

**EVELOP HARD CA-PVD COATING OF CrNiAlSiN
FOR HIGHER WEAR RESISTANT COATING IN
INTERNAL COMBUSTION ENGINE**

BY

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|Dedicated to my mother, father, brothers, and sister. |

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ABSTRACT

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The internal combustion (IC) engine is the engine that is heavily utilized in automobile transport vehicles. The major challenge in the sector of automobiles regarding IC engines is to increase the surface hardness and wear resistance in order to enhance the lifetime of IC engines and solve environmental issues. This work used CA-PVD to coat CrNiAlSiN on different surface conditions (different surface roughness) of the cast iron substrate which is the material that is usually used in the cylinder of IC engine. Then, the characterization properties were investigated, and mechanical tests were performed. From the results, it can be seen that the hardness was hugely affected positively. The enhancement of the hardness was from 211.9 HV for the substrate to 3115 HV for the average of coated samples. The CrNiAlSiN coating was beneficial for significantly reducing the wear depth. In addition, the coated sample treated with 60 grit-size sandpaper reduced the wear rate by approximately 38 times.

ملخص الرسالة

الاسم الكامل: محمد عيسى خطيب عبد العزيز

عنوان الرسالة: تطوير طلاء الكروميوم- نيكل- ألومنيوم- سيلكون- نترأيد باستخدام تقنية التبخير الفيزيائي لزيادة مقاومة التآكل في محركات الاحتراق الداخلي

التخصص: الهندسة الميكانيكية

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تهدف هذه الرسالة لابتكار مادة طلاء جديدة تمتاز بالصلابة والمقاومة العالية للتآكل لاستخدامها في محركات الاحتراق الداخلي للسيارات. ذلك أن أجزاء محركات الاحتراق الداخلي وخصوصا الاسطوانات الداخلية، تتعرض لحرارة وضغط شديدين، مما يستلزم مادة طلاء ذات صلابة عالية ومعدل تآكل منخفض. وهذه المشكلات التي تتعرض لها الاسطوانات الداخلية تتسبب في كثير من المشكلات التي تنقص من العمر الافتراضي لمحركات الاحتراق الداخلي فضلا عن المشاكل البيئية جراء الانبعاثات الضارة لتلك المحركات. في هذا البحث تم تطوير مادة طلاء جديدة أساسها عنصر الكروميوم مع إضافة كميات بنسب قليلة من عناصر السيلكون والنيكل والألمونيوم. هذه المادة استخدمت كطلاء باستخدام تقنية التبخير الفيزيائي لمقاومة تلك المشاكل الناتجة من محركات الاحتراق الداخلي، ومن ثم تم قياس الخواص الفيزيائية لها، بالإضافة إلى الاختبارات الميكانيكية التي أجريت عليها لقياس مدى كفاءة تلك المادة. لوحظ من نتائج التجارب أن الصلابة بعد الطلاء قد تحسنت بشكل كبير، فقد زادت من HV 211.9 للركيزة إلى HV 3115 وهي القيمة المتوسطة لجميع لعينات المطلية. لوحظ أيضا أن الطلاء كان مفيداً في تقليل عمق التآكل. بالإضافة إلى أن معدل التآكل قد انخفض في جميع العينات المطلية، إلا أن العينة المطلية ذات السطح الأخشن أظهرت أفضل النتائج، فقد قللت من معدل التآكل 38 مرة.

CHAPTER 1

INTRODUCTION

The internal combustion (IC) engine is the type of engine utilized in transport vehicles in the automobile sector because it is more compact than an external combustion engine and requires less space. On the other hand, IC engines are the greatest consumers of fossil fuels in the world due to the high wear of their components [1]. Thus, the major challenge in the sector of automobiles regarding IC engines is to increase the wear resistance. Decreasing the resistance of the wear effects negatively on the performance of IC engine, oil consumption, and lifetime of IC engine [2]. These problems cause critical environmental issues around the world such as global warming, cleaning the forested land, reduction of the ozone layer, air pollution that causes photochemical smog, and acidification. So, there is a need to address the problem of the high wear rate to improve the performance of motors or engines as they are like the heart of vehicles. Researchers are trying to find solutions to increase the efficiency of IC engines and address this problem. Improving the performance of IC engines is still a hot topic for researchers. This work is a trial to enhance IC engine performance from the perspective of materials and surface engineering. The way of the experiment is to use CA-PVD to coat CrNiAlSiN on different conditions of the surface of cast iron which the material

used in the cylinder of IC engine investigated. Additionally, the characterization, metallurgical, mechanical, and tribological properties of the coating are studied.

CHAPTER 2

LITERATURE REVIEW

2.1 Internal combustion (IC) engine

IC engines are the engines that are powering the major section of automobiles in the whole world [3]. IC engine, Fig. 2.1, is an extremely important part of the automotive industry that has to be tackled to improve the performance of the engine and reduce energy consumption. The main parts of IC engine are cylinder, piston, piston rings, valves, connecting rod, crankshaft, crankcase, and flywheel. Figure 2.2 illustrates those parts [4]. The cylinder is one of the most important and critical parts of IC engine, Fig. 2.3 illustrates the cylinder of IC engine. The main function of the cylinder is to guide the piston [5, 6]. The piston moves in the cylinder upward to downward in a reciprocating motion [7]. The relative movement between the cylinder and the piston generates high friction between the inner surface of the cylinder and the piston [8]. Thus, less friction coefficient [9] and high wear resistance are required for the fast-moving in cylinders [10]. For these reasons and due to the high pressure introduced in cylinders, high-strength material must be used. The material that is usually used is cast iron [11]. This material behaves good, but for lower friction and less energy consumption, higher wear resistance material could improve the mechanical efficiency and the performance of the IC engine [12].

