adhesion, their coating showed earlier local failure. This is attributed to the relatively higher roughness peaks compared to the substrate surface resulting from the micro blasting being performed under a higher pressure [32].

Also, by increasing the coverage percentage, the amount of plastic deformation and thus the hardness increased. When peening with very fine particles, the roughness was observed to increase. However, by increasing the coverage percentage beyond 100%, the roughness might not change with overlapping passes. In addition, micro shot peening has been observed to be very effective in reducing surface defects by plastically flowing the material to fill small cracks and voids present in the surface [24].

Substrate damages such as decreased surface topography and surface integrity caused by grinding the carbide tools can be removed by selecting an appropriate mechanical surface treatment. With peening the surface of cemented carbide, the amount of Cobalt binder decreases. Using smaller shots can further increase this effect. If the shot size is bigger than the size of carbide grains, peening will have plastic deformation effect while with shots smaller than carbide grains, the abrasive effect will be more obvious [33].

Peening cemented carbide tools was observed to remove a layer of Co binder which effectively increased the amount of tungsten carbide grains available at the surface for interlocking with the coating. Better coating adhesion can thus be explained by the micro peening roughening effect which increased R_t while decreasing the distance between peaks (R_{ms}). In addition, the tensile residual stresses caused by coating deposition can be avoided by applying micro peening/blasting on the substrate. Higher deformation happened when the residual stresses on the substrate were low which also deteriorated the tribo-mechanical properties of the coating. Pressure was a crucial parameter that helped increasing the surfaced hardness and residual stress levels [7].

After applying a peening treatment on the carbide substrate, if the induced stresses become higher than its yield stress, it will have a negative effect on the cutting performance [34][32]. Both wear and fracture resistance influence the cutting performance of tools. It has been reported that shot peening cemented carbide was found to enhance its fracture toughness [35].

When applying a low-stress coating, the residual stress of the substrate becomes very important. It can be said that the stress state of the substrate plays an even more critical role than the stress present in the coating [34].

After the peening process, if R_t is higher than the mean tungsten carbide grains radius, the bonding between the grains and Co binder will be weaken. After depositing the coating on the surface of the WC tool, the chance of adhesive coating failure during machining will increase [36]. Also, When using peening processes as a pre-treatment on cemented carbide tools, the enlargement of residual stress mainly happens due to Co-binder deformation [37].

2.6.2 Peening after coating deposition

Bouzakis et al. also used micro blasting as a post-treatment on coated carbide tools. He also reported that the surface roughness increased due to Co binder and carbide particle removal. His SEM images showed that micro blasting created local coating removal. In Bouzakis's case, the tools with post-treatment had poor cutting performance compared with untreated tools. He suggested that the possibilities of coating failure can be reduced if the substrate has lower roughness so there will be a lower potential of carbide grain removal after applying micro blasting on the coating. Accordingly, post-treatment of coated tools should be done very carefully as it can remove the coating and thus deteriorate tool life [32].

If micro peening is done properly on the coating, it can improve its hardness as well as toughness and result in higher tool life. In [38], the effect of different micro blasting pressures and duration times on the mechanical properties of the coating, cutting geometry, and cutting performance of PVD coated carbide tools were investigated. Increasing the peening pressure improved the superficial film hardness. Increasing the duration time had the same impact as pressure on the film hardness. Also, it was observed that high pressure and long processing time can change the cutting edge leading to substrate exposure. As a result, the thermal barrier property at the cutting edge roundness was locally damaged and cutting heat flows directly into the tool. In this study, the best cutting performance with a measured 50% improvement in tool life was achieved when using a lower blasting pressure of 0.2 MPa. Increasing the pressure beyond this value was observed to reduce the tool life even compared with untreated tools. This was attributed to a higher level of substrate exposure.

According to [39], micro blasting the coating produced compressive residual stresses near the surface and also increased the surface hardness. However, film brittleness was also increased. Blasting time and process pressure had a strong effect on the cutting performance of the coated tools. Increasing the pressure resulted in a deeper plastically deformed layer without changing the maximum yield stress. TiAlN coatings with 3µm thickness were deposited on cemented carbide tools. Sharp edge Al_2O_3 and spherical ZrO_2 shot particles were applied with different pressures and processing times. For Al_2O_3 grains, a large coating material removal was observed and was found to be dependent on the blasting pressure and duration. To avoid abrasive wear during micro blasting, the duration time should be less than 6 s. However, when using ZrO_2 shots, even at the highest pressures and durations, no coating material removal was observed. When blasting with sharp Al_2O_3, less grain energy is used for plastic deformation, therefore, the treated surface had a higher roughness and lower nano scale surface hardness as compared to blasting with ZrO_2 under the same conditions.

As mentioned above, increasing the pressure for blasting with Al_2O_3 or ZrO_2 increased the hardness. However, when using ZrO_2, most of the shot's kinetic energy is used for surface plastic deformation rather than abrasion which resulted in higher surface hardness but was also associated with higher film brittleness. Increasing the pressure also increased the cutting edge radius. The effect of using ZrO_2 shot particles was still less than Al_2O_3 when using the same peening conditions. For both grains, applying micro blasting with a pressure of more than 0.6 MPa reduced the thickness coating at the cutting edge. Interestingly, the chances of revealing the substrate were more pronounced when using ZrO_2 shot particles at 0.4 MPa pressure. This was because of higher film brittleness. At 0.2 MPa pressure, the cutting performance improved by approximately 40% for both grains. But after 0.4 MPa performance was observed to deteriorate [39].

Bouzakis et at. in [29] investigated the effect of different micro blasting particle sizes (10 & 100 um) on the properties of TiAlN coated carbide tools. Finer grains resulted in higher surface roughness, lower nano-hardness, and a more intense material removal rate as compared to coarse grains. For both grain sizes, by increasing the pressure the film hardness increased. However, a more intense coating deformation was achieved when using coarse grains which also resulted in higher brittleness and more coating removal. Cutting edge radius enlargement happened when blasting with both particle sizes. Increasing the cutting edge radius by less than 5 μm did not affect the tool wear rate substantially since it did not change the stress field along the flank and rake face of the tool. However, if the enlargement of edge radius was higher it would have affected the substrate and increased the thermal and mechanical loads leading to lower cutting performance.

When using shots with an equal or lower hardness than the coating, blasting will have more of an effect of the material deformation with a very small abrasion effect. Therefore, the topography of the coating does not change with micro blasting. In conclusion, micro blasting a coating can improve coating strength while the surface integrity and the adhesion remains unchanged [28].

Micro blasting the TiAlN coated tool will increase the stress on both the coating and carbide substrate near the cutting edge region which will also increase the surface hardness. These effects will enhance the wear behavior of the tool. Depositing coating directly on either a ground or polished substrate can result in poorer adhesion. However, micro blasting ground tools can result in increased adhesion. The bonds to the hard WC particles are stronger than the bonds forming to the soft binder. Therefore, the excessive loss of the binder phase at the surface leads to a better mechanical interlocking of the coating [7].

2.7 WPC Treatment or Fine Particle Peening

Wide peening and cleaning (WPC) also known as fine particle peening is a relatively new peening process invented by Fuji Manufacturing Co., Ltd and Fuji Kihan Co., Ltd with US Patent No. 6038900 [1]. WPC has similar principles to micro shot peening; it uses extremely fine and hard particles which are applied at a much higher velocity as compared to conventional peening techniques. The velocity of shots in conventional peening is around 70-80 m/s while WPC has a velocity which is 3 times higher [40].

The maximum residual stress induced by the WPC process is restricted close to the surface. Such a residual stress field can effectively prevent small surface fatigue cracks from forming and propagating [41].

As it was mentioned before, the depth of the plastically deformed layer and the energy density per unit volume is controlled by shot size. The kinetic energy of the shots in WPC is relatively low, therefore, the plastically deformed layer is very shallow. However, the induced energy density is much higher than conventional peening since numerous micro shots will impact at the same position and thus result in higher compressive stresses but at a reduced depth [42][43].

WPC can be applied on ceramic coating with a depth of 10 μm or smaller. The treatment applied on the surface of the coated metal can sufficiently influence the base metal. According to Fuji [2], applying WPC on cemented carbide tools with TiC+TiN CVD coating can refine the internal structure of the surface. They also claim that it will induce internal compressive residual stresses in the surface region.

WPC can improve the abrasion resistance of a part by creating a hard surface layer. Also, it produces small dimples that can help to capture the lubricant in parts under sliding and so it reduces the contact area and the friction coefficient [40].

WPC has been applied on different engine parts, sliding parts, torsion bars, pumps, cutting tools and die-cast components in an effort to improve surface performance. Using WPC for coated cemented carbide products can result in an increased level of compressive residual stress [2].

2.8 Summary

Many studies have been done on the effect of different surface treatments being applied on carbide tools both before and after coating deposition. However, WPC is currently mainly applied in the automotive and aerospace industry. Therefore, in this study, the effect of WPC is investigated on the properties and cutting performance of uncoated cemented carbide inserts. The aim of applying WPC on uncoated tools is to better understand its influence as a post-treatment and to examine the potential of using WPC prior to coating deposition to improve adhesion.

3 Experimental Procedure

3.1 Introduction

As it was mentioned before, the list of the main process parameters as reported in the literature includes particle material, size, pressure/velocity, exposure time and distance. It is important to find the parameters that not only do not damage the tool but also, lead to the best mechanical properties and cutting performance. In order to investigate the effects of these parameters on uncoated tools, first 2 parameters, P1 and P2 are selected. All the others will be fixed while P1 and P2 have three different values. The same treatment is applied on 2 tools under each set of processing conditions.

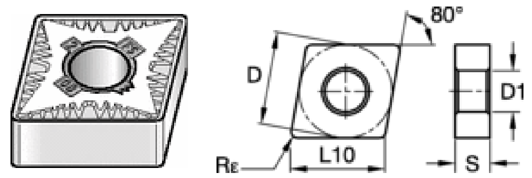
Peening pressure and duration time have a significant effect on peening performance [38]. Therefore, in this research, P1 and P2 are respectively set representing different pressures and duration times.

In the following study, the selected tool and the WPC parameters are explained. Then, the two workpiece materials for tool life investigations are introduced. How to investigate the surface characteristics using surface morphology, energy-dispersive X-ray spectroscopy analysis, and roughness measurements are explained. Then further investigations were done through edge radius, residual stress, and nano-hardness measurements.

3.2 Cutting inserts

Kennametal uncoated cemented carbide finishing inserts are selected for this experiment. The uncoated tool is not commercially available but has same geometry as a coated Kennametal insert with ISO Catalog Number CNGG120408FS (Table 2).

Table 2- Geometry of both coated and uncoated tools

	D	L10	S	RƐ	D1
	12.7 mm	12.9 mm	4.76 mm	08 mm	5.16 mm

- Kennametal K313 (Uncoated)

Uncoated cemented carbide tools are usually used for cutting heat resistant super alloys, titanium alloys, and low speed turning hardened materials [5]. K313 is an unalloyed WC/Co fine-grained grade with 6% of hard binder content. It is best for cutting stainless steel, cast iron, non-ferrous metals, and hardened materials.

- Kennametal KC5010 (Coated)

An advanced PVD AlTiN coating is deposited on a very deformation resistant unalloyed carbide substrate. KC5010 is suitable for machining most steels, stainless steels, cast irons, non-ferrous materials and super alloys at higher cutting speeds under stable conditions.

3.3 Applying WPC

The main goal of this research was to investigate the possibility of using WPC as a pre and/or post-treatment applied on carbide inserts. As mentioned earlier, it is very critical to select the peening process parameters according to the application and the process and material requirements. Choosing parameters that are too low will have minimal effect on the surface while choosing extreme parameters can easily damage the tool surface or the cutting edge. In the first attempt of this study, the tools with WPC were damaged. The details of this experiment can be found in Appendix 1. For the next step, Fuji (inventor of WPC) agreed to collaborate throughout this research.

As mentioned before, very few studies have been done on the effect of mechanical surface treatments on cemented carbide turning inserts while no reports were found in the available literature on the effect of WPC on turning carbide inserts.

Therefore, 10 uncoated inserts were sent for WPC treatment to Fuji. The details on the treatment are provided in the following section.

3.3.1 Fuji WPC Treatment

As was mentioned previously, the list of the main process parameters from the literature include particle material, size, pressure/velocity, exposure time and stand off distance. Based on the literature, the pressure and duration time have a significant effect on the resulting surface properties and the cutting performance of carbide tools [36][39][44]. Therefore, in this thesis, pressure and duration time were selected as the parameters of study with all the others kept the same.

Applying an extreme pressure and extended processing time can easily damage the coating, the cutting edge, or the tool surface. Also, if too low of a pressure or time is used no effect on the cutting tool will be realized. A common range of peening pressure for coated and uncoated cemented carbide tools is between 0.1 MPa to 0.6 MPa. Higher pressures will reveal substrate for the case of coated tools and produce a relatively high cutting edge radius in case of an uncoated tool. A commonly used duration time is reported to be between 2 s to 30 s [34][38][39][45][46][47]. According to the literature [39], using spherical shot particles even with the highest duration time does not result in coating removal. However, the high plastic deformation would lead to high film brittleness. Therefore, even when there is no substrate revelation, duration time should not be set to be too long.

In this research, pressure and duration time were selected with the help of the literature and experience gained by the Fuji Company. Fuji is using steel shot particles with approximately 15 µm diameter, a 50 mm stand-off distance and a 90° angle of impact for maximum plastic deformation.

The pressure (P) is varied from 0.2 MPa to 0.4 MPa, P1 being the minimum pressure and P3 being the maximum (Table 3). The duration time (T) is also varied from 2.5 s to 10 s with T1 and T3 being the minimum and maximum respectively (Table 4).

Table 3- Tools treated for constant Duration

T2=5s	Uncoated	Coated
P1 = 0.2MPa	U_{12}	C_{12}
P2 = 0.3MPa	U_{22}	C_{22}
P3 = 0.4MPa	U_{32}	C_{32}

Table 4- Tools treated for constant Pressure

P2=0.3MPa	Uncoated	Coated
T1 = 2.5s	U_{21}	C_{21}
T2 = 5s	U_{22}	C_{22}
T3 = 10s	U_{23}	C_{23}

The effect of using the WPC as a surface treatment on the microstructure, surface roughness, edge radius, residual stress, nano-hardness and the cutting performance of an uncoated carbide tool are investigated in the following chapters.

3.4 Workpiece Material

For investigating the cutting performance of uncoated tools, finish turning was done on two different workpiece materials. As mentioned earlier, uncoated CNGG120408FS cemented carbide inserts of grade K313 with 6% Co, supplied by Kennametal, were used in this study. Ductile cast iron was selected since it was one of the recommended options for K313. AISI 4140 is a very popular alloy steel and was thus selected for this investigation since it provides high abrasion wear and it is harder than cast iron so it requires less machining time for the tool to fail and so makes the testing quicker to perform.

It should be noted that the insert is not recommended by the supplier for cutting alloy steel. However, for the purpose of this study its use allows for the investigation of the behavior of different treated and untreated inserts and highlights the effects of surface treatment by WPC. In addition, although 4140 is not recommended to be machined using an uncoated K313 tool, it is recommended to be machined using a coated K313 tool. Thus, the K313 tool is mostly used as a coated tool. During preliminary testing, 4140 was observed to provide consistent cutting test results which is important for making the comparisons in this study.

Ductile cast iron and heat treated alloy steel AISI 4140 are both known for their abrasive wear. Therefore, many researchers have used these materials to examine the effect of surface treatment on cutting tools [20][25][34][38]. In the following, a brief introduction of these materials is provided.

3.4.1 Ductile Cast Iron

A 80-55-06 grade of ductile Cast Iron was chosen due to its highly abrasive characteristics. This material is also recommended to be machined using both an uncoated and coated K313 tool.

The microstructure of ductile cast iron consists of a ferrite-pearlite matrix with spherical graphite dispersed randomly inside the matrix. Ferritic ductile cast iron has high ductility but low strength which is in contrast with pearlitic ductile cast iron. The changes in ductility and strength strongly influence tool performance [48]. As the name of this material highlights, ductile cast iron has better ductility as compared to white cast iron and a lower production price than malleable cast iron. Therefore, this material is widely used in the automotive industry, machine components and piping accessories.

Many researchers reported that adhesion (BUE) is more severe when machining ferritic ductile cast iron [49]–[51]. However, the tool life was notably lower when machining pearlitic ductile cast iron, which was also the case for this study.

In this study, a 228 mm diameter 305 mm long bar of 80-55-06 grade ductile cast iron was used.

3.4.2 AISI 4140 Alloy Steel

AISI 4140 alloy steel is a chromium, molybdenum, and manganese-containing low alloy steel. It has high fatigue strength, abrasion and impact resistance, toughness, and torsional strength. Machinability (based on AISI 1212 having a machinability of 100) is set at 65 [52]. 4140 steel is often used in the automotive, agricultural, and defense industries. There are many applications for 4140 steel such as shafts, crankshafts, bolts/nuts, gears, milling spindles, collars, jigs, steel conveyors and rolls, fixtures and steel coupling to name a few.

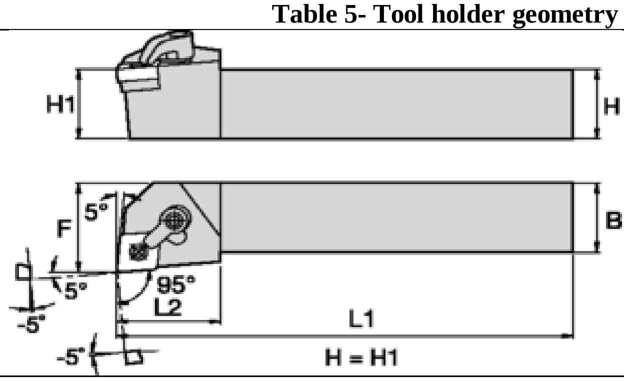
A 305 mm long, 127 mm diameter bar of AISI 4140 heat treated steel with Rockwell hardness of 30 HRC is used in this study. The cutting tests were done on a diameter range greater than 115-105 mm of the bar. This was done to eliminate the effect of changes in hardness with depth and to keep vibration of the bar under the cutting loads low.

3.5 Tool Life

According to ISO standard 3685, 0.3 mm of flank wear or a sudden failure is set as the end of tool life. The cutting performance was evaluated by doing several turning tests until reaching

300 µm flank wear. The machine used for the turning tests was a Nakamura-Tome SC-450 CNC lathe center. A Kennametal right-handed tool holder was used (MCLN-5°) with the following geometry (Table 5).

Table 5- Tool holder geometry



Dimensions			
H	B	F	L1
1 in	1 in	1.25 in	5 in

The parameters were selected in a way to be suitable for finishing operations. The parameters are outlined in detail in the result and discussion section. The flank wear is measured using a Keyence VHX-5000 microscope.

3.6 Cutting Forces

Cutting forces were measured using a Kistler type 9129AA Tool Dynamometer. The Kistler LabAmp Type 5167A charge amplifier is used for amplifying the force signals. DynoWare Type 2825D-03 software is utilized for data acquisition and analysis.

3.7 Surface Morphology

Before performing any cutting tests, the surface characteristics of the tools with and without WPC were investigated. The surface morphology of the tools was examined by Scanning Electron Microscopy (SEM) and Electron Diffraction Spectroscopy (EDS). The images were collected using JEOL 6610LV. To improve the elemental contrast between different phases, backscattered electron images were also obtained. All the EDS elemental maps, point and line scans are done using Aztec Version 3.3 Oxford Instrument software.