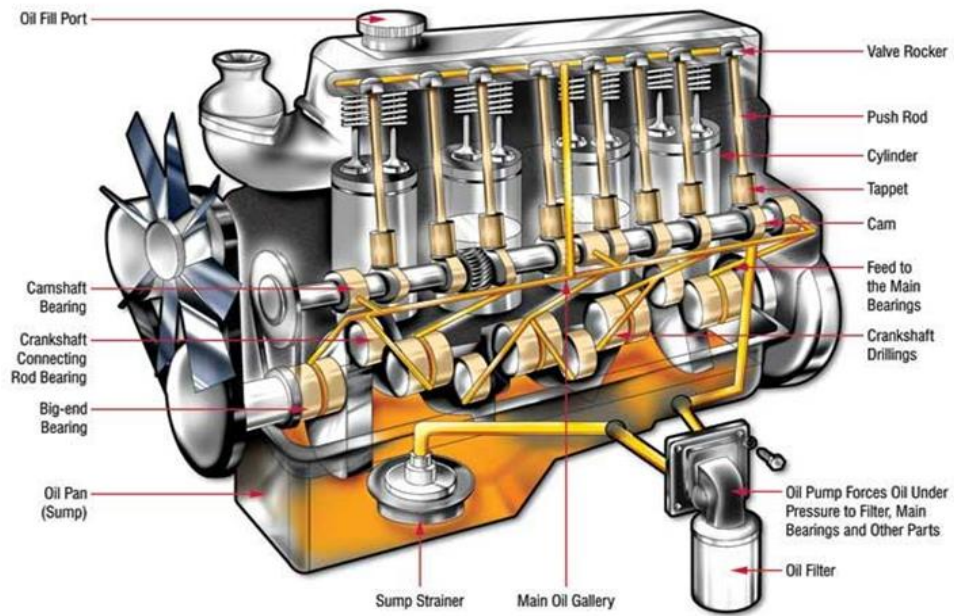


Figure 2.1: IC engine [5]

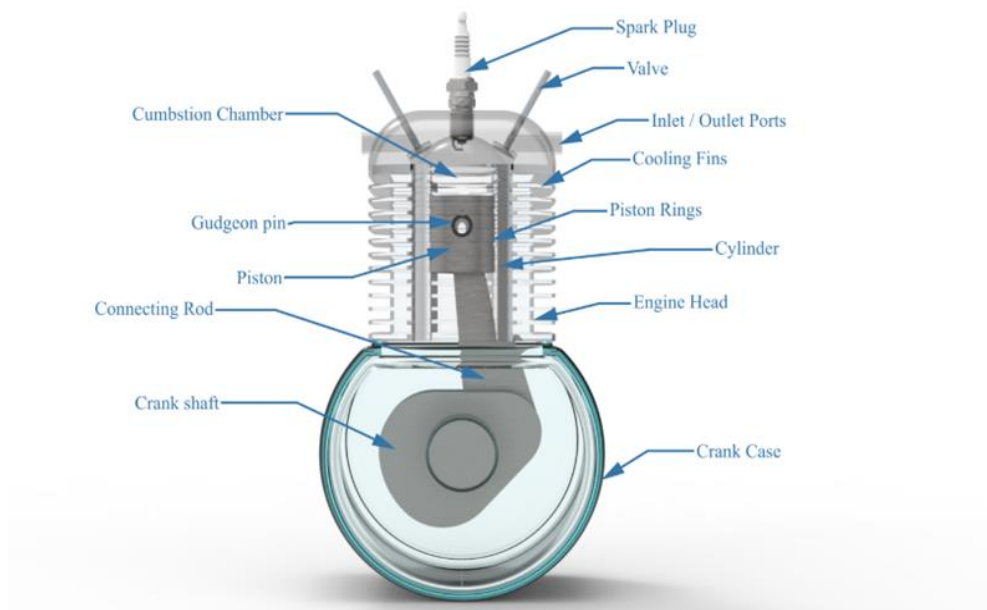


Figure 1.2: Components of IC engine [7]



Figure 2.2: Cylinders of IC engine [10]

Developing hard coating on cast iron is one of the modern techniques to enhance the mechanical properties of cylinders and reduce their frictional force. However, hard coating materials that are used are still limited. Hard coating protects the surface of the substrate [13]. There are many technologies available for the hard coating of engine components. However, physical vapor deposition technology is considered an effective technique in automotive [14]. Some important reasons that make physical vapor deposition is the best way for automotive, are its attractive characteristics such as good wear resistance, high hardness, and low friction [15]. So, physical vapor deposition been paid great attention in recent decades [16].

2.2 Hard coating by physical vapor deposition (PVD)

The development of PVD coating technology started in 1970 as the first generation with binary compounds ceramic materials such as TiN, TiC, TiB₂, etc. The second generation

was in 1985 when solid solutions, such as Ti-Al-N-C, Ti-Al-N, etc, were involved. In 1990 the third generation was started with multilayer structures. The fourth generation was in 2002 with structures with nanocomposite and nanostructures doped that have solid components such as dry lubricant [17, 18]. Figure 2.4 shows the evolutionary history of PVD coating technology.

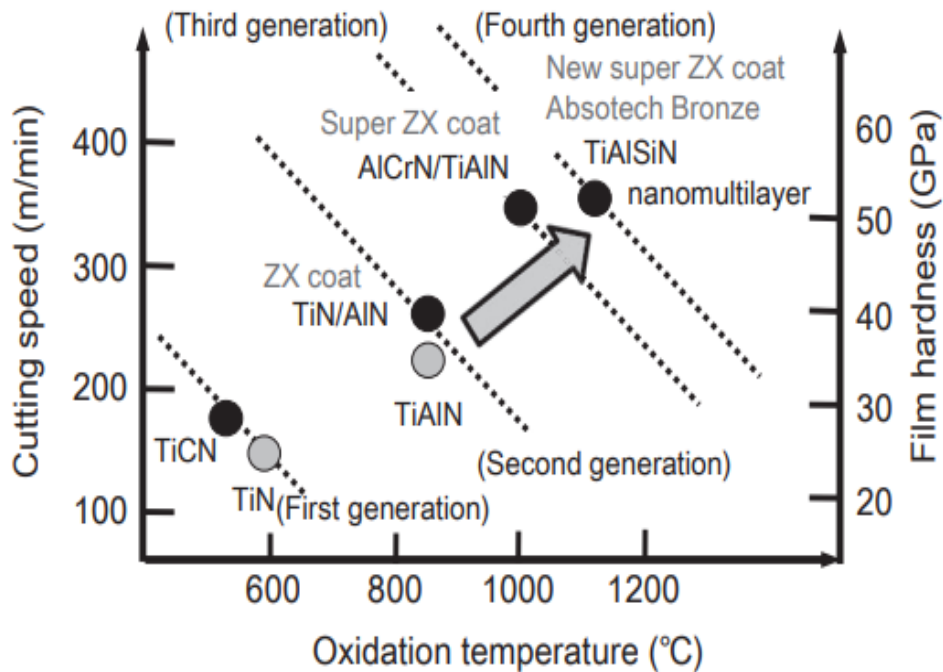


Figure 2.3: The evolutionary history of PVD coating technology [18]

PVD coating is a technique that deposits a thin-layer material that can utilize a broad range of materials at a relatively cheap price [19]. In PVD, the source or the coated material is set inside the chamber in a solid form along with the substrate. During physical processes, the solid material is vaporized physically, and then vapor hits the surface of the substrate to coat it. So, vapors that come from the solid coating material need the energy to generate

it from a solid or liquid form to a vapor form [20]. PVD coatings are basically used to protect and improve properties of the base material that will be coated [21]. The properties that will be improved are mainly wear-resistant, corrosion-resistant, abrasion-resistant, chemical-resistant, thermal-resistance, and friction [20]. PVD coating is used in machining, metal forming, and plastic processing. Specific PVD coatings are also used in sensitive fields such as medical sectors, and the food industries [21]. There are many procedures in a gaseous state in the case of PVD technique. However, the most common methods are magnetron sputtering, evaporation deposition, electron beam evaporation deposition, and cathodic arc deposition.

2.2.1 Thermal evaporation

In thermal evaporation, the source or the coating material of coating goes from solid state then liquid to finally gas state by using heat. The gas atoms which evaporate from the source are traveling through a vacuumed chamber toward the substrate and they condense on the surface of the substrate. Thermal evaporation is mostly used with metals because the melting point for metal is relatively low and that can produce very steady deposition rates. However, non-metals can also be used and deposited in this technique. There is a small container called a boat inside the vacuum chamber which carries a little amount of the coating source material. This boat is mainly a sheet metal that has a high melting point such as tungsten. This boat is heated by an electrically resistive heat element or filament [22]. The mechanics of this deposition technique are very simple. An electric current pass through that tungsten boat by two electrodes that are clamped in the boat, and they carry a current with hundreds of amps. As a result, the source material in the boat melts and

evaporates. These evaporated material atoms strike the surface of the substrate and condense to form the desired layer [23]. Figure 2.5 illustrates the diagram of the process of thermal evaporation. Thermal evaporation can be used with metals and nonmetals with a high deposition rate and a low cost. However, it has poor uniformity and low density [24].

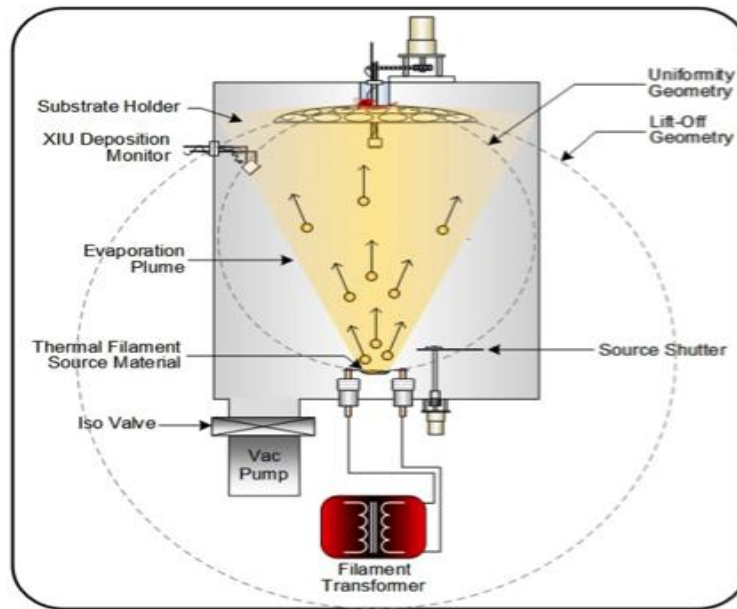


Figure 2.4: The diagram of thermal evaporation process [22]

2.2.2 Magnetron sputtering

The source material in magnetron sputtering is in the form of a flat plate which we call a target. In the vacuum chamber, an inert gas is inserted in the vacuum chamber and accelerated to release the atomic particles from the target. The gas that is usually used is argon. A high voltage that is applied between the cathode, which is called the target, and the anode, which is called the substrate, along the direction of the magnetron causes that acceleration. Inert gas is used because it is not reactive and will not result in unwanted chemical reactions during our process. Atomic particles from the target fly off in all directions including toward the substrate that wants to be coated and this process continues

until the substrate is coated with the desired thickness of material. Figure 2.6 shows schematic drawings of the two PVD coating processes which are (a) magnetron sputtering and (b) thermal evaporation using argon gas as the inserted inert gas [23]. Magnetron sputtering is good for metals with a high deposition rate (higher than thermal evaporation) and poor uniformity with a high cost [24].

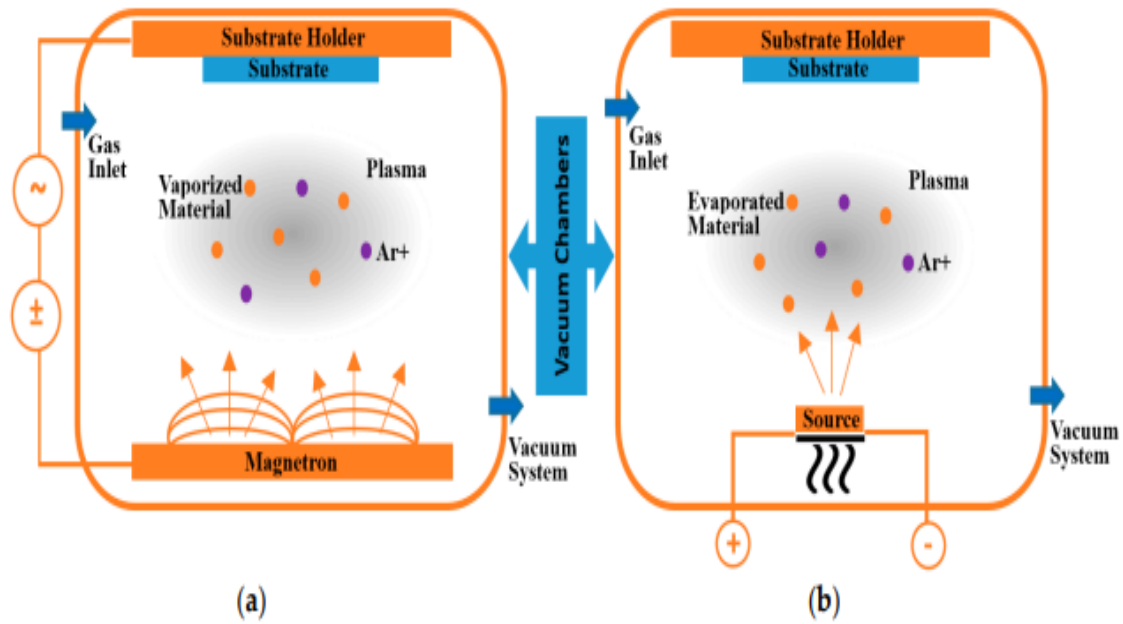


Figure 2.5: Schematic drawings of the two PVD coating processes: (a) magnetron sputtering and (b) thermal evaporation [23]