3.8 Surface Roughness and Edge Radius

Roughness can be calculated on a line (R_a, R_q, …) or a surface (S_a, S_q, …). ISO 25178 defines the areal roughness parameters. Since the surface of the tools are very smooth (~100 nm), it was decided to measure the areal roughness values. The surface roughness values were measured using the Alicona Optical microscope under ISO standards 4287 and 25178 [53]. In order to see the effect of WPC on the surface roughness, four areas were selected on four flank surfaces of each tool close to the cutting edge (Figure 3). Also, the roughness of the two tools with the same WPC parameters were measured. This means that for each WPC condition, 48 measurements are provided. All roughness values were measured with the 50x lens with a field of view of 286 µm x 218 µm. The points are about 500 µm away from each other. It should be mentioned that the points do not have a fixed coordinate, but they are selected approximately. The areal roughness parameters are introduced in Table 6.

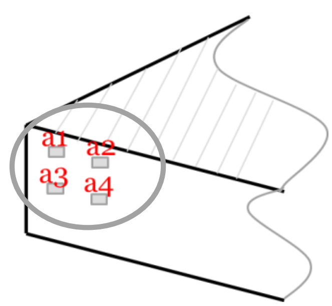


Figure 3- Selected points on the flank face for roughness measurement.

Table 6- Surface roughness parameters

Name	Description
S_a	Average height of selected area
S_q	Root-Mean-Square height of selected area
S_p	Maximum peak height of selected area
S_v	Maximum valley depth of selected area
S_z	Maximum height of selected area

The cutting edge radius is also measured for all four edges of 2 tools for each WPC condition with the same instrument using the 10x lens.

3.9 Residual Stress

The residual stresses on the flank and rake face of the uncoated tools were measured using a 2-dimension X-Ray Diffraction (XRD) system, Bruker D8 Discover device. This instrument uses cobalt radiation and 1.79 Å (K_α). LEPTOS software was used for calculating the residual stresses based on the sample-detector distance, and goniometer angles ω, χ, ϕ [54].

3.10 Nano Hardness

A Nanoindentation tester, NHT^3 from Anton Paar was used for measuring the surface hardness (Figure 4). This instrument can apply loads ranging from 0.1 to 500 mN. Also, it provides depth measurements in the nanometer scale [55].

For this study, the tools were mounted to ensure they are properly held in place. 20 indents were done on the flank face of the tools close to the cutting edge. The applied load was 200 mN with a duration of 5 s. The average of the hardness with their standard deviation is provided in chapter 4.

Figure 4- Nanoindentation tester.

After preliminary testing, the best value for P1 and P2 was selected as the optimized parameters for the WPC process for the uncoated carbide inserts used in this study. Based on these values, the next set of experiments was designed.

4 Results and Discussion- Uncoated Tools

In order to investigate the effect of WPC on carbide inserts, the surface morphology, surface roughness, the edge radius, residual stresses, and surface hardness were evaluated. Furthermore, tool wear studies were performed on both the treated and untreated tools to better understand the cutting performance improvement associated with the WPC treatment.

4.1 Surface Characterization

4.1.1 Surface Morphology and Micro Structure

As it was mentioned earlier, peening processes can change the surface properties such as the topography and microstructure. In order to investigate the effect of different WPC parameters on the surface of an uncoated carbide tools, Scanning Electron Microscope (SEM) and Energy Dispersive X-Ray Spectroscopy (EDS) were used to study the cutting edge and the rake face of the tools.

4.1.1.1 Cutting Edge

Scanning electron microscopy was done at 15 kV electron beam energy. No obvious defects were visible on the cutting edges of the uncoated tools even for the tool under the most extreme WPC parameters as shown in Figure 5. This indicates that applying WPC with a maximum pressure of 0.3 MPa and a duration time of 10 s using steel beads does not damage the edge of the uncoated carbide tools.

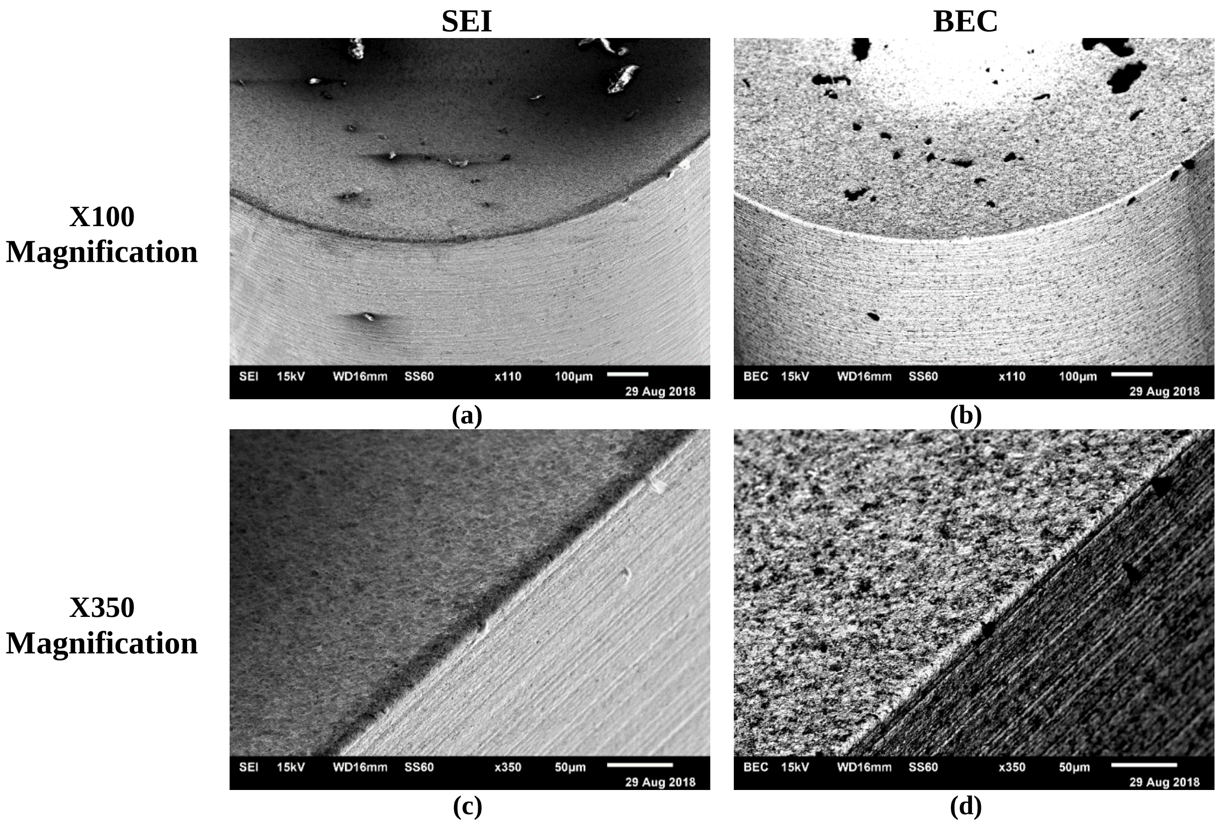


Figure 5- SEI and BEC images of cutting edge of uncoated Tool U32 -P3=0.4 MPa T2=5 sec (a,b) x100, (c,d) x350.

4.1.1.2 Rake Face

When positioning the tools under the microscope on a 45° holder, especially in images with 1000 times magnification, some variations can be witnessed between the treated and untreated tools. In Figure 6, SEI images of the tool with WPC under the highest pressure (U32-0.4 MPa 5 s) and the untreated tool (U00) are compared. All the images are taken from the rake face close to the cutting edge of the tools positioned at a 45° angle with an SEM setting of 15kV and spot size of 60 nm.

A dimple pattern can be observed on the U32 sample as a result of micro shot impacts during WPC. From the images in Figure 6, it can be noticed that the surface roughness is changed. In the next section, the variations of the surface roughness will be explained.

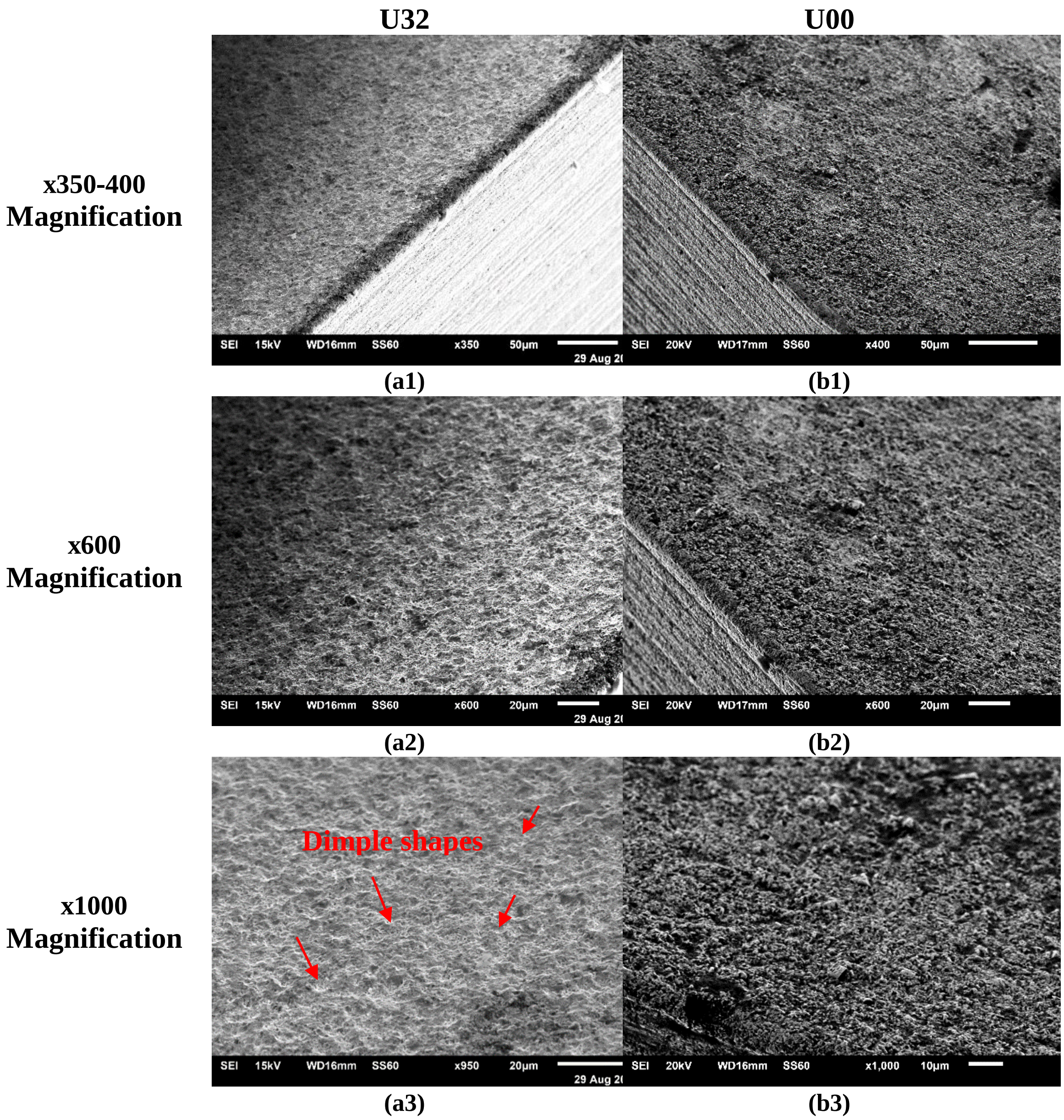


Figure 6- SEI images of rake face of (a1, a2, a3) uncoated Tool U32 (0.3MPa5s), (b1, b2, b3) U00 (untreated).

The rake face of the treated and untreated uncoated tools are carefully investigated using SEM and EDS while holding the tools horizontally. The tungsten carbide grains can be seen very clearly under high magnification for all treated and untreated uncoated tools (Figure 7).

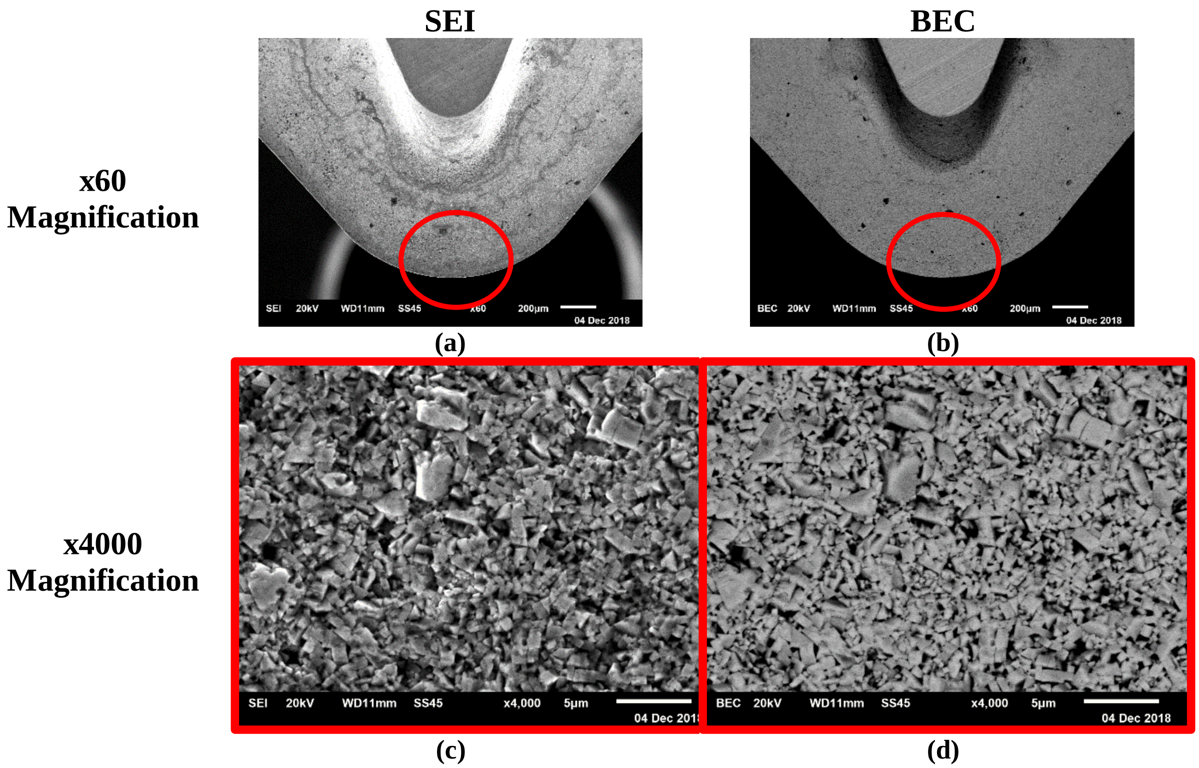
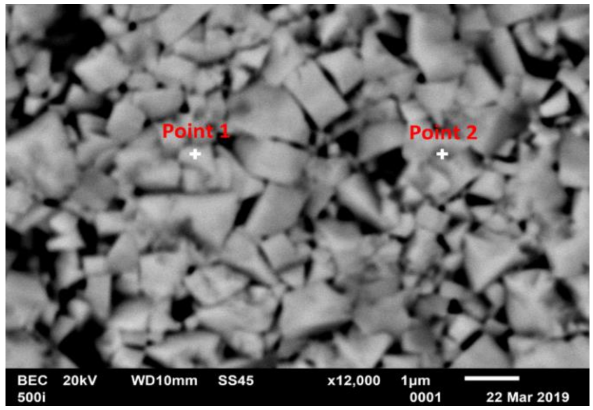
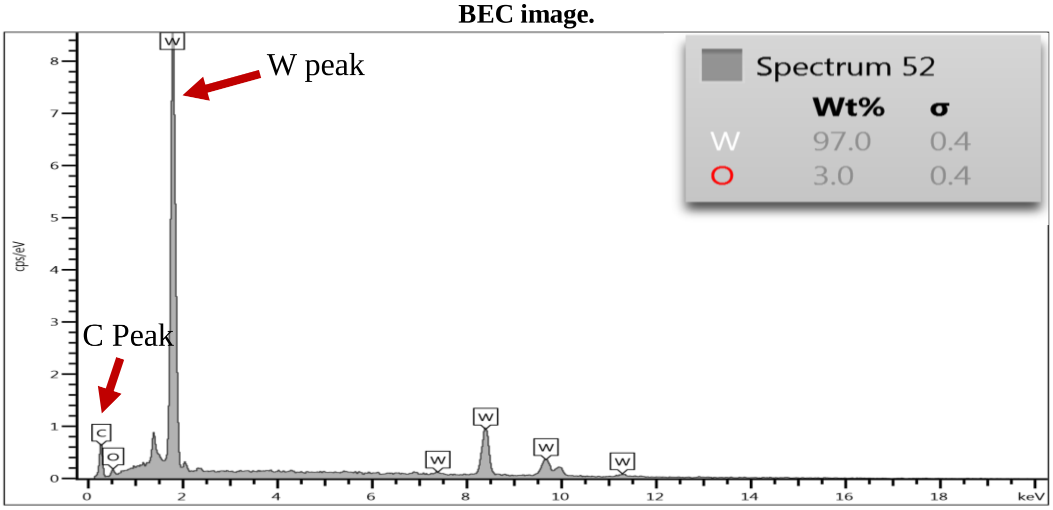


Figure 7- SEI and BEC images of rake face of U00 untreated uncoated tool (a), (b)-x60, (c), (d) x2000.

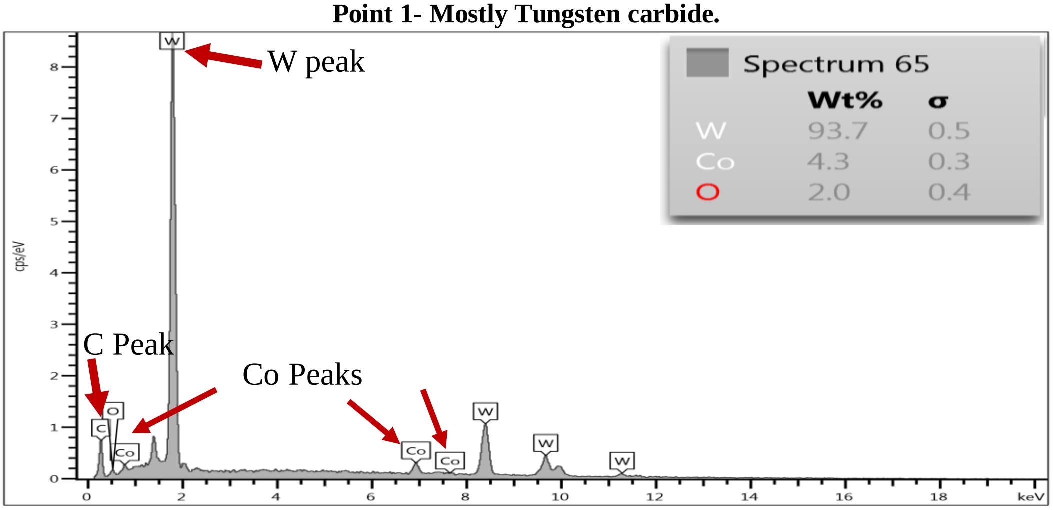
In Figure 8, a quick composition analysis is done on the untreated uncoated tool (U00). With point & ID analysis, it is shown that the cubic grains are hard ceramic tungsten carbide grains which are bonded together with cobalt. Point 1 is selected on the brighter parts which are the tungsten grains and point 2 is selected from the darker parts which appear between the tungsten grains. Since point 2 is completely surrounded with WC particles, still high peak intensities of W and C are detected for point 2. However, the results clearly show the cobalt binder at the WC boundaries.



BEC image.



Point 1- Mostly Tungsten carbide.



Point 2- Tungsten carbide with Co binder.

Figure 8- BEC image with x12000 magnification, U00, with point & ID analysis.

In order to see the effect of WPC intensity on the surface morphology of the tools, SEI images with x4000 magnification of the tools treated with different pressures are provided in Figure 9, Figure 10, and Figure 11. Similarly, for untreated tools, the images are taken from the rake face close to the cutting edge of the tools using a 20 kV electron beam energy.

By looking at the treated tools, in the sections with arrows, the carbide particles do not seem as sharp as the similar section from the untreated tool. It was assumed that the impact of micro shots resulted in WC grain deformation. However, by looking more carefully at the backscattered electron composition (BEC) images, some darker areas can be observed as presented in Figure 10-b, and Figure 11-b. In BEC images, darker areas are the result of lighter elements in the periodic table. Thus, the mentioned areas should have elements lighter than W. In addition, it can be seen that there are more dark areas in the images of the tool treated under a higher process pressure (Figure 11-b).

As mentioned earlier, the shot particles that were used are made of steel. Tungsten carbide is much harder than steel and therefore, it was expected that steel adheres to the WC grains after bombarding the surface.

For a deeper investigation, Energy-dispersive X-ray spectroscopy (EDS) is done on the uncoated tool treated under the maximum pressure (U32-0.4 MPa 5 s). Figure 12 shows the SEI and BEC images from the rake face of U32 with x2000 magnification along with a layered EDS image and the elemental maps. It can be perceived that the black areas in the BEC represent the presence of Fe adhering on the surface of the tool. To investigate this further, the same images are provided with an x5500 magnification in Figure 13. As can be seen, the darker areas consist of Fe and Cr which are strong evidence for the adhesion of steel shots to the surface of the tool.

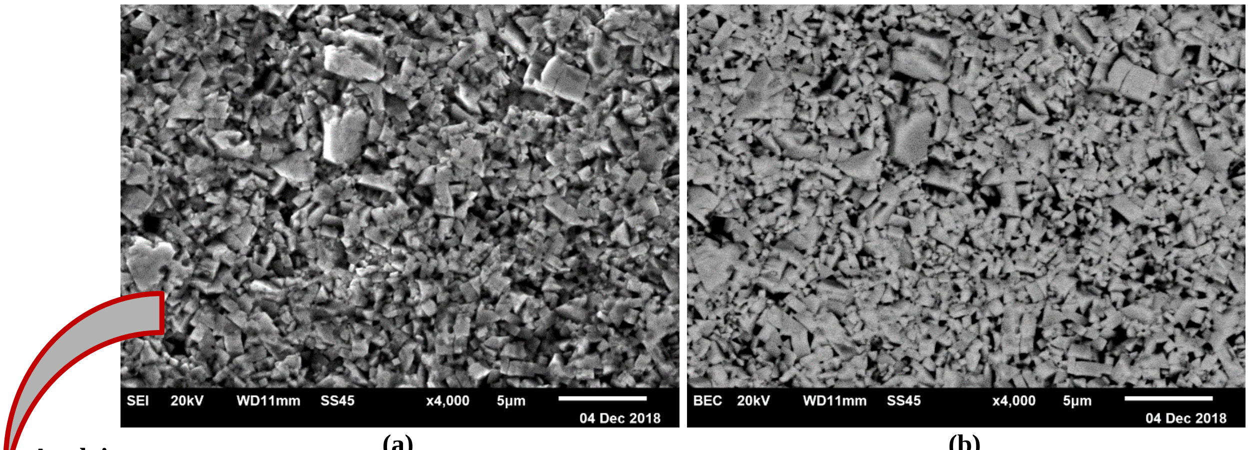


Figure 9- (a) & (b) SEI & BEC image-Rake face of U00-untreated uncoated tools- x4000.

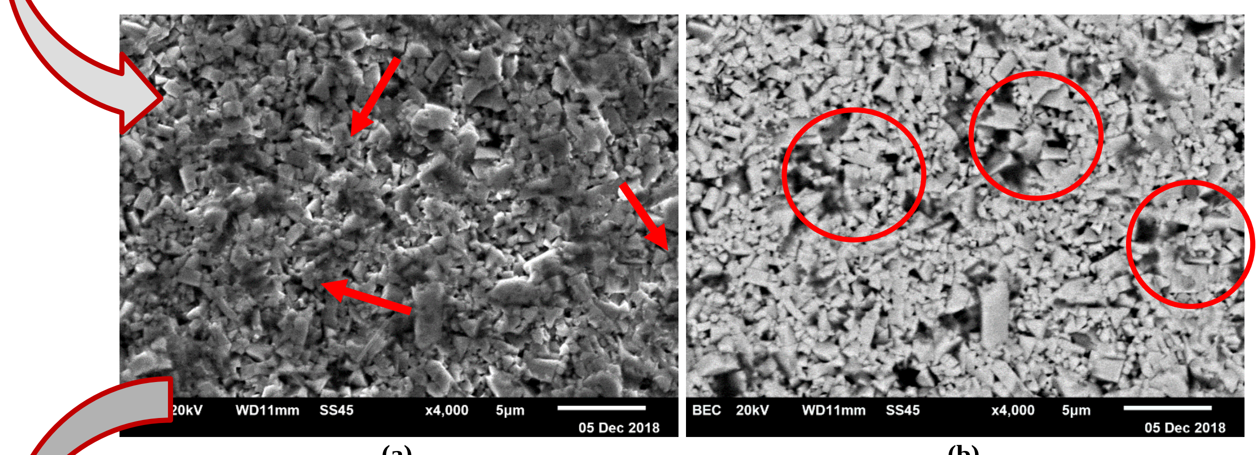


Figure 10- (a) & (b) SEI & BEC images-Rake face of U12-P1=0.2 MPa, T2=5 s- x4000.

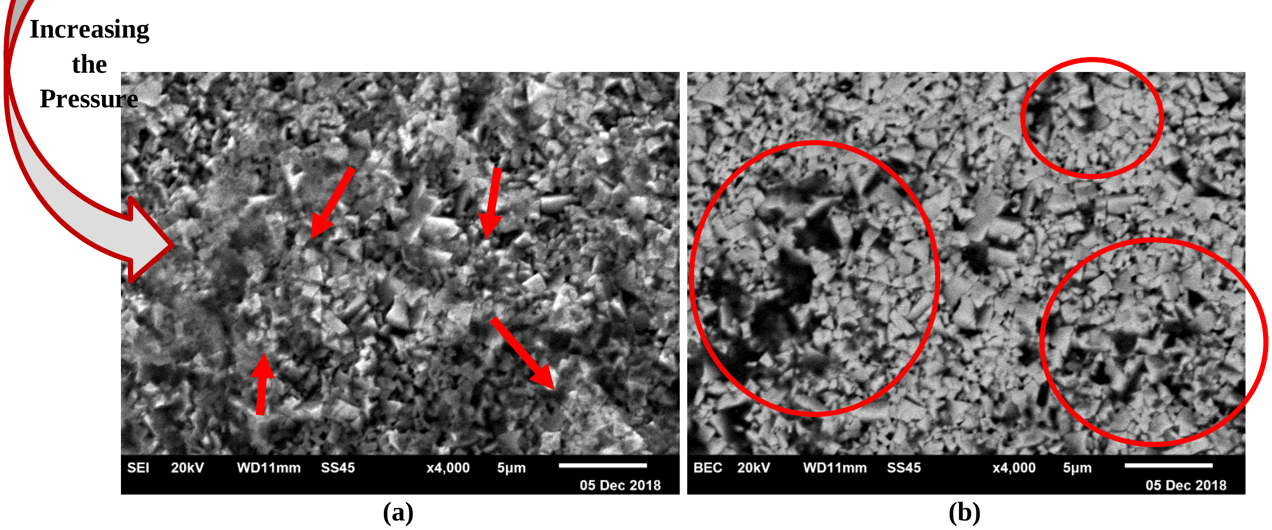
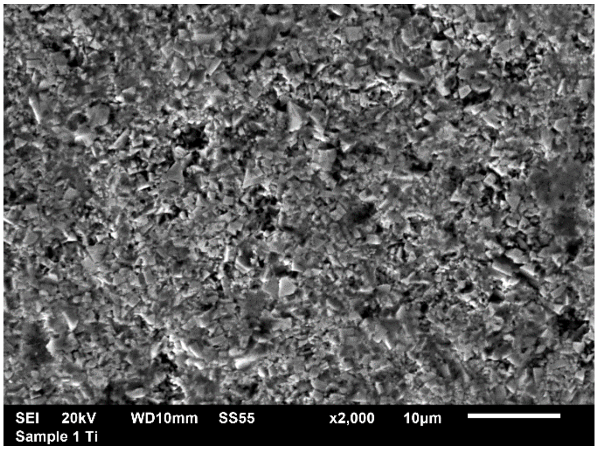
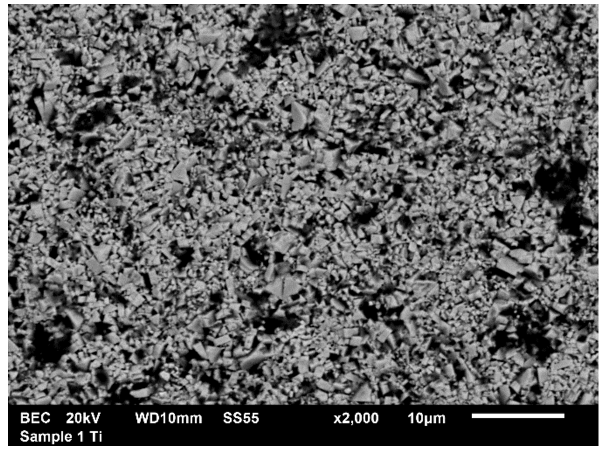


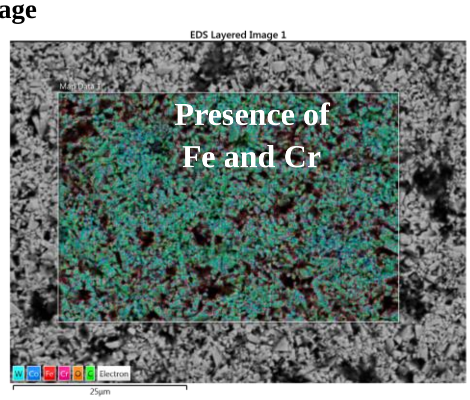
Figure 11- (a) & (b) SEI & BEC images-Rake face of U32-P3=0.4 MPa, T2=5 s- x4000.



(a) SEI image



(b) BEC image



(c) Layered EDS image

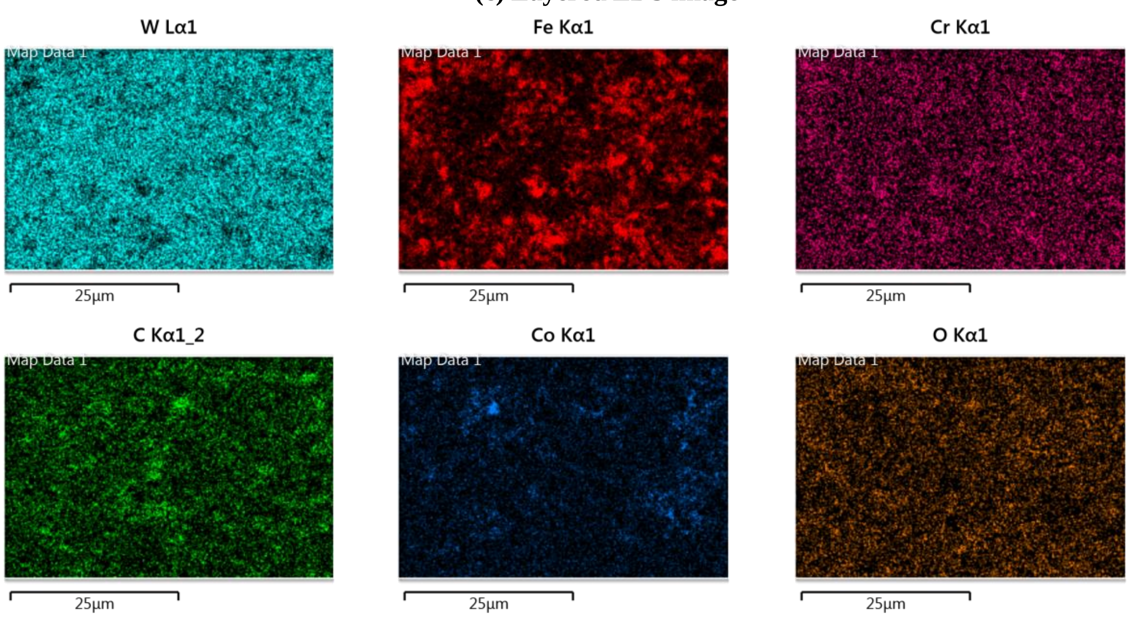
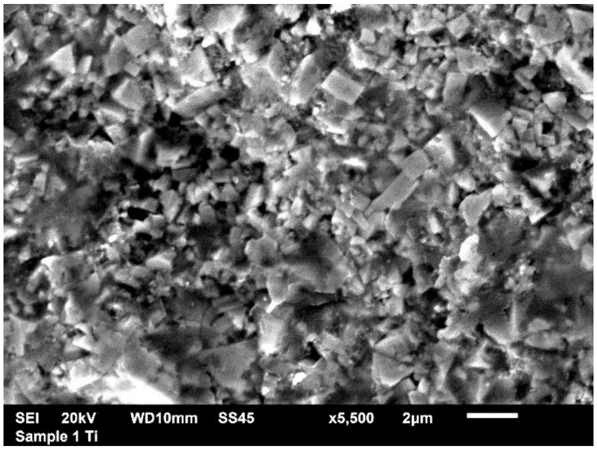
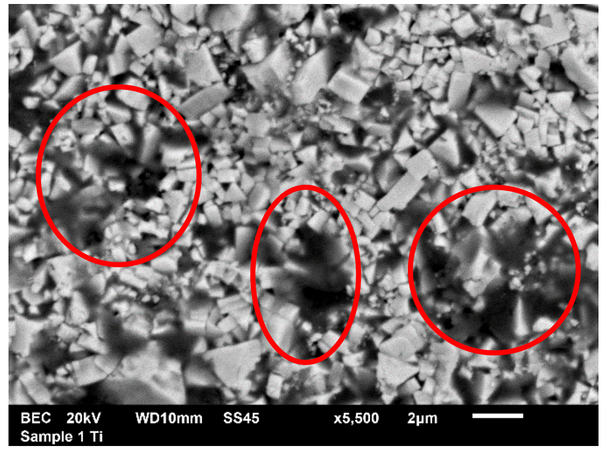


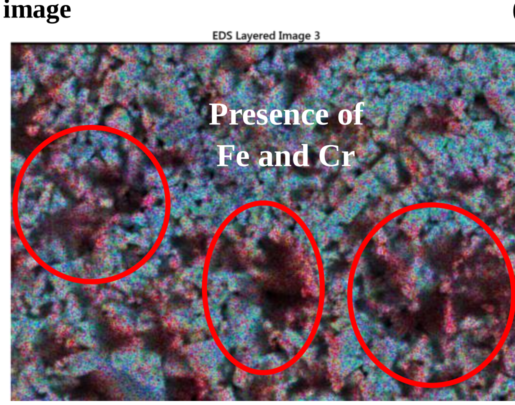
Figure 12- (a) SEI image with 2000 magnification, (b) layered EDS image, and element mapping of rake face of uncoated U32(0.4 MPa 5 s).



(c) SEI image



(d) BEC image



(c) Layered EDS image

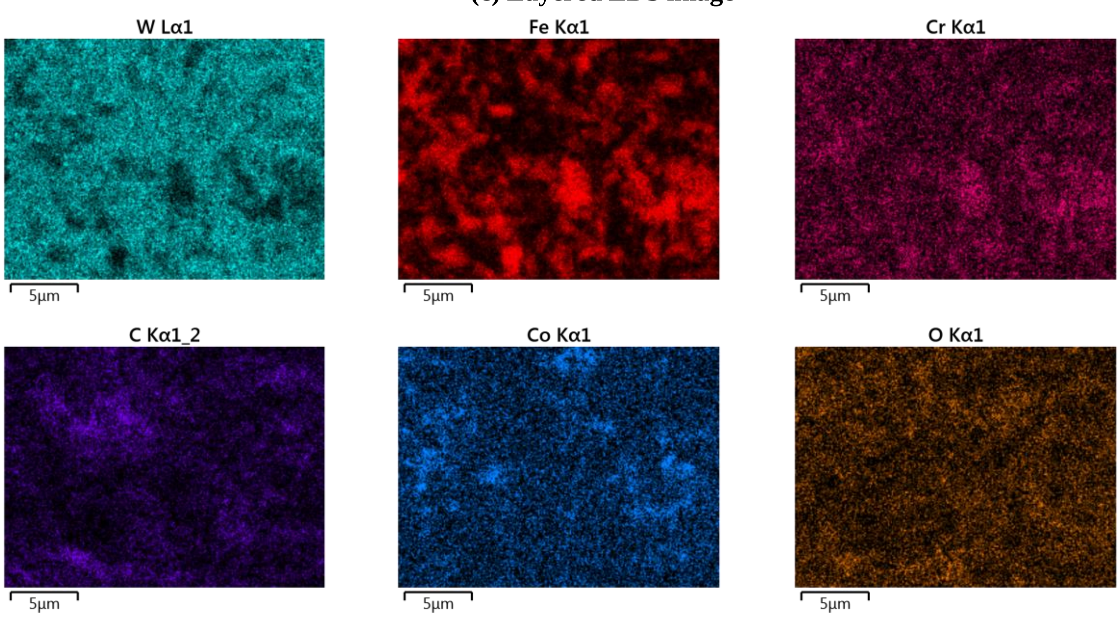


Figure 13- (a) SEI image with 5500 magnification, (b) layered EDS image, and element mapping of rake face of uncoated U32(0.4 MPa 5 s).

In conclusion, applying WPC with the proposed parameters using steel shots on tungsten carbide tool was observed to change the surface morphology without significantly damaging the tool edge. Since the shot particles are softer than the peened surface, there will be adhesion. When using harder shot particles such as Al_2O_3 this effect can be eliminated. However, based on the literature, when the shot material has a lower hardness than the peened surface, peening will have more plastic deformation and have less of an abrasive effect on the peened part [28]. In addition, there is a possibility of changes in roughness which will be investigated in the next section.

4.1.2 Surface Roughness

Some variations were seen in surface morphology and microstructure of cemented carbide tools after WPC, which is known to modify the surface roughness.

In Figure 14 and Figure 15, the surface roughness of tools treated under different pressures and different times respectively are compared with an untreated tool.

It can be seen that WPC has a roughening effect on the surface of the cemented carbide tools. All treated tools have 5-12% higher surface roughness on the flank as compared to the untreated tools. In addition, it is observed that increasing the pressure and time resulted in higher values of surface roughness. If this roughening effect is controlled it can be very beneficial for coating deposition since it changes the surface structure and therefore, results in a better mechanical interlocking between the film and the substrate.