2.2.3 Electron beam evaporation

Another technique that uses the heating concept to evaporate the coating material is electron beam evaporation. This process works like a thermal evaporation technique but utilizes a flow of electrons as the source of heating. A well-confined electron beam is focused on a tiny spot of material and heats it to melt and then evaporates the source

material in a vacuum chamber as demonstrated in Fig. 2.7. The material is evaporated and then condenses on the substrate's surface as in PVD coating stages. One advantage of EB evaporation is that can be used for complicated shapes such as turbine airfoils. An electron beam evaporator can be characterized by four main components, first is the electron gun or source which produces the flow of electrons, and it can be straight (Fig. 2.7 a) or electromagnetic deflected (Fig. 2.7 b). Second is the crucible which is usually made of copper. The source material that wants to be evaporated is placed in that crucible which can be for small or large quantities. Third is the substrate which is the part of the material that wants to be coated. Finally, is the vacuum chamber which is sited for many coating applications [25]. Electron beam evaporation is also good for metals with a high deposition rate and good film density. The energetic target material can cause substrate heating which is a big disadvantage [24].

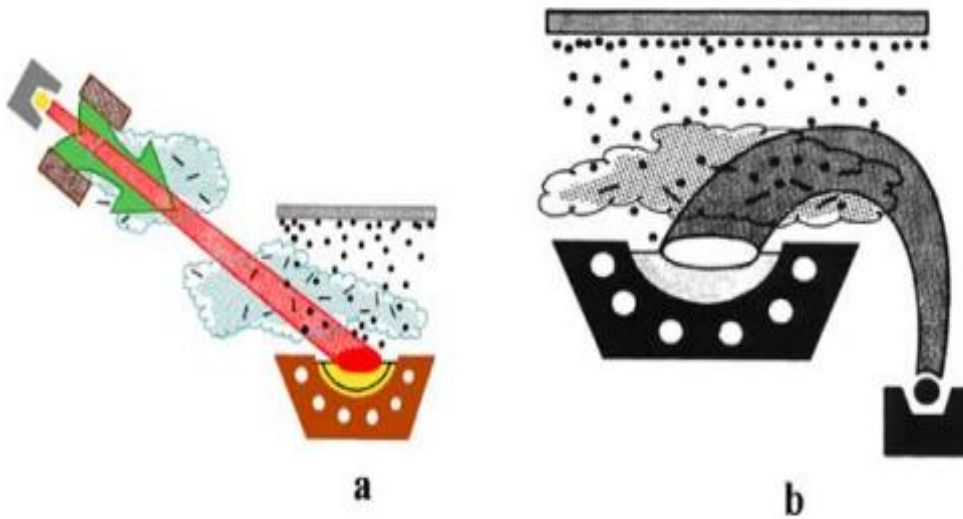


Figure 2.6: Diagram for: (a) straight electron beam gun, and (b) electromagnetic deflected electron beam gun [25]

2.2.4 Cathodic arc deposition

The cathodic arc deposition process uses a DC power supply to apply an arc that is concentrated electrical discharge. This arc has low voltage and high current, and it is directed toward the cathode which is the coating material or the target. The arc forms an extremely focused stream of electrical energy to create a tiny zone on the target surface called cathodic spot to heat it up to above the melting point. This spot is heated up to a temperature that exceeds the melting point to then vaporize the target material. An electromagnetic field directs the arc to provide a homogeneous resultant layer that is uniform. A reactive gas is introduced in the vacuum chamber during the process to provide for ionization, disassociation, and excitation. There are water-cooling channels that are provided with a cathode design to dissipate the heat that is generated by the electric arc when it strikes the target surface.

Cathodic arc deposition has become a widely used technology in a wide range of production applications such as hard coatings [26]. The cathodic arc deposition method will be used in this experiment because of the great advantages that are provided by our application. Relatively low substrate temperatures can be used in the cathodic arc process due to the energetic ions that form compact films without needing additional thermal energy [27] and that is important for cylinders of IC engines since significant heat is not preferred in this application during the coating process [28]. Cathodic arc deposition layers or films have greater adhesion characteristics, and they are denser compared to the production of other techniques. This behavior of adhesion happens because of the penetration of the coating atoms to the surface [27]. Also, this method is more stable for refractory metals such as Ti, Cr, and Zr compared to other methods [29]. It is good to

synthesize highly hard coatings such as TiN, CrN, TiAlN, AlCrTiN, TiAlSiN, etc. for wear resistance [26]. All these features make the cathodic arc process a good choice for coating cylinders of IC engines.

2.3 Some common PVD hard coating in internal combustion engine

Several nitride coatings are the coating that is well-established for hard and tough industrial environments where the materials can exposure to tough conditions and experience a high temperature or a severe wear. Chromium nitride-based coatings are used for protective reasons along with some transition metals that can be for example silicon (Si), aluminum (Al), and titanium (Ti) that are deposited by PVD. This method offers good features such as reducing friction behavior, low internal stress, and excellent corrosion [30-33]. Chromium nitride coating also has some important properties such as high adhesion and good wear resistance, which make it better than titanium-based coating which is more brittle [34-36]. M.A. Ezazi et al. used magnetron sputtering process to deposit a binary (Cr/CrN) thin film on AL7075-T6, and they found that the hardness surface was increased up to 5 times [37]. Cengiz Öner et al. used cathodic arc deposition process to deposit a layer of CrN on a single cylinder made of cast iron in IC engine. the experiment was performed at 300 C. The thickness of CrN coating was 1.8 ± 0.2 μm . The roughness of the coated cylinder was 0.25 μm and 0.40 μm for uncoated cylinder. Since the roughness of the coating decreases, the coefficient of friction decreased. In addition, hardness was increased from 250 HV for coated cylinder to 1800 HV for uncoated cylinder [38]. If Al is added to CrN, that causes an increase in oxidation resistance due to adherent protection.