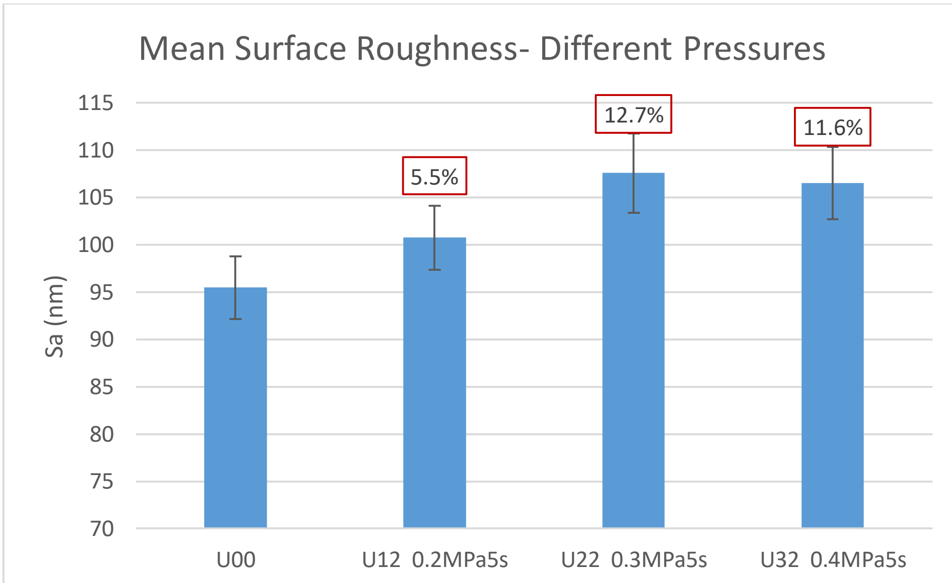


Figure 14- Mean surface roughness (S_a) of uncoated tools treated under different pressures.

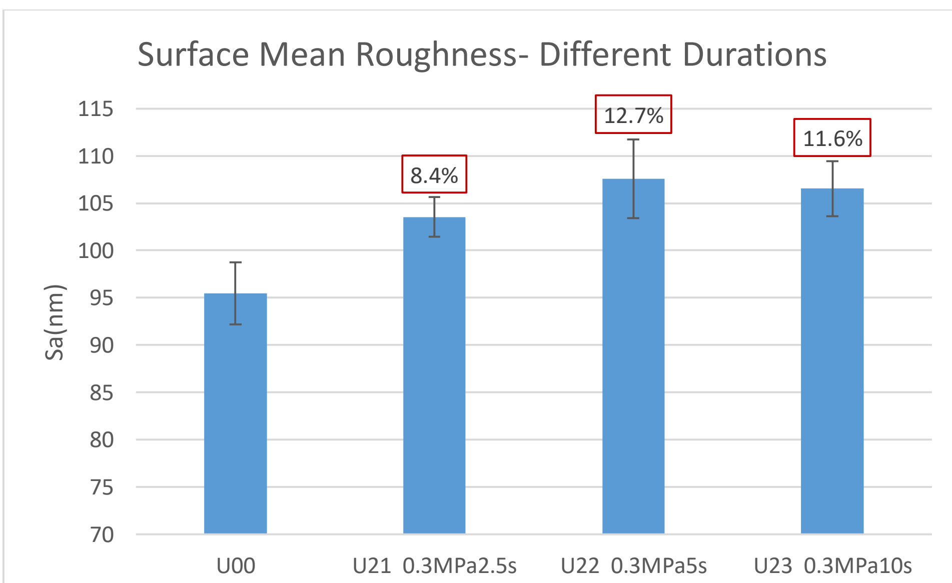
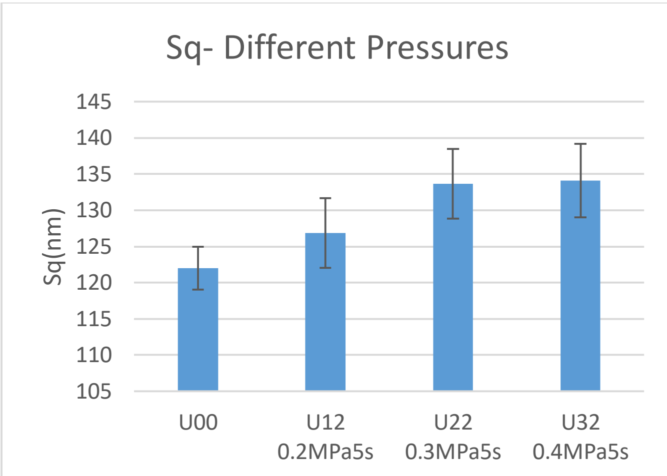
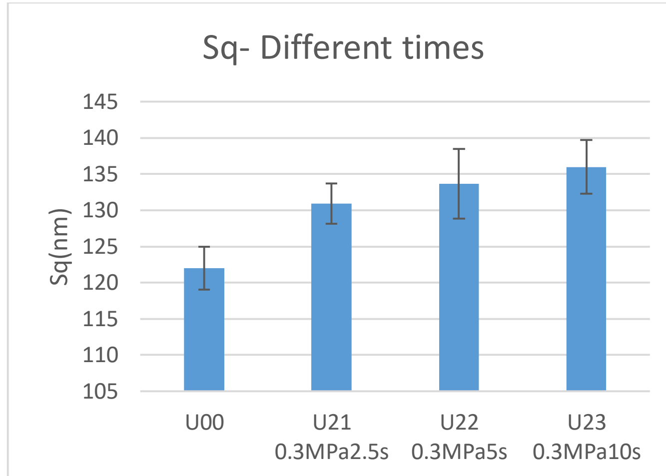


Figure 15- Mean Surface Roughness (S_a) of uncoated tools treated for Different Times.

For all cases with WPC, the average of the root-mean-square height (S_q) has increased. Figure 16 also shows that increasing both time and pressure will increase the S_q value of the tool's surface. This can be due to the fact that the surface has more peaks and/or valleys. It also can be because of larger undulations in the surface.





(a) **(b)**

Figure 16- Average of root-mean-square height (S_q) for uncoated tools with WPC (a) under different pressures, (b) with different duration times.

In Figure 17 and Figure 18, the average of the maximum valley depth and the maximum peak height of the treated and untreated tools are compared. It can be observed that the maximum valley depth has increased while the maximum peak height did not change significantly.

The Cobalt binder is more ductile compared to tungsten carbide grains [32]. Applying WPC on cemented carbide can remove the Co binder from the surface of the tool and reveal more WC grains [32][37][56]. This effect can explain why the maximum valley depth has increased for all cases after WPC compared to untreated tools shown in Figure 17 and Figure 18. The Co removal effect can also increase the mean roughness which can be seen in Figure 14 and Figure 15. However, it is not possible to quantify the change in the amount of tungsten carbide grains revealed and the amount of Co binder removed using SEM or EDS. This issue is mainly because the quantity of Co binder at the surface of the cemented carbide is very limited and thus changes in concentration are hard to detect [36].

Increasing both pressure and/or time will remove more Co binder from the surface and result in higher roughness. If peening is continued or if it's done at a high pressure, the binder will be removed completely. As mentioned earlier, the maximum roughness that can be achieved with the peening processes is limited to WC grain size [56].

In this study, the WPC process used steel shot particles which have lower hardness than tungsten carbide. The impacts from the softer shot cannot remove many of the carbide grains and the maximum peak height remained almost constant while the average of the maximum depth of the valley in to the softer binder increased (Figure 17 and Figure 18). Also, carbide grains are more revealed due to the Co-binder removal which was also observed in [57][7]. When depositing the coating, the nucleation rate of the formed transient junction is higher on the Co-free tungsten carbide surface resulting in better film adhesion [37].

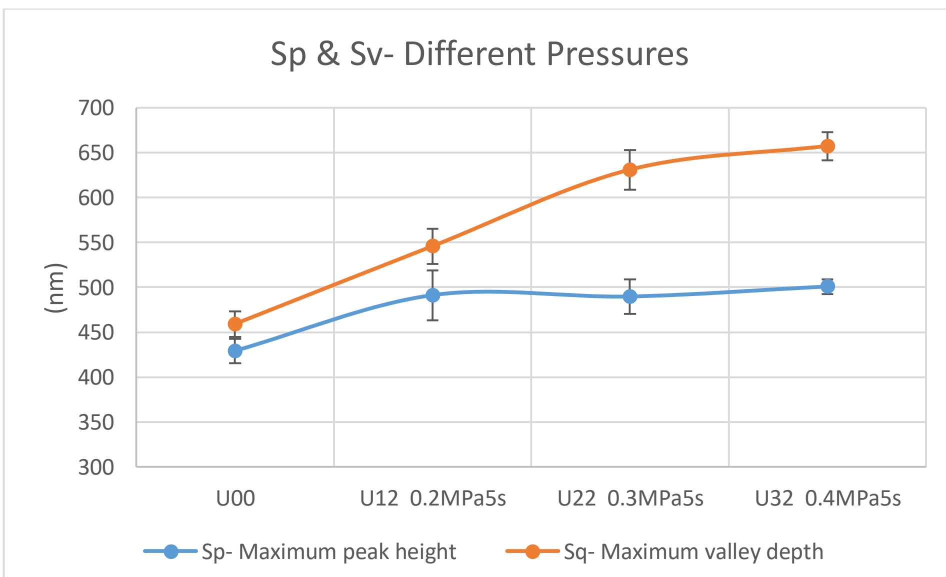


Figure 17- Maximum peak height (S_p) and maximum valley depth (S_q) for uncoated tools with WPC under different pressures.

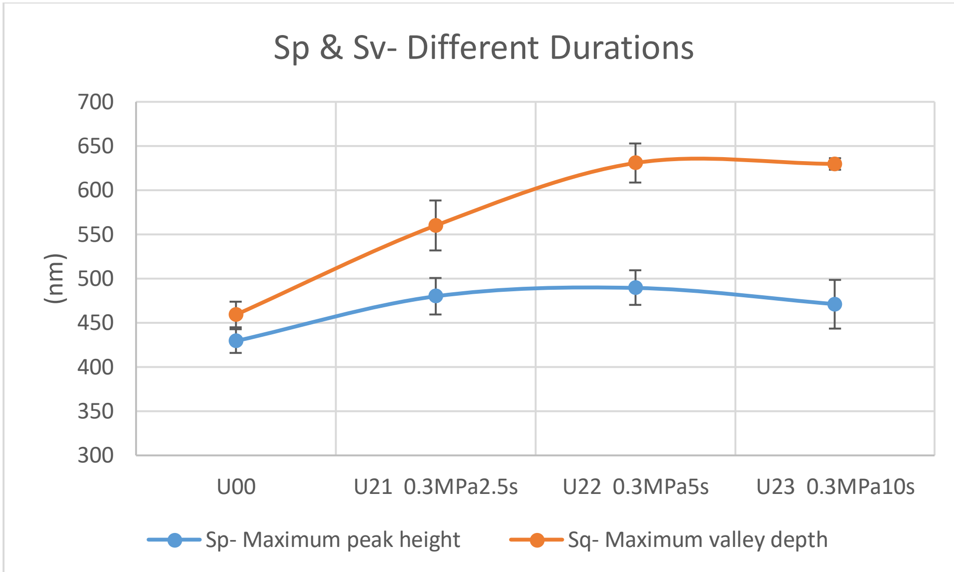


Figure 18- Maximum peak height (S_p) and maximum valley depth (S_q) for uncoated tools with WPC with different duration times.

It should be mentioned that WPC uses spherical shots in an effort to reduce the material removal aspect as compared to processes in which shots with sharp edges are utilized. As mentioned earlier, WPC alters the surface properties through plastic deformation and microstructure changes. Thus, when employing fine spherical shot, most of the impact energy will be consumed through plastic deformation rather than abrasion. Consequently, this resulted in smaller roughness development and also higher surface hardness compared to peening with sharp edge shot under the same process conditions. Using sharp edge shot induces more microchipping and thus has more intense material removal effect [39].

According to the literature, Co binder removal and higher roughness can improve the coating adhesion since the coating better adheres to the WC grains [57].

4.1.3 Cutting Edge Radius

The cutting edge radius was also measured with an Alicona high-resolution optical microscope using a 10x magnification lens. The radius of all 4 edges was measured for both tools treated with the same parameters meaning there are 8 edge radius measurements for each WPC condition. In Figure 19 and Figure 20 the average values of the edge radius for the treated tools are compared with the untreated tools.

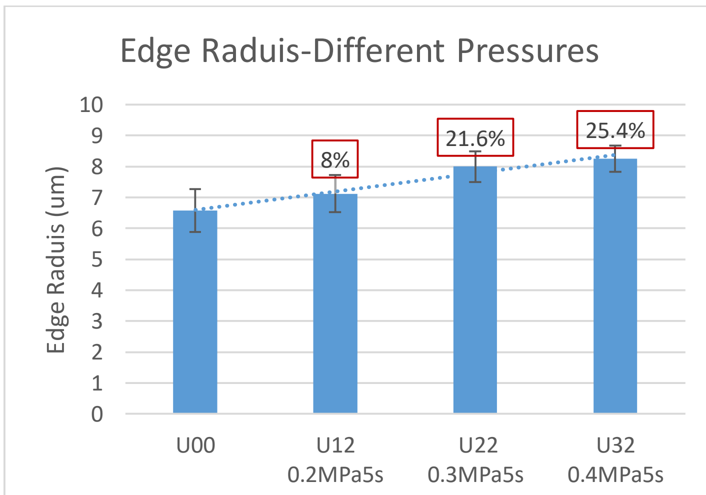


Figure 19- Mean edge radius of uncoated tools treated under different pressures.

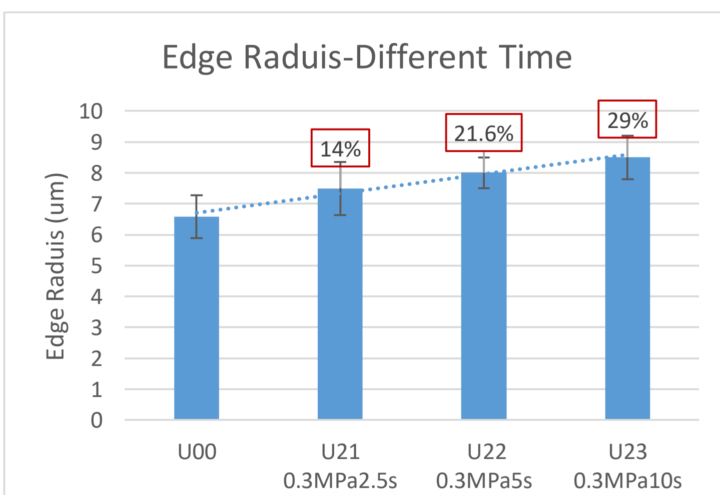


Figure 20- Mean edge radius of uncoated tools treated for different time.

As expected, applying WPC was observed to increase the cutting edge-radius by 10-30% as compared to the untreated tool. Cutting edge radius enlargement is also reported in the literature [44] [7]. The uncoated tools used in this research have around a 6 μm edge radius. After applying WPC, this value increased to 9 μm. Increasing the edge radius up to a point can improve the wear behavior since it will strengthen the tool edge [7]. It should be mentioned that there are limits as a very large edge radius can result in high stresses and temperatures and therefore, decrease the tool life.

As can be seen, applying WPC with higher pressure and duration time has increased the edge radius due to higher plastic deformation of the edge.

4.1.4 Residual Stress

The residual stresses were measured on both rake and flank face of uncoated tools using an XRD instrument.

4.1.4.1 Rake Face

In order to pick a point with a more obvious difference in residual stresses and less error, 3 points were selected on the rake very close to the cutting edge. The distances are scaled based on the instrument. By looking more carefully at the tool, the rake face consists of an area with chip breakers and a ground area. P1 and P2 were respectively 80 and 100 units away from the cutting edge while P3 was located 100 units away from the edge of the ground area (Figure 21). It should be mentioned that 100 unit of the instrument's camera is around 0.3 mm.

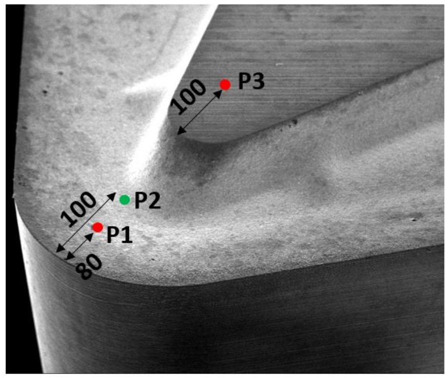


Figure 21- Points for measuring the residual stresses on the rake face.

Based on the results, location P2 showed a better improvement in the residual stress state between the treated and untreated tools. This is attributes to the fact that P1 is located too close to the cutting edge so the surface was not flat enough. In order to minimize the amount of residual stress induced by grinding, location P2 as shown in figure 21 is selected for further investigations.

The residual stress on the rake face of the tool at P2 is measured for all edges of uncoated tools after WPC and compared with an untreated tool. Figure 22 shows the average of residual stresses of all 4 edges of uncoated tools. Measurements were repeated twice. As it can be seen, tools with WPC have 70-120% higher mean compressive residual stress (-1100 MPa) compared to the untreated tool (-540 MPa).

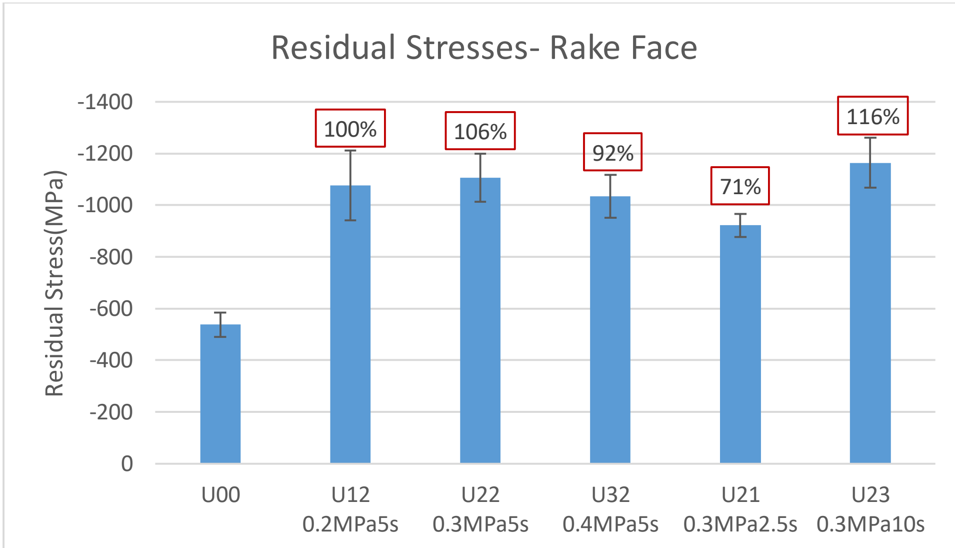


Figure 22- Mean Residual Stress on Rake face of uncoated tools at P2.

In order to see the effect of pressure and time on the residual stresses, Figure 23 and Figure 24 are presented. When using 5 s duration time, applying WPC under 0.2 MPa pressure induced around 500 MPa compressive residual stress on the surface of the tool. Increasing the pressure from 0.2 to 0.3 MPa while keeping the duration time constant did not result in noticeable variations in residual stress. The same results were achieved when further increasing the pressure to 0.4 MPa.

Applying 0.3 MPa WPC pressure with 2.5 s duration time resulted in about 70% higher compressive residual stress. Unlike increasing the pressure, increasing time from 2.5 s to 5 s results in 30% improvement in compressive residual stress. This value almost stays constant when doubling the time from 5 to 10 s.

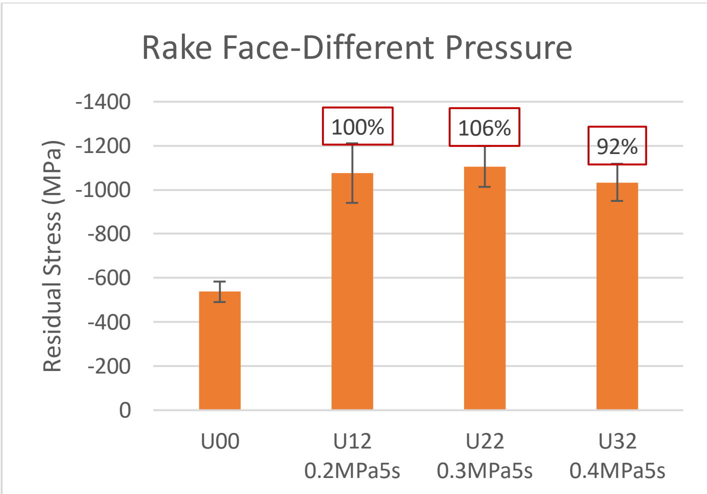


Figure 23- Mean Residual Stress on Rake face of uncoated tools treated with different Pressures.

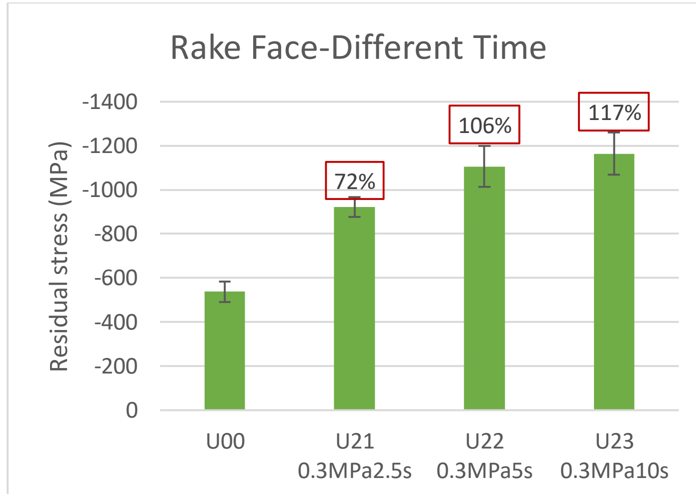


Figure 24- Mean Residual Stress on Rake face of uncoated tools treated with different Times.

4.1.4.2 Flank Face

Two points were chosen on the flank very close to the cutting edge as shown in Figure 25 and Figure 26. The points are 200 units away from the rake face. Since the edge wasn't very clear on the XRD device, the line shown in both figures was selected as the reference. Point 1 and 2 have respectively 200 and 600 units distance from the line (approximately 0.6 and 1.8 mm).

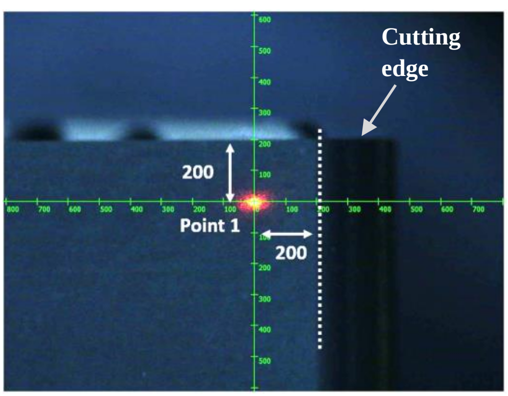


Figure 25- Point 1 on Flank face.

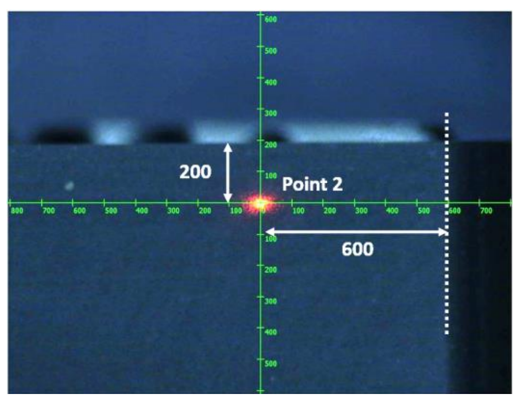


Figure 26- Point 2 on Flank face.

The residual stresses were measured on the flank face of 2 edges for each tool treated under different pressures. Figure 27 shows the average residual stresses of point 1 and point 2 on both edges.

The untreated tool showed around -500 MPa compressive residual stress on the rake face (non-ground area) while it had around -1000 MPa on the flank face. This is because grinding can induce some amount of compressive residual stress to the surface as well.

As it can be seen, applying WPC with 0.2 MPa pressure for 5 s resulted in 22% higher CRS. Increasing the pressure from 0.2 to 0.3 MPa caused a 40% further improvement in CRS while varying the pressure from 0.3 to 0.4 MPa did not cause a significant change in CRS.

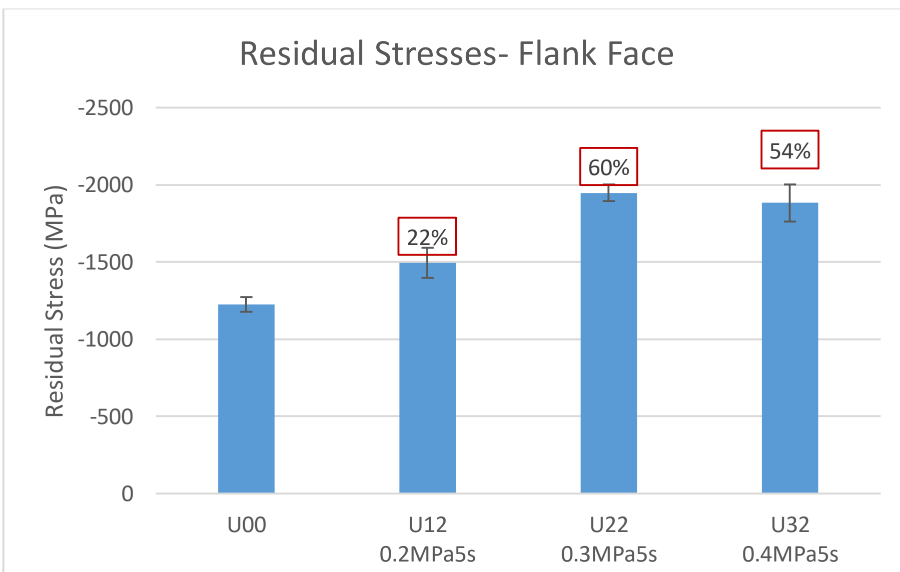


Figure 27- Mean Residual Stress on Flank face of uncoated tools treated with different Pressures.

As can be seen, the residual stress on both the flank and rake face stays unchanged after a certain pressure or duration time.

4.1.5 Nano Hardness

Surface hardness was measured on the flank face of the treated and untreated tools as measured using a Nanoindenter device. Nanoindentation can be used to show the effect of high compressive residual stresses near the surface [35].

Figure 28 and Figure 29 show the average Vickers hardness on the tools treated with different pressures and duration times with a comparison to an untreated tool. As it was expected, the surface hardness increased after applying WPC due to the layer of plastic deformation. There was a 20-30% improvement in surface hardness. Surface hardness and induced compressive residual stresses are strongly related [58]. It should be mentioned that the penetration depth of the indents ranged from 700 to 800 nm.

High hardness is beneficial in a cutting process and can increase the tool life. However, no significant change can be observed by changing WPC pressure or time.

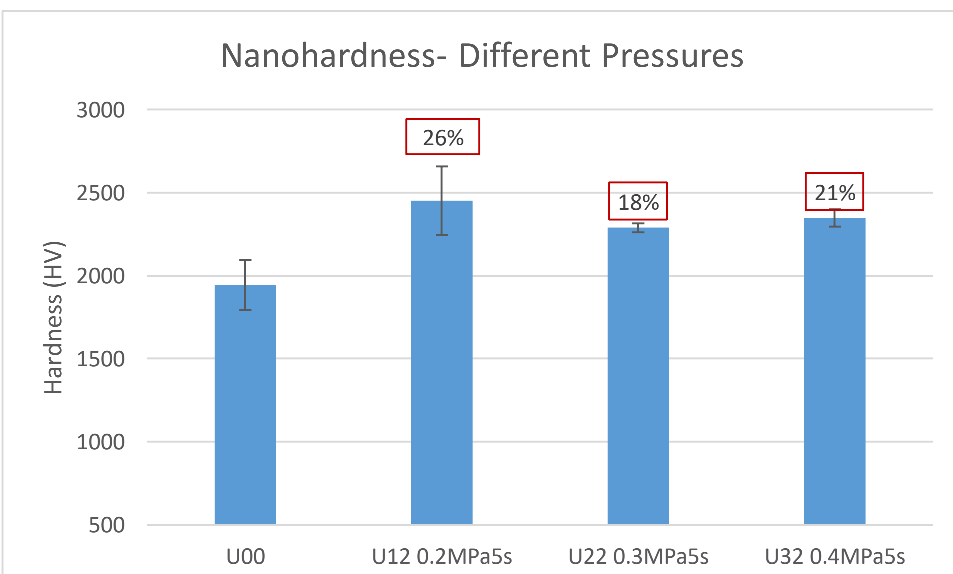


Figure 28- Mean hardness on the flank face of uncoated tools treated with different Pressures.

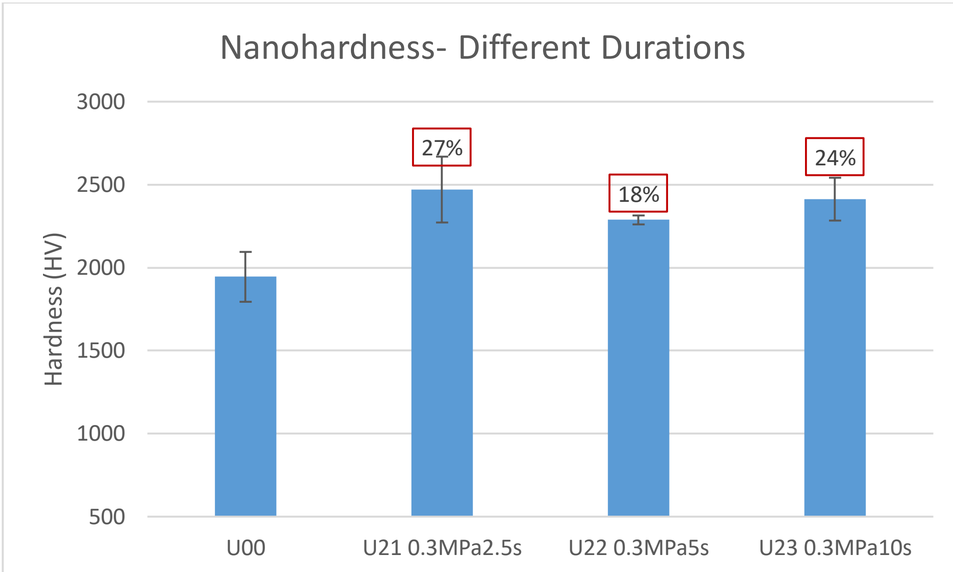


Figure 29- Mean hardness on the flank face of uncoated tools treated with different durations.

4.2 Cutting Tests (Wear and Cutting Forces)

In order to see how WPC affects the cutting performance, single pass turning tests were performed. In the following, the details of the cutting tests and their results are provided.

4.2.1 Study A (ductile cast iron)

4.2.1.1 Cutting Conditions

Cutting tests are done using treated and untreated uncoated carbide tools on a 3-axis Nakamura CNC Turning machine. The flank wear was measured for each pass using a Keyence VHX-5000 optical microscope. The cutting conditions are selected based on industry recommendations and literature for finishing operations and are provided in Table 7. In addition, cutting forces were measured during each pass using a KISTLER dynamometer.

Table 7- Finishing tests on Ductile Cast Iron

Cutting conditions	Value	Units
Speed	180	m/min
Feed rate	0.1125	(mm/rev)
Depth of cut	0.25	mm (Rad)

Three tools U00, U21, and U22 were tested using single pass turning. It is common to have variations in microstructure in a bar of ductile cast iron at different radiuses. To make sure that the test conditions are consistent, the workpiece is divided into 3 sections with similar depth as shown in Figure 30.

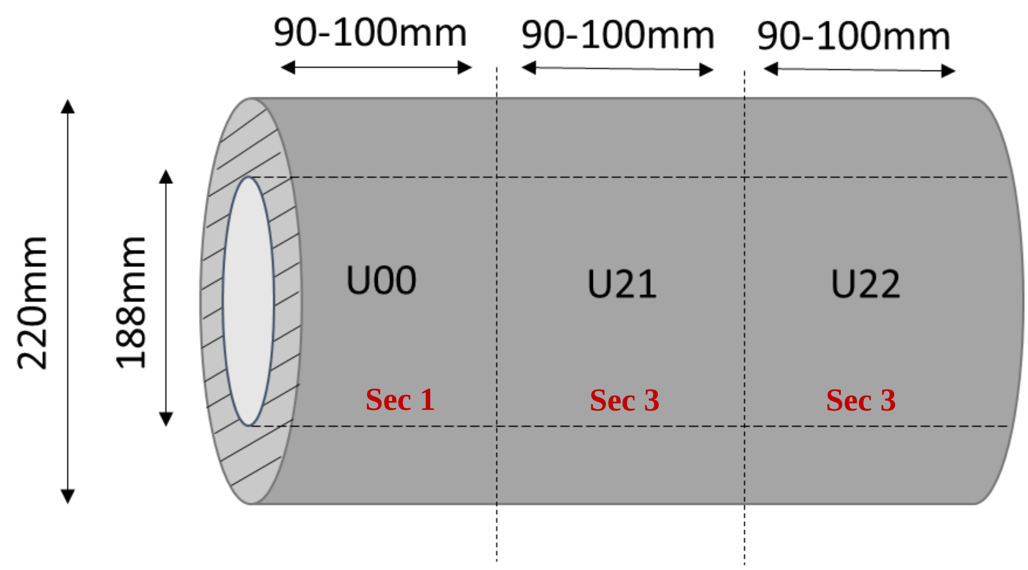


Figure 30- Ductile cast iron bar.

4.2.1.2 Tool life

The flank wear versus the total cutting length is plotted in Figure 31. It can be seen that the U21 (0.3 MPa-2.5 s) had the longest tool life while the untreated tool (U00) had the shortest. Statistically, by considering the untreated tool as the reference, U21 had 13.5% improvement while U22 (0.3 MPa-5 s) showed 9.5% tool life improvement (Figure 32).

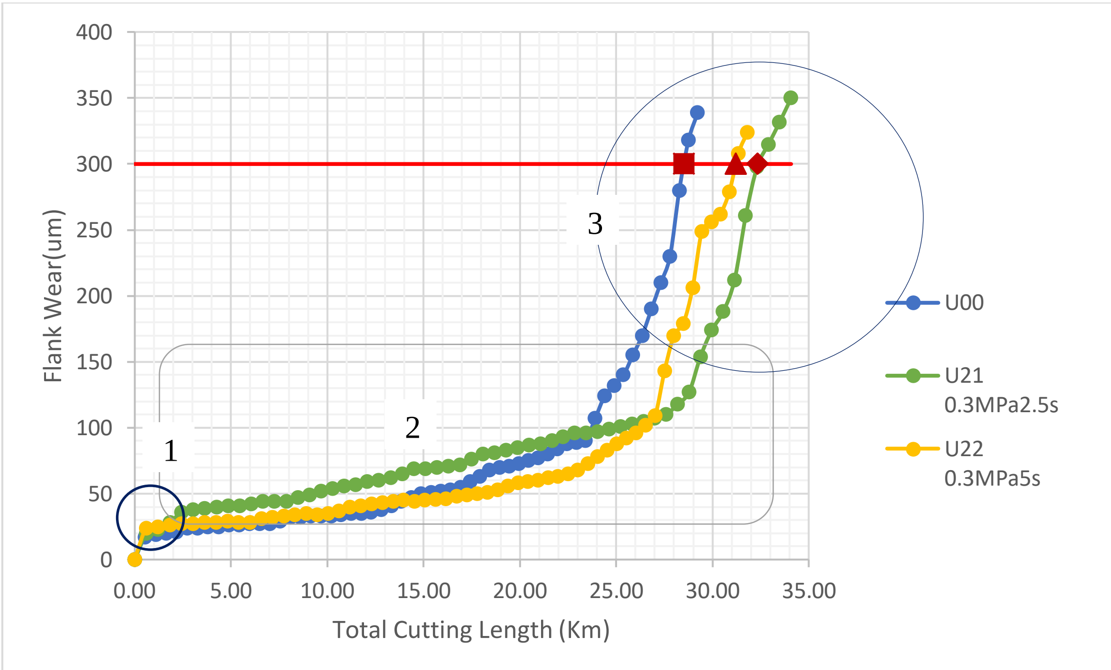


Figure 31- Tool life when cutting ductile cast iron.

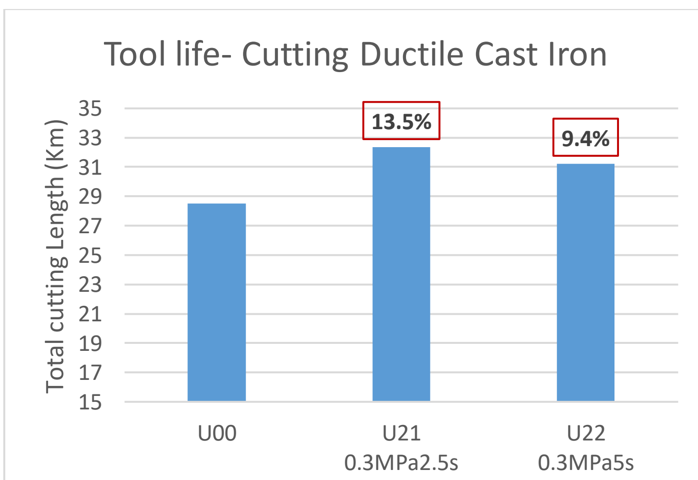


Figure 32- Tool life improvement percentage for untreated and treated tools when cutting ductile cast iron.

4.2.1.3 Cutting Force

The Average cutting forces and their difference compared to the reference tool (untreated) are shown in Figure 33. The tools are sorted out from the lowest tool life to the highest tool life. The results showed no significant variation in the cutting forces since the variations are in the error bar. Thus it can be said that WPC of uncoated tools does not significant change the cutting forces.

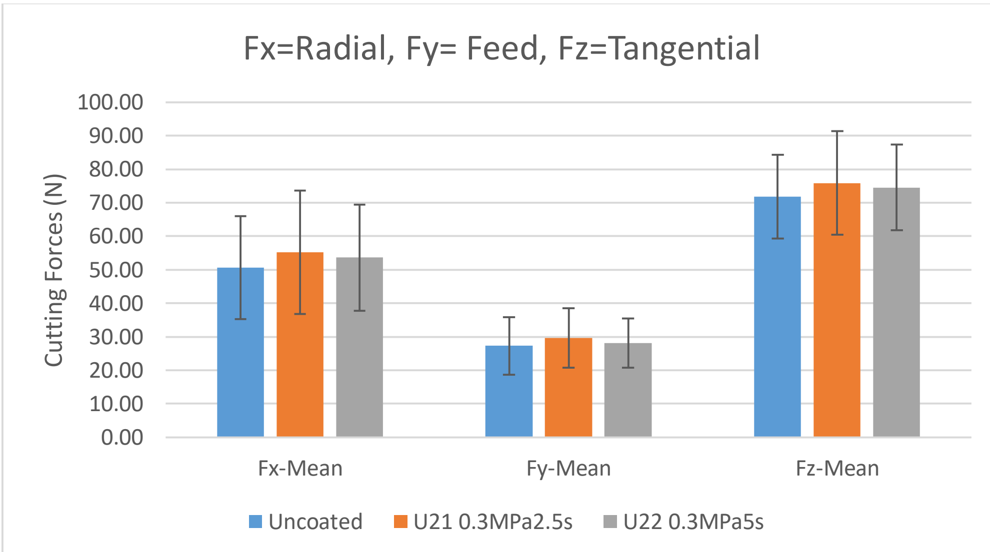


Figure 33- Average cutting forces when cutting ductile cast iron.