(Cr, Al)-oxide layer which creates elevated temperatures on the coating surface that make the oxidation processes slower in the coating [39-42]. To further enhance the mechanical features of CrAlN, alloying with silicon (Si) element has been shown to be an attractive material [43, 44]. When adding Si, it leads to form a nanocomposite coating that consists of crystalline grains with an SiN_x grain boundary phase and that resulting in an improvement of the mechanical features [45, 46]. Tritremmel et al. noticed an increase in the hardness for CrAlSiN coatings by using the arc-evaporated method when the size of the grain is reduced to 15 nm while the started size was 35 nm and that happen because of the integration of Si [47]. Micro-abrasion tests represented those coatings that have low concentrations of AlSi on the surface and showed higher wear rates. This result is because of the lower values of the toughness or the critical load that induced brittle behavior [48]. Chang et al. mentioned that the multi-component TiAlSiN coating and CrAlSiN coating are appropriate for hard machining and handling with materials that are hard to machine, and they have good durability and excellent wear resistance. Also, they are characterized by good durability and excellent thermal stability. However, CrAlSiN coating exhibits better mechanical properties in term of wear resistance and a lifetime of the cutting and this leads to better performance compared to TiAlSiN coating [49] and provides excellent thermal stability [50]. Chen et al. deposited the CrAlSiN hard films on two substrates which are glass and tungsten carbide. The experiment ran at 350-degree Celsius (°C). In general, CrAlSiN hard film demonstrated good adherence with no signs of cracking or peeling off after it was deposited on both substrates [51]. Drnovška et al. used magnetron sputtering to deposit CrAlN and CrAlSiN hard coatings to analyze their mechanical properties and tribological features at high temperature. The experiment was performed at a temperature

starting from almost 27 °C, which is the room temperature (RT), up to a very high temperature (~700 °C). The CrAlSiN coating shows a higher hardness in RT compared to the CrAlN coating. The hardness decreases as the temperature increases up to 400 °C at nearly the same rate (2 GPa per 100 °C) for both coatings. With further increasing in the temperature up to 700 °C, a lower rate of decreasing of the hardness is observed in CrAlSiN coating compared to the CrAlN coating. Also, CrAlSiN coating showed a better wear resistance in HT compared to the CrAlN coating. In general, the CrAlSiN hard coating exhibited better mechanical properties and tribological features than the CrAlN coating for all the range of temperatures [52]. There is an important element that can be added to this combination, and it is promising for the coating of parts of IC engine for its good characteristics, that element is Nickel. Nickel based composite coatings such as nickel–silicon nitride, nickel–calcium fluoride, and nickel fly ash, showed higher friction resistance and better wear resistance [53].

Surfaces are critical parts of any engineering component. Mechanical components usually operate in harsh environments. Thus, the adjustment of the surface is crucial to improve the performance and the functional integrity of the engineered surface [54]. There are many attempts that have been studied the impact of the roughness of substrates on coatings, and that will be discussed next.

2.4 Effect of the substrate surface roughness on the coating properties

The last decade has witnessed a huge effort to enhance the coating by modifying the roughness of varieties of substrates such as metals, alloys, composites, etc. before the target

is deposited [54]. Zhiming Li et al. tested six samples with different substrate roughness to study the effects of the different roughness on the behavior of the coating. They deposited NiCoCrAlY on GH3128 nickel-based superalloys by using the magnetron sputtering technique. The results showed a direct relationship between the roughness of the substrate and coatings. As the roughness of the substrate decreases, the roughness of the coatings also decreases. Another result was adhesion. The experiment showed that as the roughness of the substrate decreases, the adhesion strength of the coatings increases. The decrease of internal stress in the coating at the interface is the main cause of that trend [55]. However, when Zemian et al. studied the impact of modifying substrate roughness of cold-sprayed Al coatings, they noticed that rougher the surface of the substrate is better for the coating adhesion [56]. Ali Ostadi et al. did the same by using PVD and electron beam evaporation processes to deposit ZrO_2 -8wt% Y_2O_3 on nickel-base superalloy substrates. They set three levels of the roughness of the substrate. These levels are 0.55 μm , 1.58 μm , and 3.43 μm . As a result, the coating roughness becomes 0.62 μm at the first level, 1.73 μm at the second level, and 3.71 μm at the third level. The behavior of adhesion strength in this experiment was the same as Zhiming Li. experiment. Also, increasing the roughness of the substrate caused increasing the porosity of the coating as shown in Fig. 2.8 [57]. Song-sheng LIN et al. used the vacuum cathodic arc deposition method to deposit Ti/TiN/Zr/ZrN multilayer coatings on substrates of Cr17Ni2 steel which have some surface roughness that are 1.348, 0.435, 0.326, and 0.037 μm . The results indicate that as the substrate surface roughness decreases, the adhesion force increases (Fig. 2.9) as well as the erosion resistance [58].

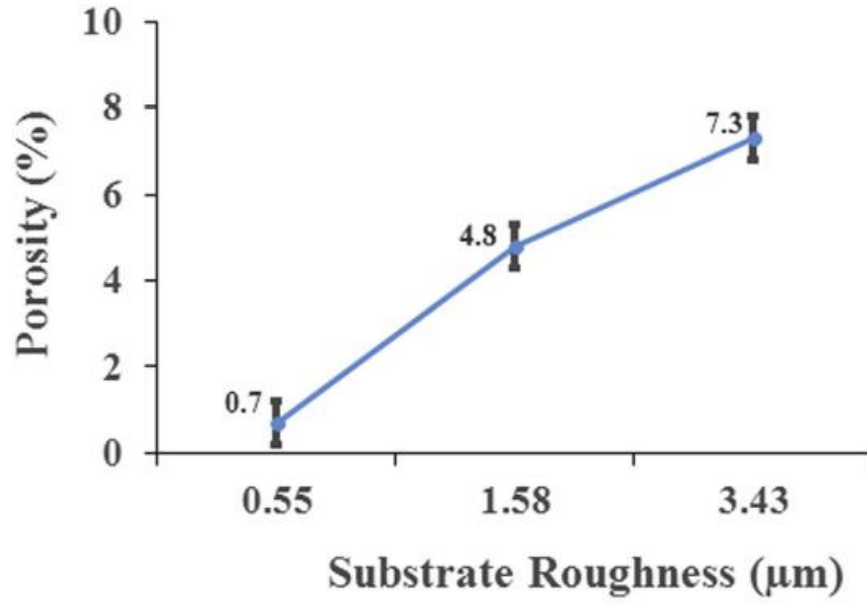


Figure 2.7: The porosity percentage of the coating in roughness's substrates of 0.55 μm , 1.58 μm and 3.43 μm [57]

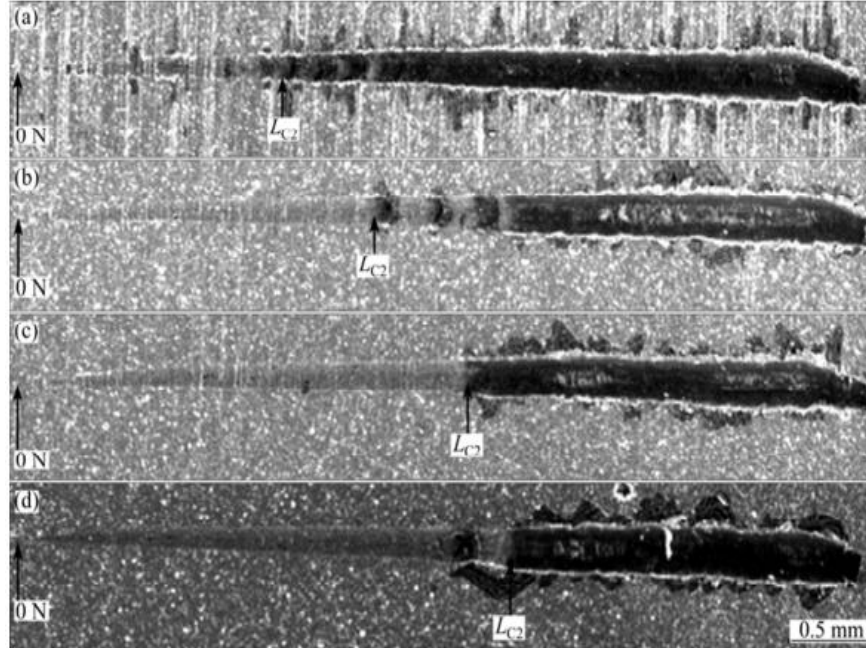


Figure 2.8: Scratch morphologies of Ti/TiN/Zr/ZrN coatings on roughness of: (a) $R_a=1.348$, (b) 0.435, (c) 0.326 and (d) 0.037 μm [58]

T.D. Atmani et al. used the reactive DC magnetron sputtering deposition method to deposit TiN/CrN multilayer coatings on XC48 steel. Two levels of surface roughness are used. The coatings on the rougher substrate surface showed increasing in adhesion strength [59]. This is due to the surface asperities of the substrate that act as mechanically interlocking spots at the interfaces of the substrate and the material coating [60]. Also, as the substrate surface roughness increases, the hardness increases [59]. The wear mechanism of coatings highly depends on the conditions of the interface between the two rubbing surfaces. At high loads, stresses within the substrate and the contact area between the coating and the substrate cause plastic fatigue deformation of the substrate. This plastic deformation initiates vertical cracks in the coating that lead to fragmentation and removal of the coating. In B.V. Padmini et al. experiment, low carbon steel was used as the substrate and NiCr-based alloy as the coating that deposited by the kinetic spray technique. Different levels of surface roughness were obtained by using four methods which are vertical face milling cutting, water jet cutting, and grit blasting using coarse alumina has a size of $\sim 550 \mu\text{m}$ (GB1) and fine alumina has a size of $\sim 100 \mu\text{m}$ (GB2). Table 2.1 shows the different levels of surface roughness for the different preparation methods that are used [54].

Table 2.1: Surface roughness for different surface

Surface roughness	Milled	GB (Fine)	GB (Coarse)	Water Jet Cut
Ra (μm)	0.68	2.33	3.58	6.61

All the coated samples showed excellent wear resistance compared to the bare sample. Amongst the four methods, the surface prepared by grit blasting exhibits the best wear resistance. There was no obvious and constant trend of the effect of the surface roughness of the substrate on the wear resistance. The roughness value that yields the best result was approximately 2.33 mm and this value is not the maximum nor the minimum. Thus, there is an optimum roughness value of the substrate to get a good outcome and obtain a coating with good quality. In term of porosity, grit blasted samples (G1 and G2) showed the minimum porosity values while the sample that has the highest roughness which was prepared by the water jet cut, exhibited the maximum porosity as demonstrated in Fig. 2.10 [54].

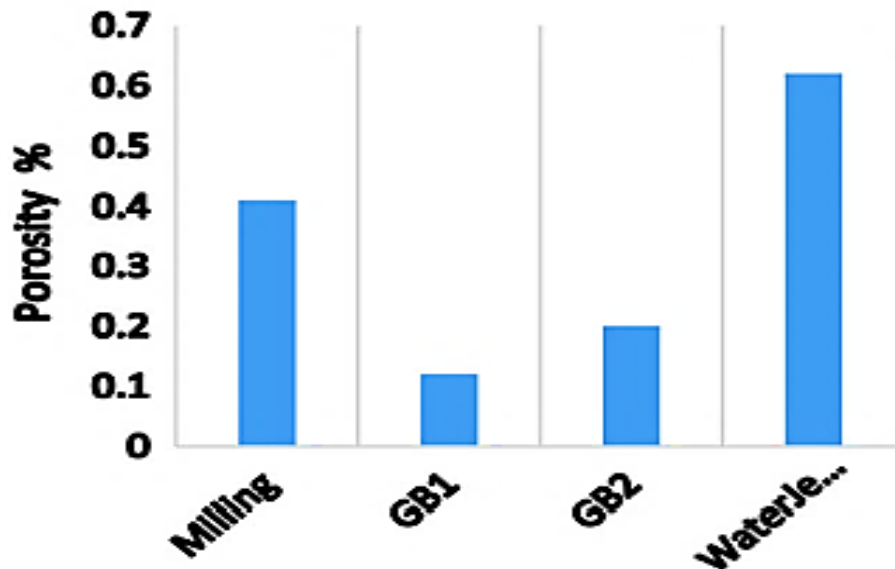


Figure 2.9: Values of porosity of coating deposited on different substrates [54]

For the impact of the substrate condition on the hardness, the hardness of the coatings in all the modified conditions was higher more than twofold than the coating of the base

material. However, the result showed that the roughness of the substrate has almost no impact on the hardness of coatings in the modified conditions. Results are exhibited in Fig. 2.11 [54]. Weiwei Xiao et al. deposited TiN coating on Zr-4 substrates by using the process of magnetron sputtering with three levels or groups of surface roughness (Table 2.2). When they decrease the substrate roughness, the finishing of the surface coating is improving as shown in Fig. 2.12 [61].