4.2.1.4 Challenge

Assuming that the microstructure of a workpiece is homogenous is not a valid assumption [59]. After reaching a diameter of around 179 mm, the wear behavior of the tools changed dramatically. However, no significant variations were observed when measuring the hardness using a portable hardness measurement device. Therefore, some samples were taken out of the workpiece to investigate their microstructure and possible changes in hardness to ensure this difference did not influence the results.

80-55-06 ductile Iron has a pearlite/ferrite structure as shown in Figure 34. As it is illustrated, the round dark grains are graphite, ferrite grains are the light parts surrounding the graphite, and pearlites are the dark needle-like structures. Pearlite is harder than ferrite and generally results in higher tool wear. With this in mind, some images with 20, and 50 times magnification are provided in Figure 35 from a sample taken from the outer and inner diameter of the ductile cast iron workpiece. When cutting the cast iron bar, the micro-hardness is obviously changing from a mostly-ferritic to pearlite/ferrite cast iron. It is expected that the sudden changes in wear behavior measured at this point were because of changes in the microstructure of the bar. Therefore, cutting ductile cast iron was stopped at this bar diameter.

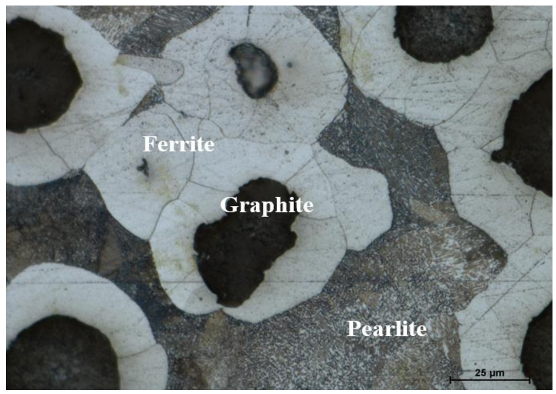


Figure 34- Pearlite/ferrite micro structure of ductile cast iron.

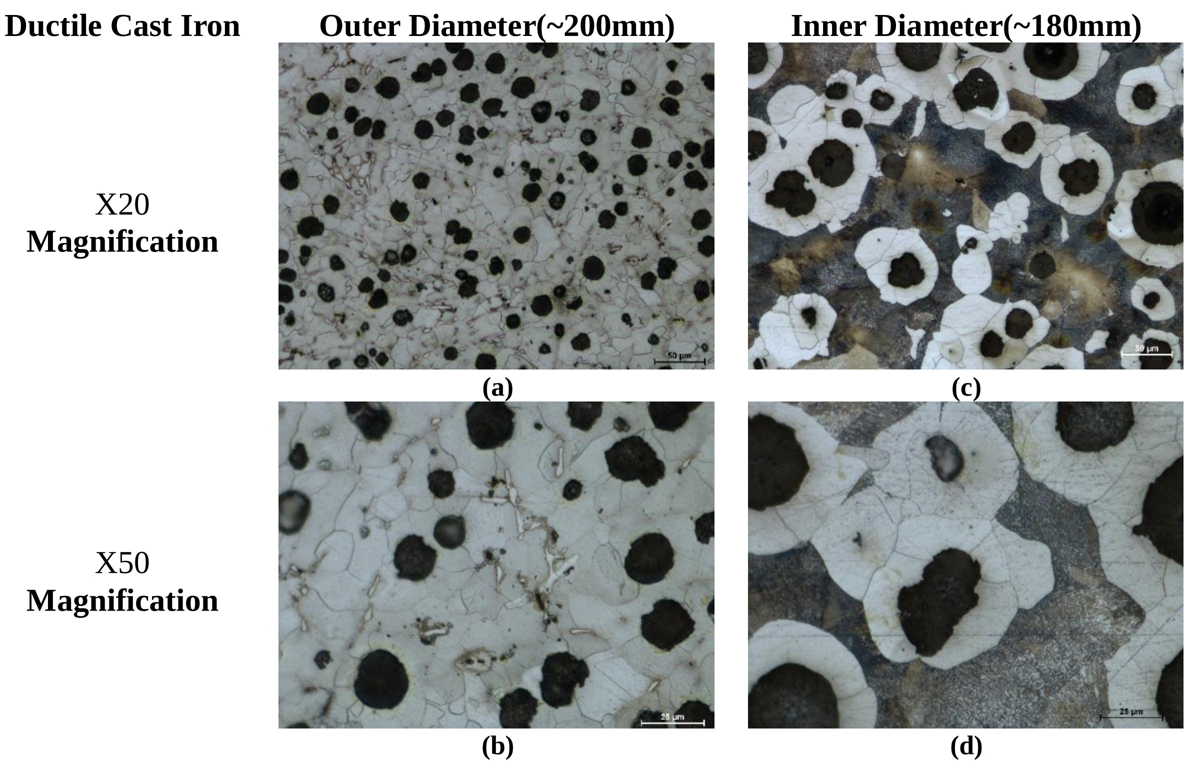


Figure 35- Microstructure of ductile cast iron bar (a),(b) from outer and (c),(d) from inner diameter.

Alloy steel AISI 4140 is also known for its abrasive wear. Therefore, in the following study 4140 was used for evaluating the cutting performance of tools with WPC.

4.2.2 Study B- Constant Speed (AISI 4140)

4.2.2.1 Cutting Conditions (Study B, C, D)

Three sets of cutting tests, Study B, C, and D were done with the same feed rate and depth of cut of 0.125 mm/rev and 0.25 mm respectively (Table 8). In Study B, all the uncoated tools were used in dry conditions with the same cutting speed of 120 m/min to study the effect of WPC time and pressure on their wear performance. Study C was done in both dry and wet conditions for an untreated tool and 2 treated tools with different pressures. Study D performed dry cutting but with different cutting speeds, as shown in Table 9.

Table 8- Fixed cutting conditions

Fixed Conditions	Value
Feed rate (mm/rev)	0.125
Depth of cut (mm)	0.25

Table 9- Cutting conditions in each study

		Study B	Study C	Study D
		Vc:120 m/min, Dry	Vc:120 m/min, Wet	Vc:90,150 m/min, Dry
Uncoated	U00	X	X	X
	U12	X	X	
	U22	X		X X
	U32	X	X	
	U21	X		
	U23	X		

4.2.2.2 Study B- Constant speed/Dry

As mentioned earlier, Study B used the same feed and speed for all tests. Figure 36 shows the flank wear versus total cutting length until the failure point (300 µm flank wear). Since this workpiece is much harder than ductile cast iron, the curves tend to be closer to a straight line and the cutting length decreased dramatically. The choice of material used in this study was made to provide a comparison to a material with similar wear mechanisms.

Overall, it can be seen that all the treated tools are performing 12-30% better than the untreated tool (Figure 37). The tool life improvement can be explained with higher compressive residual stresses and higher surface hardness of tools with WPC.

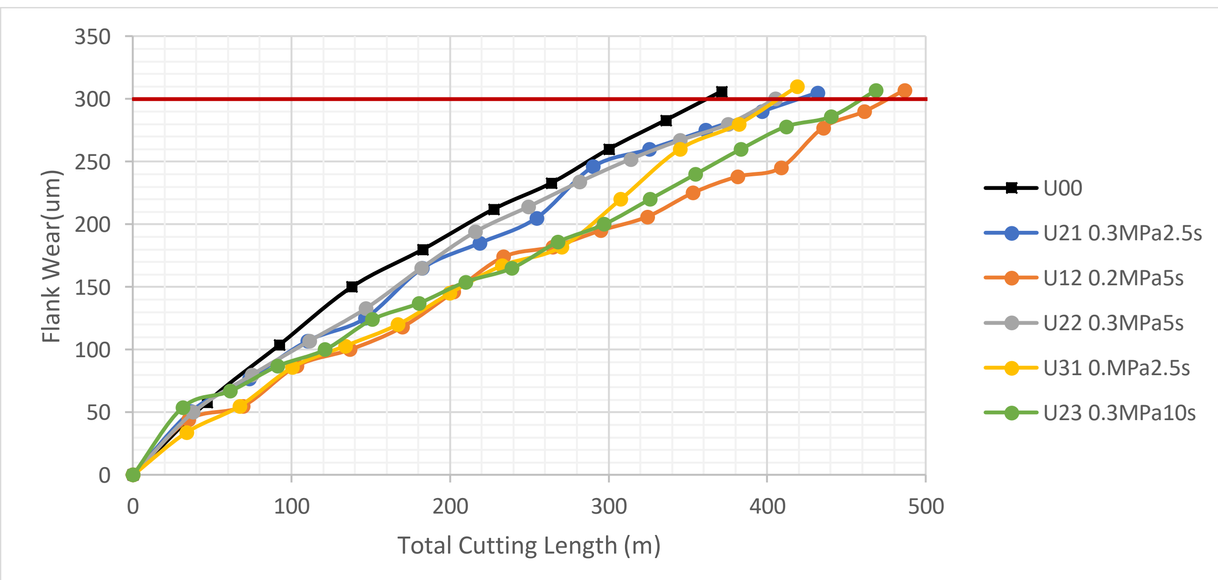


Figure 36- Tool life for untreated and treated tools when cutting AISI 4140, f=0.125mm/rev, DoC=0.25 mm, Vc=120 m/min.

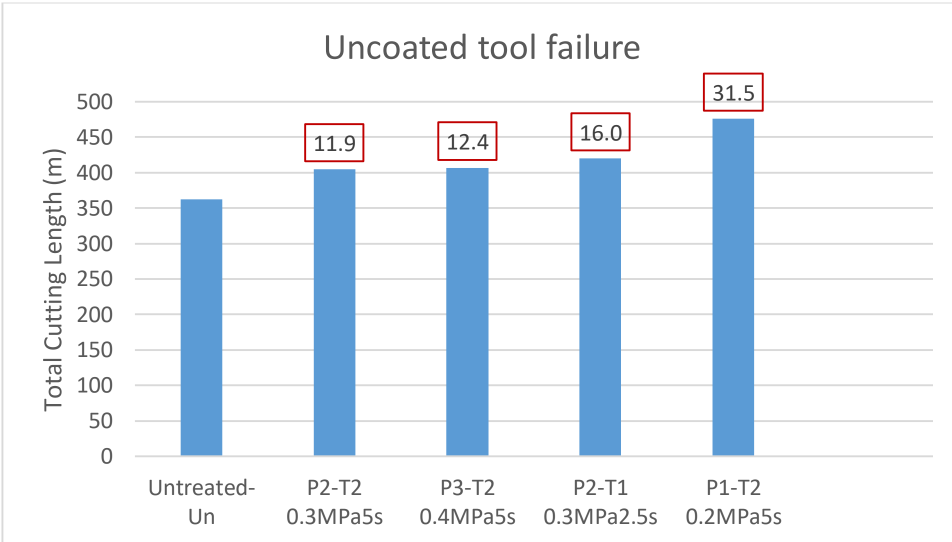
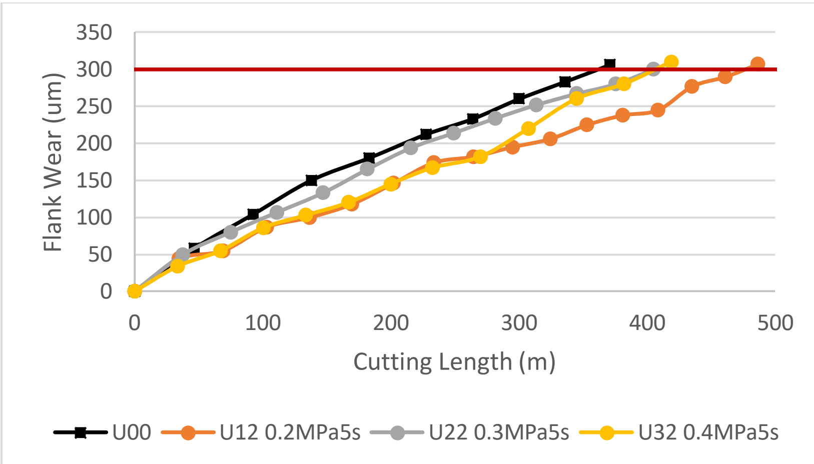


Figure 37- Tool life improvement percentage for untreated and treated tools when cutting AISI 4140.

To examine the effect of pressure and time, tools treated with same time and pressure are separated in Figure 39 and Figure 41. In both cases, the minimum intensity of pressure and time resulted in the best cutting performance. Figure 39 shows that applying WPC with 0.2 MPa pressure resulted in the best cutting performance with a 31% tool life improvement as compared to the untreated tool. By increasing the pressure to 0.3 MPa, the improvement of the tool life was reduced to almost 12%. Interestingly, the tool life did not change with a further increase in pressure from 0.3 MPa to 0.4 MPa.

WPC duration time variation behaved like the applied pressure from the aspect of cutting performance. The minimum duration time of 2.5 s and 0.3 MPa pressure resulted in maximum tool life enhancement of 16% compared with other tools treated under the same pressure (Figure 41). By increasing the time from 2.5 s to 5 s, the percentage of tool life improvement was reduced to around 12 % and it stayed almost unchanged when a further increase in duration to 10 s was used.



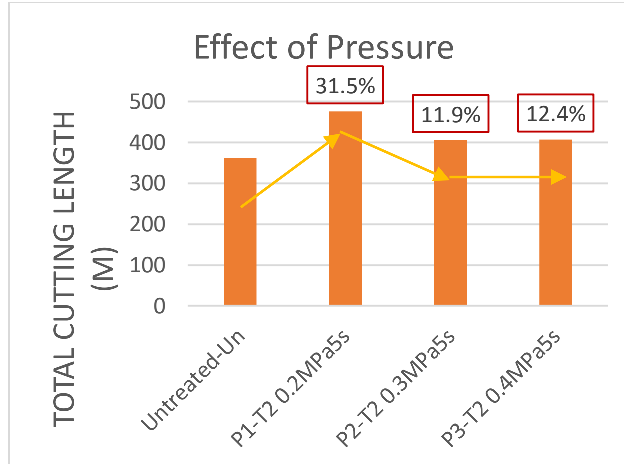
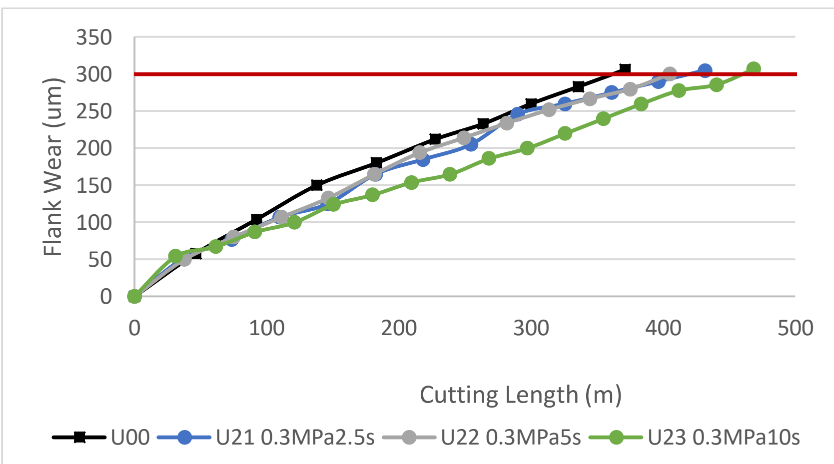


Figure 38- Tool life of tools treated with different pressures when cutting AISI 4140.

Figure 39- Effect of WPC pressure on tool life when cutting 4140.



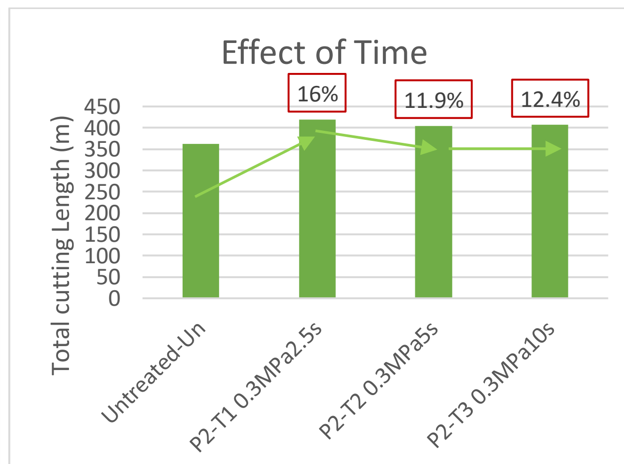


Figure 40- Tool life of tools treated with different duration times when cutting AISI4140.

Figure 41- Effect of WPC time on tool life when cutting 4140.

4.2.2.3 Repeating Study B

This test has been repeated for U00, U12, and U32. Due to the limited number of tools with WPC, the test could not be done on U21, U22, and U23. This test was performed on a diameter range of 127-115 mm. Based on hardness measurements the outer layer of the bar has a bit higher hardness compared to the previous test (about 33 HRC). Consequently, the total cutting length for all 3 tools was reduced. However, as shown in Figure 42, the trend was the same as the previous test. The tool treated with the minimum pressure U12 (0.2 MPa 5 s) had the best cutting performance showing a 60% improvement. U32 (0.4 MPa 5 s) still had a 37% higher tool life as compared with the untreated tool while performing worse than U12.

As mentioned earlier, in order to eliminate the effect of workpiece hardness variations with diameter, the tests are done with the same diameter range.

All the results are discussed in the Discussion section Part I.

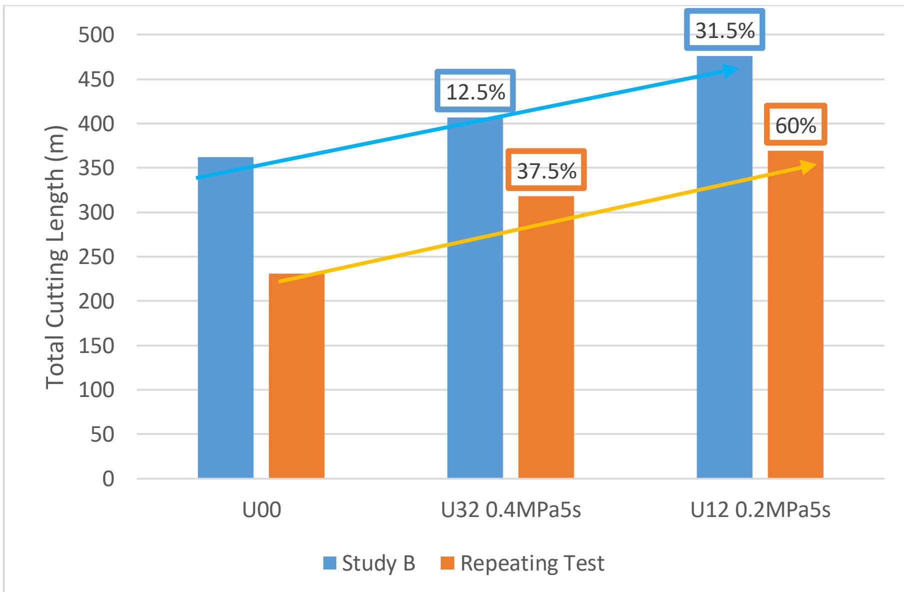


Figure 42- Percentage of tool life improvement for Study B and the repeating cutting test.

Due to limited prepared edges, the exact cutting test as either study A or B could not be performed. However, 3 different groups of prepared tools were tested and compared to an untreated tool using ductile cast iron and AISI 4140. In all three tests, the tools followed a same trend. All the treated tools had higher tool life compared to untreated tools. Also, in the selected range of WPC pressure and time, tools with minimum pressure and time had the best performance compared to the other treated tools.