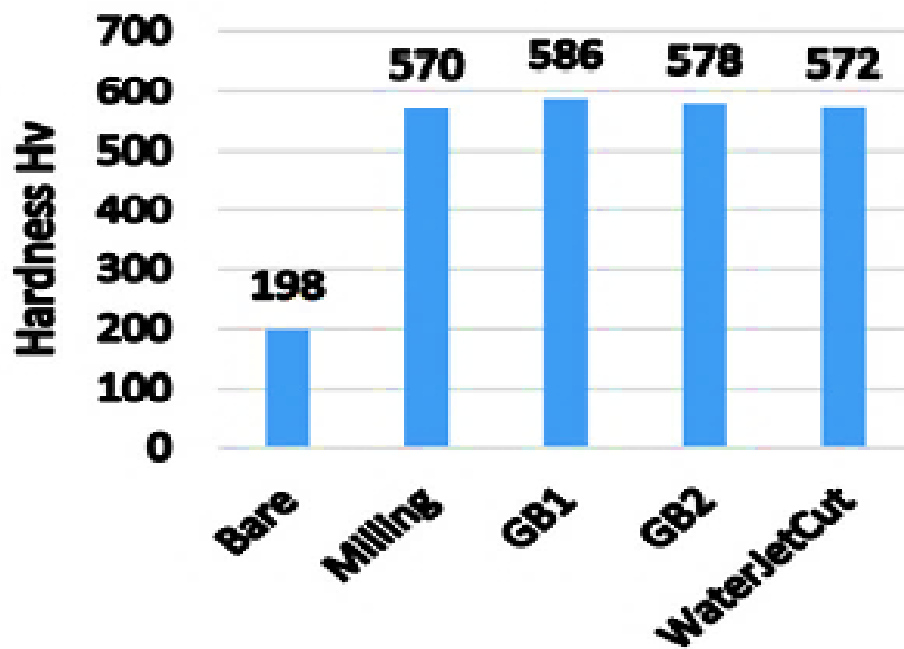


Figure 2.10: Values of hardness of coating deposited on different substrates [54]

Table 2.2: Different substrate roughness for sputtering process parameters experiment

Sets	Roughness (μm)
X1	0.08 (± 0.03)
X2	0.2 (± 0.03)
X3	0.3 (± 0.03)

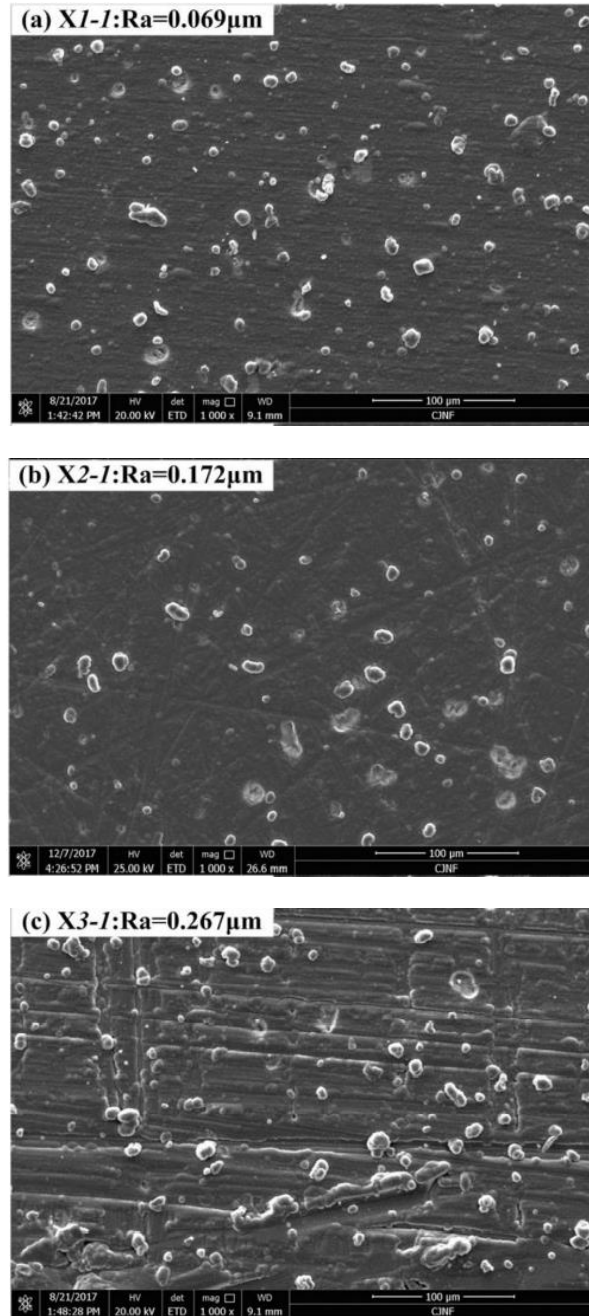


Figure 2.11: Surface micrographs of TiN coatings with three groups of substrate roughness [61]

Figure 2.13 illustrates samples of the coating with different substrate roughness and the critical load that indicate the adhesion strength. The surface roughness in the middle ($Ra=0.172$) has the highest adhesion strength, while the lowest one is the specimen that has the

highest surface roughness. However, all three samples with different substrate roughness are not differ that much [61].

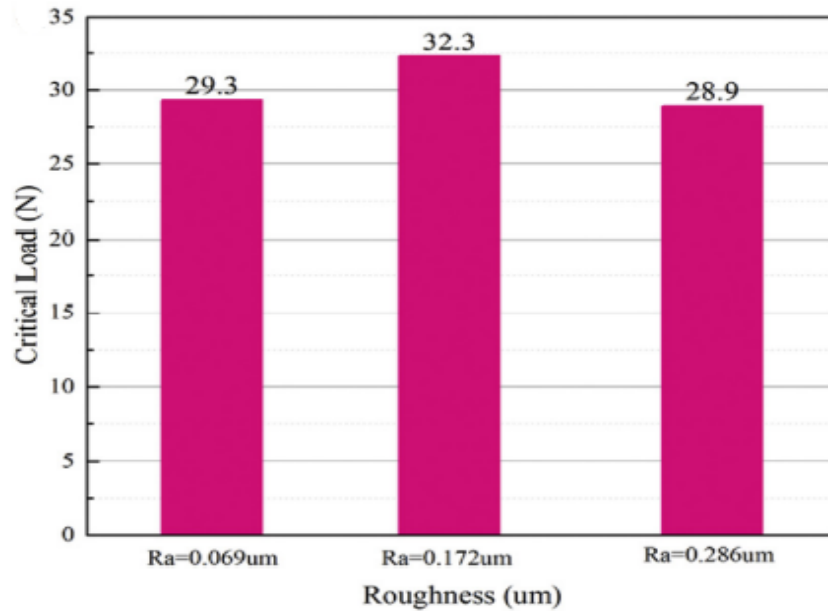


Figure 2.12: Adhesion strength of deposited TiN coatings with the three levels of substrate roughness [61]