4.2.3 Study C- Wet and Dry Cutting (AISI 4140)

The effect of coolant was also examined when cutting heat treated 4140 alloy steel using tools with WPC. The cutting conditions were kept the same as shown in Table 10.

Table 10- Cutting conditions in wet cutting.

Fixed Conditions	Value
Feed rate (mm/rev)	0.125
Depth of cut (mm)	0.25
Speed (m/min)	120

Two tools with the same WPC duration time, treated under the maximum and minimum pressure were picked for wet cutting (U12 & U32). The results were also compared with the untreated tool's performance under wet cutting condition. Figure 43 shows the total cutting length of U00, U12, and U32 in both dry and wet conditions.

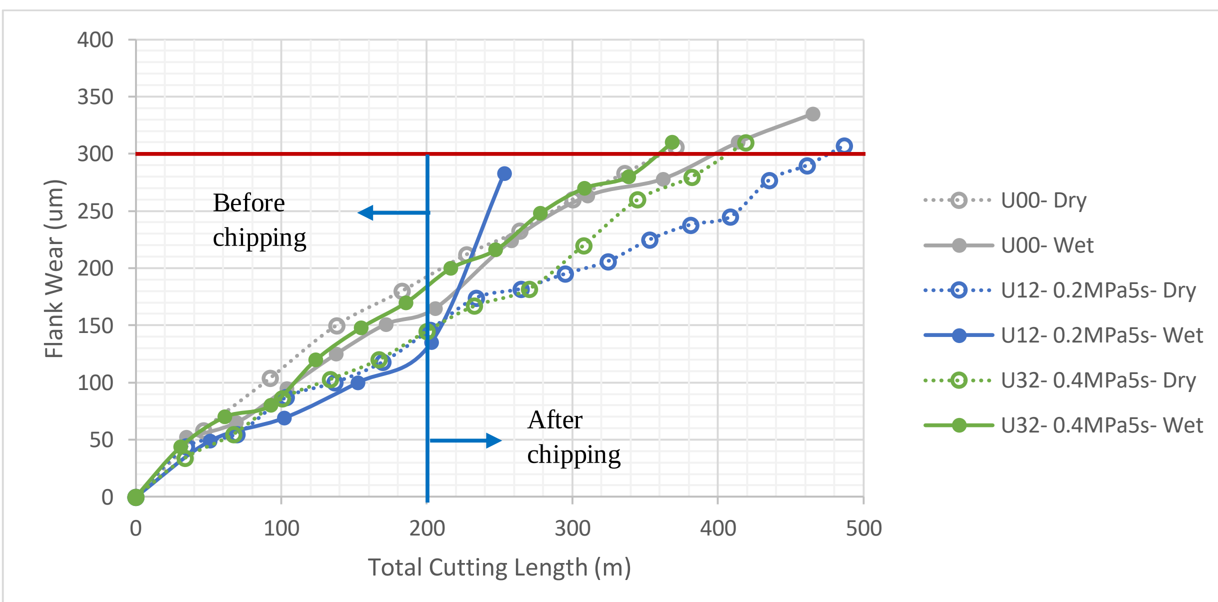


Figure 43- Tool life in wet/dry condition for untreated and treated with minimum and maximum WPC pressure.

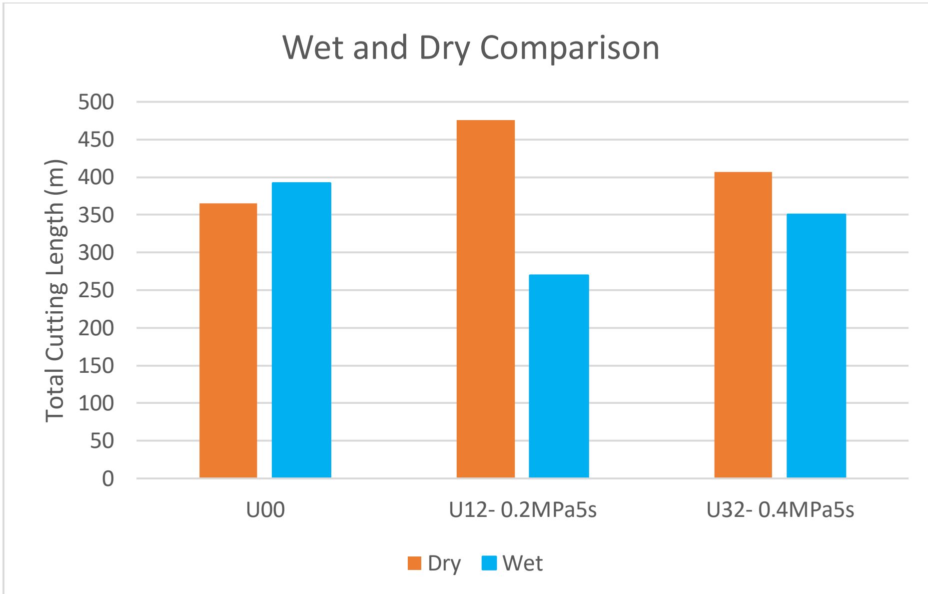
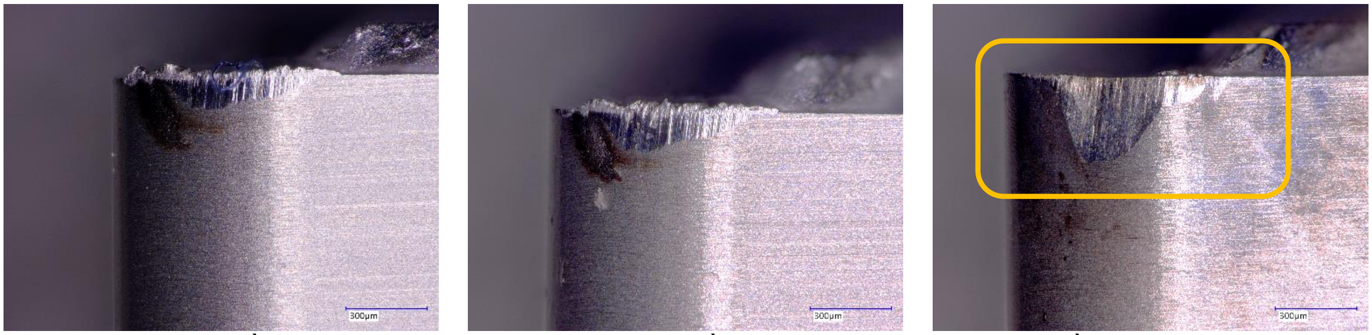


Figure 44- Effect of WPC on uncoated tools when using coolant.

It can be seen that coolant has reduced the tool life for both treated tools (Figure 44). Using coolant on the untreated tool resulted in a minor improvement in its cutting performance. In addition to the worse cutting performance of U12 and U32 under wet cutting conditions compared to dry cutting, U12 failed earlier than U32 as a result of chipping. Figure 45 presents the gradual flank wear of U12 in the 3rd and 4th pass and shows how it suddenly chipped in the 5th pass.

It was observed earlier that U12 performed better that U32 in dry conditions. However, it failed earlier in the wet condition due to chipping. When avoiding the effect of chipping, U12 and U32 flank wear values were compared at 200 m total cutting length. Although using coolant is reducing the cutting performance in comparison with dry, interestingly, U12 (0.2 MPa 5 s) still performed better than U32 (0.4 MPa 5 s).



(a) 3rd pass **(b) 4th pass** **(c) 5th pass- sudden chipping**

Figure 45- Tool wear and chipping of wet cutting U12.

4.2.4 Study D- Different Speeds (AISI 4140)

In order to see how the tools with WPC will perform in different cutting speeds, U22 (0.3 MPa 5 s) with initially 12% improvement was selected for turning with 3 different speeds: 90, 120, and 150 m/min. (Since the number of edges were limited, the best performing tool wasn't selected.)

The total cutting length versus the flank wear for U22 in all 3 cutting speeds are shown in Figure 46. As can be seen, U22 had the best performance at 120 m/min. The cutting speed of 150 m/min caused chipping and early failure. Also, at 90 m/min, the BUE is very high as shown in Figure 47-(a) which reduced the tool's cutting performance. In addition to abrasion wear, Figure 47-(b) shows that oxidation wear is also happening on the flank face.

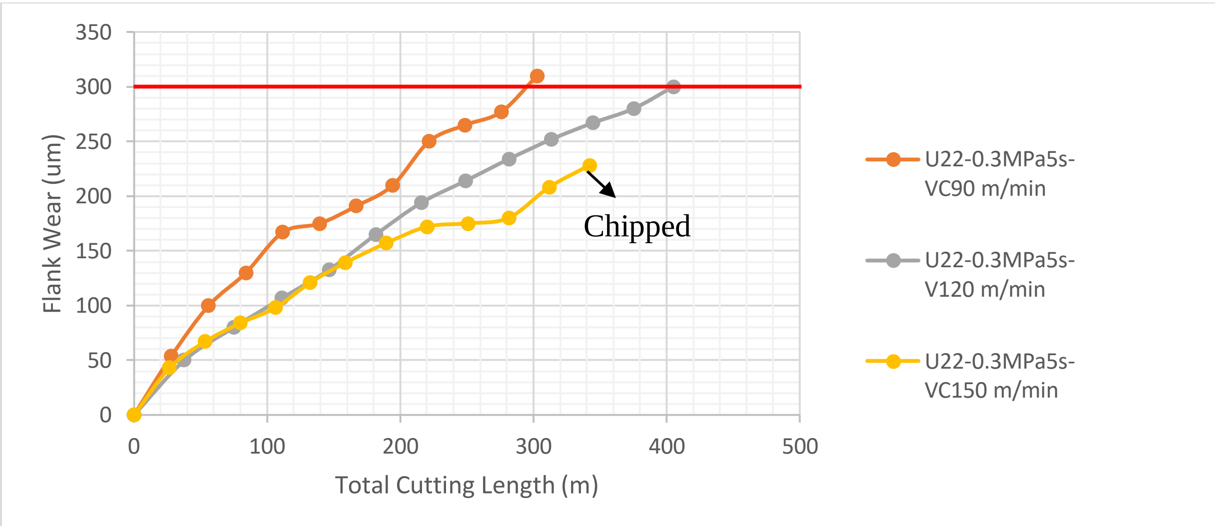
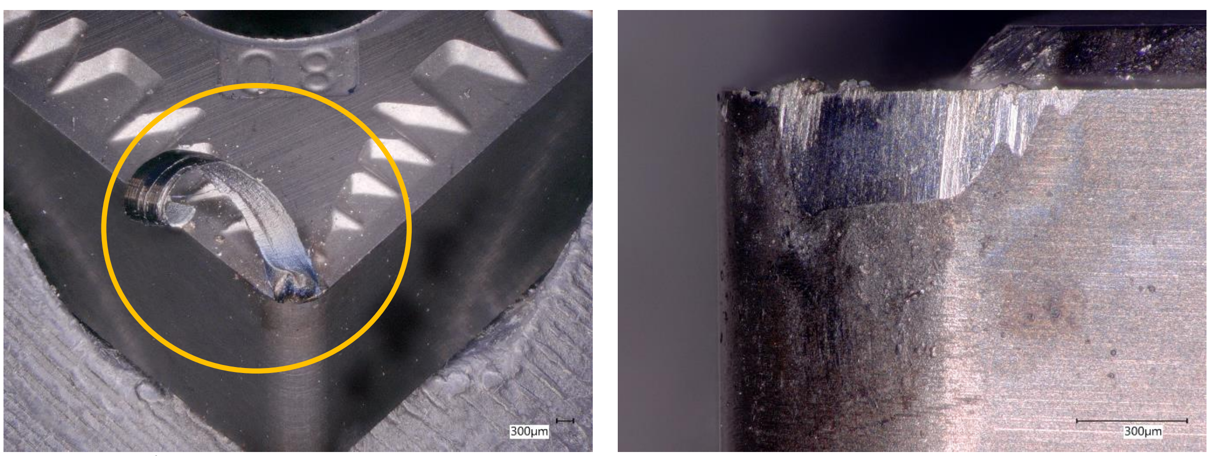


Figure 46- Effect of different cutting speeds on tool life of tools with WPC.



(a) 1st pass- chip sticking to the rake face **(b) Failure- abrasion & oxidation**

Figure 47- (a) High BUE and (b) oxidation wear for U22 at cutting speed of 90m/min.

The cutting speed of 90m/min was too low for the tools and resulted in a high amount of built-up-edge on the rake face and led to early failure. With increasing the speed from 90 to 120 m/min the tool life increases with a very linear wear growth. However, further increasing the cutting speed to 150 m/min resulted in chipping as it can be seen in Figure 48.

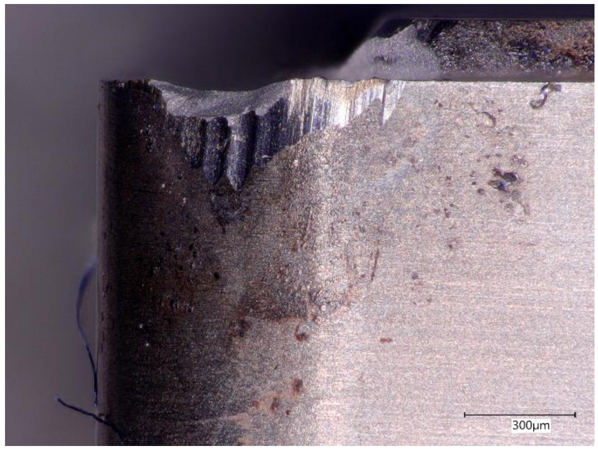


Figure 48- Failure due to chipping when cutting at 150 m/min.

4.3 Discussion

It was observed that increasing the peening pressure or time increased the surface roughness mainly by generating deeper valleys due to Co removal. Higher roughness, more WC grain revelation, and higher Co removal is beneficial for coating deposition. This indicates that WPC can be used as a pre-coating treatment on cemented carbide tools. Although removing Cobalt is very beneficial for coating deposition, it can reduce the WC surface strength and result in lower tool life. Conversely, increasing pressure and time also induced higher and deeper compressive residual stresses on the surface which led to higher surface hardness and fatigue life. The above-mentioned conditions resulted in better cutting performance. It can be said that increasing compressive residual stresses is linked with having a higher amount of Co removal from the WC surface and higher surface brittleness. These 2 parameters act against each other.

4.3.1 Part I

Three similar cutting tests were done until this point:

Study A) cutting ductile cast iron using U00 (untreated tool), U12 (0.2 MPa 5 s), and U22 (0.3 MPa 5 s).

Study B) cutting AISI 4140 heat treated alloy steel using an untreated tool and all the treated tools with different WPC conditions.

Repeating Study B) cutting the same workpiece as Study B in a different diameter range using U00, U12, and U32 (0.4 MPa 5 s).

In study B, treated tools with minimum time and pressure had the best cutting performance. U12 with minimum pressure (0.2 MPa 5 s) showed the best results while U21 with minimum time and 0.1 MPa higher pressure (0.3 MPa 2.5 s) had the second-best cutting performance. With an increasing pressure and time, the treated tools still performed better than the untreated ones. However, the improvement was not significant. It should also be mentioned that U12 had the highest tool life in all 3 tests whereas increasing pressure negatively affected the tool life.

It can be seen that applying WPC with higher pressures and durations than 0.2 MPa and 5 s did not further change the average CRS values. Therefore, increasing the pressure or time cannot increase the induced residual stress after a certain point. However, it was observed to increase the roughness, caused higher Co removal, and reduced the cutting performance. In addition, applying 0.2 MPa pressure for 5 s resulted in higher residual stress and better tool life than applying 0.3 MPa pressure for 2.5 s. Before reaching the maximum residual stress achieved through this range of WPC parameters, it appears that time has more of an effect on the residual stress while pressure has more of an effect on roughness and Co removal.

To aid in understanding why the residual stresses did not change with increasing peening intensity, the mechanism behind the plastic deformation should be explained. As mentioned earlier, the transferred stress from the impact of the shots will cause defects such as dislocations to move in the peened ceramic or metal part. The movement of the dislocations are actually the deformations that happen near the surface resulting in compressive residual stresses with the stress increase related to the increase in dislocation density. As peening continues, the dislocation density will increase, making it harder for the dislocations to move further which results in higher yield strength. The downside is that dislocation interlocking will also increase the material brittleness [21][60]. After a certain point called saturation, further peening causes no or very small changes in the motion of dislocations and consequently the residual stress levels remain unchanged [22].

Many studies indicate that the most important parameter affecting the compressive residual stress (CRS) on the surface and the maximum CRS is the nature of the peened material itself. In most cases, the maximum CRS can't exceed the yield strength of the peened material. For instance, different steels show a maximum compressive residual stress between 40-60% of their original yield stress. In [61], the maximum CRS induced by shot peening carbon steel, alloy steel, and stainless steel was around 40% of the material's yield strength under all peening conditions. Also, Wang et al. reported the maximum CRS of steels with an ultimate tensile strength of more than 1000 MPa, lies between 40-60% of their ultimate tensile strength [26]. However, under extreme shot peening conditions, the residual stresses can reach 80% of the yield stress or higher [62].

In this study, the maximum CRS values for different WPC conditions on the rake face of the treated cemented carbide tools were around -1000 to -1200 MPa. The ultimate tensile strength of WC 6% cobalt is around 2000 MPa. Also, in all the mentioned studies, the peened workpiece was made of steel. In this study, cemented carbide ceramic with very high hardness and brittleness is being utilized. Unlike metals such as steel, the ultimate tensile strength and the yield strength of ceramics have very similar values. All in all, maximum CRS of -1000 to -1200 MPa makes sense since it lies around 40-60% of the ultimate strength of cemented carbide.

The penetration depth for the X-Ray beam of the XRD instrument depends on the material and the incident angle. For measuring residual stresses, a high angle was used in which the beam will penetrate to a depth of about 2.6 µm. However, there is no depth information regarding the residual stresses. Therefore, it is doubtful that the average CRS values at this depth are actually the maximum CRS in the material.

Figure 49 shows the general distribution of residual stress on a peened material. The maximum compressive residual stress happens within the plastically deformed layer. While going deeper inside the material, the compressive stress becomes zero and the balancing subsurface with the tensile stresses will begin. As mentioned before, the tensile stresses in the sub layer do not really affect the fatigue properties of the part [21][60].

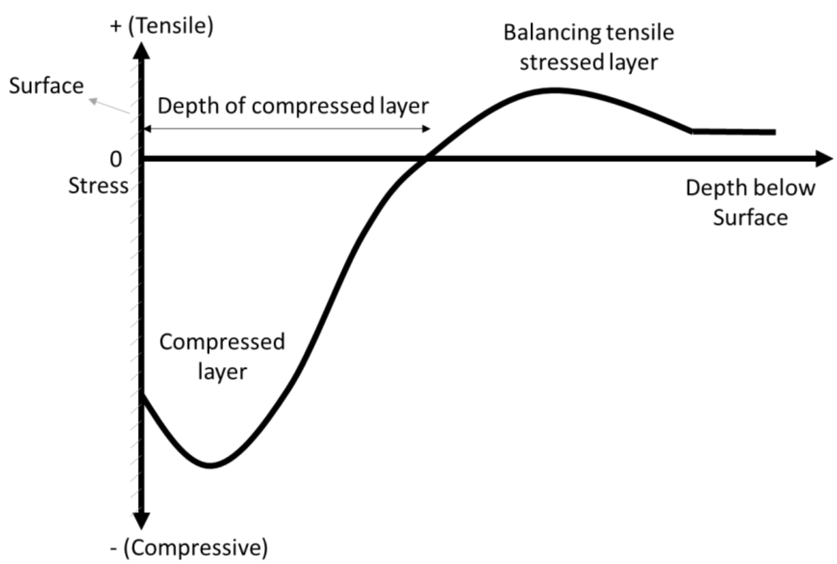


Figure 49- General residual stress distribution on a peened surface.

As shown in Figure 50, using the same peening condition, materials with a higher hardness will have a lower depth of compressive residual stress while increasing the maximum CRS [61]. In addition, the shot used in the WPC process are very small (10-15 µm). Finer shot will also result in further reducing the depth of the compressive residual stress layer.

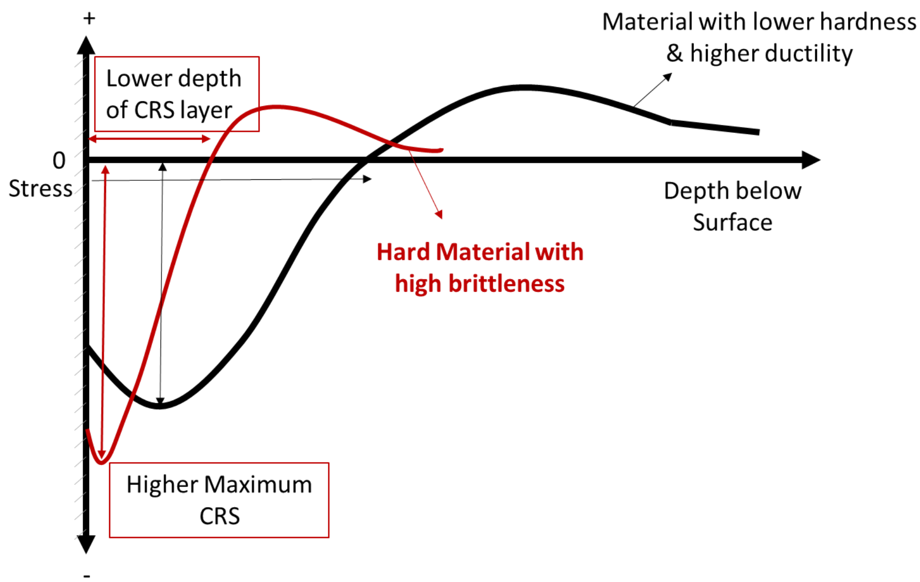


Figure 50- Residual stress distribution of hard peened material.

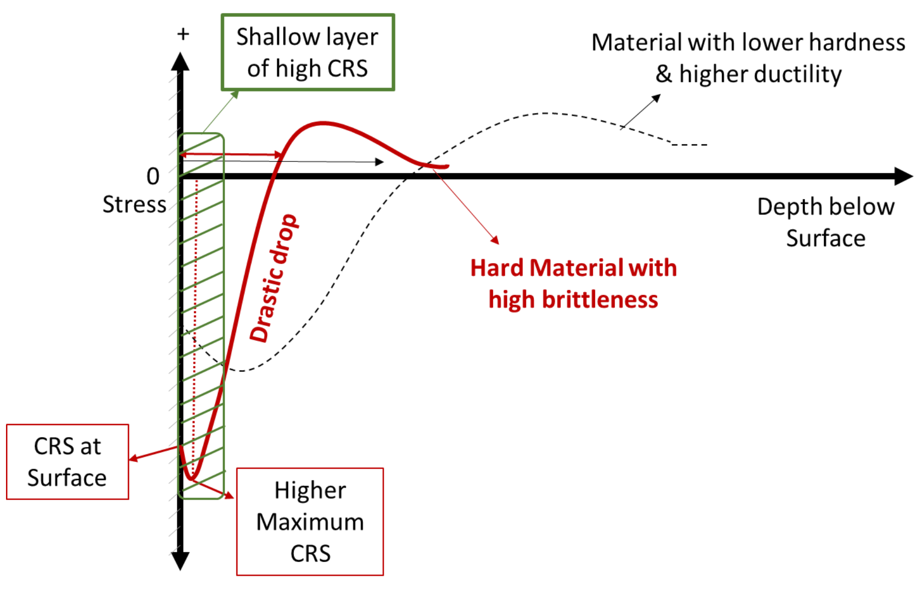


Figure 51- Shallow layer with high CRS for hard and brittle materials such as tungsten carbide.

Based on the discussion, cemented carbide tools with WPC will have a very shallow CRS layer with a relatively high maximum CRS. As it can be seen in Figure 51, the residual stress distribution graph for cemented carbide becomes steeper compared to softer material such as steel. However, by further increasing the depth, there would be a drastic drop in CRS values. Therefore, the measured CRS values are expected to be very high or very low depending on the x-ray's penetration depth. Since the values of average compressive residual stresses obtained using XRD are relatively high (around -1000 MPa), they are expected to be very close to the actual value of maximum compressive residual stress.

In the production process, the flank face of the tools was ground. Grinding also induces compressive residual stresses and thus increases the ultimate strength of the material up to a certain depth. It can be seen in Figure 51 that the average value of CRS of the untreated tool on the flank is almost double that compared to the rake face. Therefore, the compressive residual stress will become saturated in 40-60% of the new ultimate strength after grinding.

4.3.2 Part II

In **Study C**, the effect of coolant on treated tools under the maximum and minimum pressure (U12, U32) with the same duration time is investigated. The results were compared with wet cutting using the untreated tool. Cutting results indicated that using coolant has a deteriorative effect on tools treated with WPC while resulting in a minor improvement in performance of the untreated tool.

Cemented carbide tools are naturally brittle which makes them susceptible to the fluctuating thermal loads experienced on the cutting edge. These thermal shocks can easily result in severe damage on the edge [63]. This can be due to the fact that using coolant in cutting results in temperature fluctuation and thermal shocks which will lead to rapid micro-fractures on the tool [64][65]. All the above-mentioned factors are the reason why the use of coolant did not result in a significant improvement in tool life of the untreated tools.

In addition, WPC resulted in Co removal and some debonding of tungsten carbide particles. This will make treated tools more susceptible to chipping compared to untreated tools. Chipping was the reason for the failure of U12 during wet cutting which may also be another evidence for the damaging effects of coolant due to thermal shocks. In conclusion, thermal shock affected the WPC treated tools more than the untreated tools and thus resulted in a lower tool life for the WPC treated tools.

To see how the tools with WPC perform in different cutting speeds, U22 (0.3MPa 5s) with an initial 12% improvement was selected to cut under 3 different speeds in **Study D**: 90, 120, and 150 m/min. It was observed that high BUE caused early failure at a low speed. This is due to the fact that at low speeds, the temperature in the cutting zone is lower and the material does flow away from the tool but rather sticks to the edge. It should be mentioned that K313 grade is not recommended for cutting material with long chips due to its low hot hardness and toughness. When cutting at a low speed, the hot chips tend to keep sticking on the tool edge keeping the edge temperature high. This can explain the oxidation wear observed at the low cutting speed.

As can be seen, U22 had the best performance at a speed of 120 m/min. A cutting speed of 150 m/min caused chipping and early failure. The temperature also increases alongside the cutting speed so thermal wear mechanisms begin to dominate tool wear mechanisms [55][54]. As the cutting speed is increased, diffusion and oxidation mechanisms will become more important. In addition, WPC has increased the brittleness of the tool making them more fragile. This factor explains why there is a higher level of tool chipped at the 150 m/min cutting speed.

5 Conclusion

A comparative study was carried out on the effect of WPC on the mechanical properties and cutting performance of cemented carbide inserts. Five different WPC conditions were selected with peening pressure varying from 0.2 to 0.4 MPa and the duration time between 2.5 to 10 s. The effect of WPC and different peening parameters on the microstructure, surface roughness, edge radius, residual stresses, and surface nano-hardness were investigated. The cutting performance of uncoated tools in finish turning were carried out on two different workpiece materials, ductile cast iron and AISI 4140 steel, with different cutting speeds, and in dry and wet conditions.

There was no obvious damage on the cutting edge, although a dimple pattern was visible on the rake face of the treated tools. The surface roughness increased alongside higher WPC pressure or duration time mainly due to Cobalt removal and a greater depth of valleys on the surface. Higher surface roughness, Co removal rate, and more WC grain revelation are beneficial if WPC is used as a pre-coating treatment because it will increase the coating adhesion. However, Co removal can have negative effects on cutting performance of uncoated tools since it will decrease the support for the hard carbide particles and increase its brittleness.

Cutting edge radius also increased along with WPC pressure or time to a maximum edge radius value of 9 µm. This value was within the range expected to still provide strengthen of the cutting edge without substantially changing the cutting process.

Applying WPC significantly improved the compressive residual stresses (CRS) near the surface of the carbide tools. However, applying WPC with higher pressures and durations than 0.2 MPa and 5 s respectively, the magnitude of CRS remained almost constant whereas the surface roughness still grew. It can be said that increasing compressive residual stresses are linked with increasing the amount of Co removal from the WC surface as well as increasing the surface brittleness.

U12 reached the maximum CRS with WPC treatment under the minimum pressure (0.2 MPa) for 5 s. This tool showed the best cutting performance in all tests representing a tool life improvement of 31% over a similar untreated tool. Further increasing the pressure and time had no or very little influence on the CRS. At the same time, higher pressure and time lead to a higher amount of Co removal.

WPC made the tools more susceptible to temperature fluctuation. As such, the performance of the tools with WPC decreased under wet cutting conditions. Reducing the cutting speed from 120 m/min to 90 m/min increased the BUE and resulted in early tool failure. Also, increasing the speed to 150 m/min caused early chipping.

Another important point is that the selected parameters for WPC (P and T) were all in an optimum range. Because there was no damage on the cutting edge nor on the tool surface the parameters were deemed to not be too extreme. Also, pressure and time weren't too low compared to the values commonly used.

As mentioned before, no report was found on the effect of WPC on tungsten carbide inserts and this was the reason for Fuji Company's collaboration with this research. Many other considerations should be taken into account to achieve the best results. However, this study shows the significant potential of using WPC as a surface treatment on carbide cutting tools.

6 Future Work

This research is a small step towards understanding the effects and potentials of using WPC as a surface treatment on tungsten carbide inserts, yet there is still a long way to go. Some recommendations are presented for further continuing this study:

- Coating can be applied on treated uncoated tools to investigate the effect of WPC as a pre-coating treatment. The adhesion of the coating and the cutting performance of coated tools with treated and untreated substrate should be compared. It is expected that the coating adhesion will increase due to the larger amount of WC grain exposure and Co removal.
- The effect of WPC as a post-treatment on coated inserts should also be investigated.
- After depositing the coating on a treated substrate, the samples should be sent for a post-treatment to see how WPC as a pre and post treatment will affect the tools.
- Having more information on the distribution of CRS within the depth of cemented carbide surface will help improve our understanding of the WPC process.
- The tool with minimum pressure had the highest cutting performance. Therefore, testing lower WPC pressures is recommended.
- It is generally recommended to use harder shot particles as compared to the workpiece. The shot selection was limited throughout this research. However, it would be a good idea to change the shot material to a harder particle such as Al2O3 or ZrO2 for future research.

7 Appendix 1- Alternate WPC Treatment Technology

The first sets of treated tools showed a large number of defects after the treatment was applied especially on the cutting edge. In the following figure the peened area is shown:

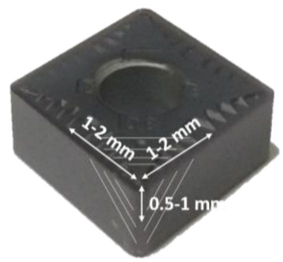


Figure 52- Peened area.

It can be seen in Figure 53 and Figure 54 that the WPC process applied with this technology has caused micro chipping on the cutting edge and extensively damaged both coated and uncoated tools. This is expected to have a negative effect on the cutting performance of the tools.

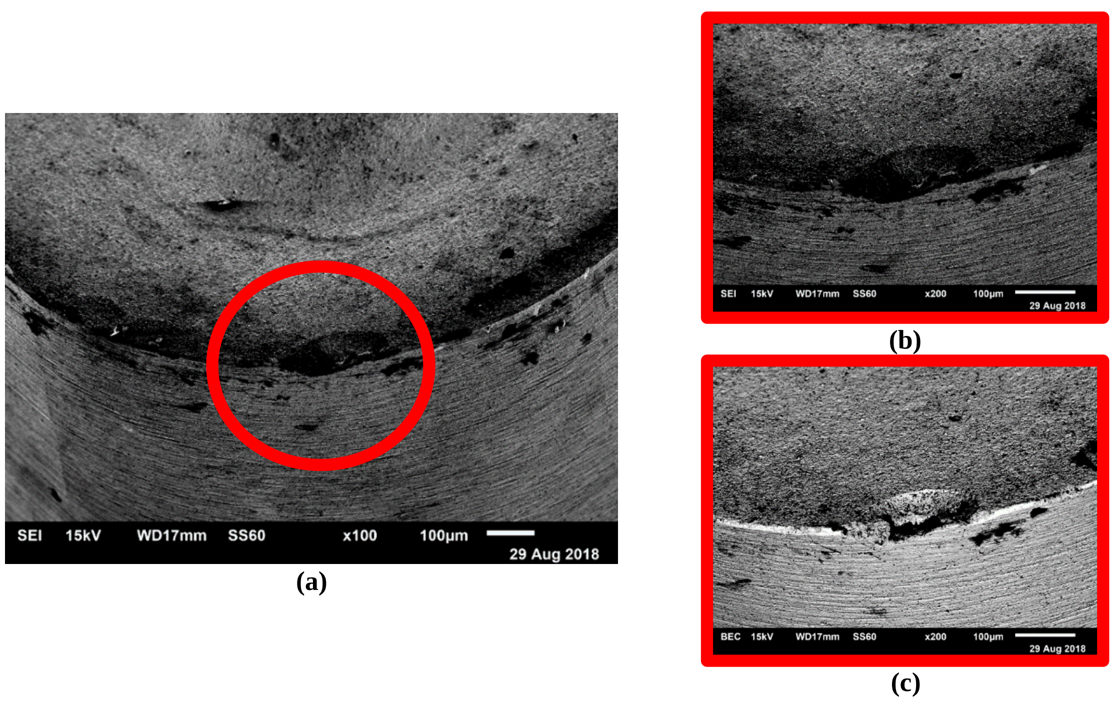
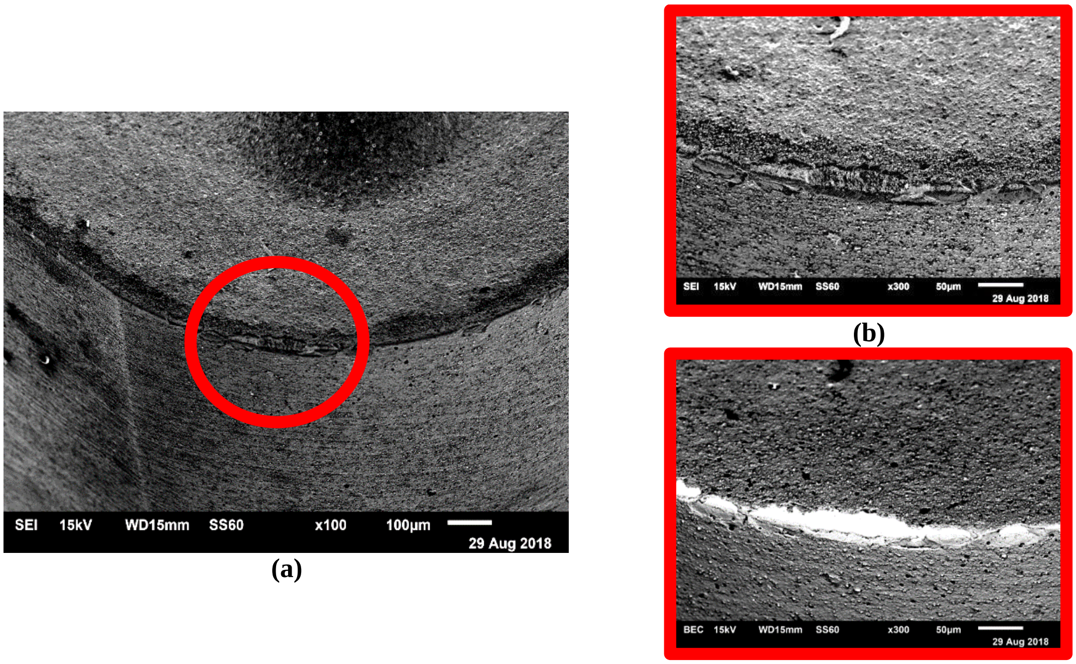


Figure 53- (s) SIE image x100, (b) and (c) SIE and BEC image x200 of cutting edge of *uncoated* tools with WPC.



(a) (b) (c)

Figure 54- (s) SIE image x100, (b) and (c) SIE and BEC image x200 of cutting edge of *coated* tools with WPC.

In order to assess the tool life, cutting tests are done with cutting parameters shown in Table 11 using a bar of Ductile Cast Iron 80-55-06.

Table 11- Cutting Conditions for tools with an alternate WPC technology

Cutting conditions	Value	Units
Speed	180	m/min
Feed rate	0.34	(mm/rev)
Depth of cut	0.25	mm (Rad)

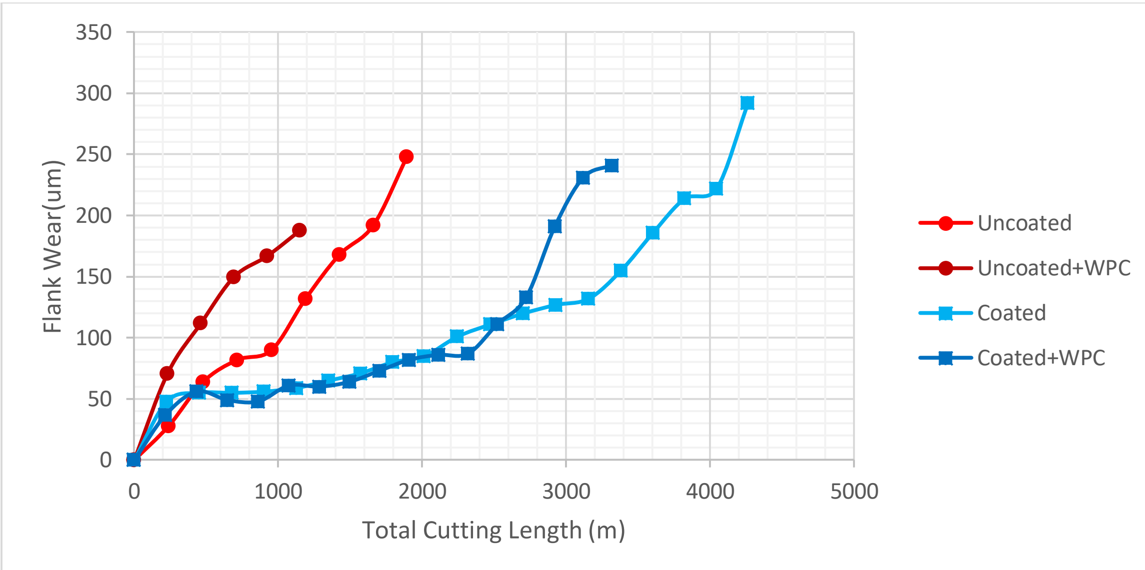


Figure 55- Tool life- Coated and Uncoated tools with and without an alternate WPC technology.

Based on the performance observed this WPC technology is not showing promising results. As expected, both coated and uncoated tools with WPC have lower tool life which can be explained by the damage done to the cutting edge. Appropriate peening parameter must be found for this technology so that neither the cutting edge nor the tool surface is damaged.

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