Cold-spray coating technique is used by C.W. Ziemian et al. to deposit pure (CP) aluminum feedstock powder on substrate made of Al2024-T351. Substrate samples were prepared before the coating by shot peening and grit blasting. In shot peening, hard steel balls that have a diameter of 2.0 mm were shot for 5 seconds by using an ultrasonic shot peening process. For the grit blasting, glass bead grit (G3) that has a particle size of 700 um in diameter and an angle of 45 was used for preparing the substrate samples. Figure 2.14 illustrates the schematic of the grit blast operation. The grit bead blast produced a higher value for the substrate roughness. Adhesion strength for the coating was better in the case of the glass bead blast preparation. A bend fatigue test was used to record the number of

cycles to failure. The results showed that the preparation with glass bead blast increased the cycles to failure, which means increasing the bend fatigue life [62].

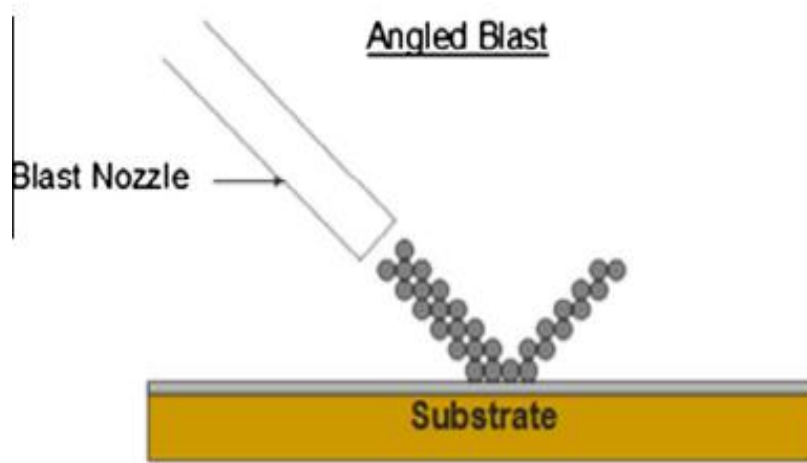


Figure 2.13: Schematic of grit blast operation [62]

Some machines and tools must be used to get information about the characteristics of the material and the mechanical properties of the coating. The next section will mention the most important tools that are used for such an objective.

2.5 Characterization and tests to evaluate the coating properties

2.5.1 Characterization

For coatings characterization, many analyses could be used. X-ray diffraction (XRD) is an important characterization used nowadays for a broad range of materials such as the material that has single crystal or polycrystalline mixtures of powders and even the material with randomly oriented amorphous. XRD can determine many parameters such as crystalline phase identification, crystallite size and strain, percent (%) crystallinity, and

molecular structure. Thus, XRD is widely utilized especially in chemistry and material science. XRD becomes an extremely important tool that pushes the ability of researchers in the field of material engineering to investigate and analyze materials on the atomic level [63].

Scanning electron microscope (SEM) is another characterization for investigating the coating properties. With this type of microscopy, researchers can visualize the topography and morphology in cross-sectional view or in planar surface view of the specimen and to investigate the depth of structures [64].

Atomic force microscopy (AFM) is a type of surface profiler that gives an image to the fraction of a nanometer of the sample surface. The AFM collects images of a sample surface by moving the probe over the surface from left to right. The data that is collected from the AFM is a high-resolution image of the sample surface. AFM studies the surface microstructure and the grain size and distribution of the thin layers or films [65]. It also studies the morphological information such as roughness and mean heights of the structures [66]. AFM can give quantitative information about the structures of the surface [67].

Energy dispersive X-ray (EDX) is an analytical technique that can provide information about chemical and elemental composition of the specimen. EDX is usually used with SEM to provide elemental analysis on small areas with several nanometers [68, 69].

2.5.2 Tests

Different tests are performed to investigate the mechanical properties of the coating.

Dry-sliding wear test is an important test to investigate the coefficient of friction of the coatings. This test is performed by using a high-frequency linear oscillation under dry-sliding conditions (Fig. 2.15) [37]. This machine is recording the kinetic frictional force during the test. The kinetic coefficient of friction (COF) value can be calculated by using this recorded value [37].

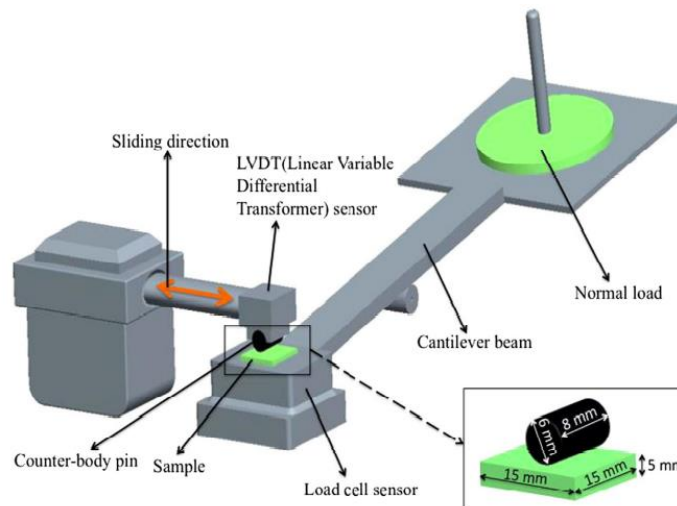


Figure 2.14: The 3D scheme of dry-sliding wear test [37]

Micro-scale abrasive wear test is an important test to evaluate the wear rate of the coating. In this test, there is a hard martensitic steel ball that rotates against the sample with an abrasive particle in the contact surfaces of the ball and the sample. Figure 2.16 represents the free-ball micro-abrasive wear test [70]. The abrasive particle used in the interface is leading to a good understanding of the characteristics of the coatings. The average diameter

of this article is usually 6 mm. From this test, the wear rate can be calculated from some simple mathematical models [48].

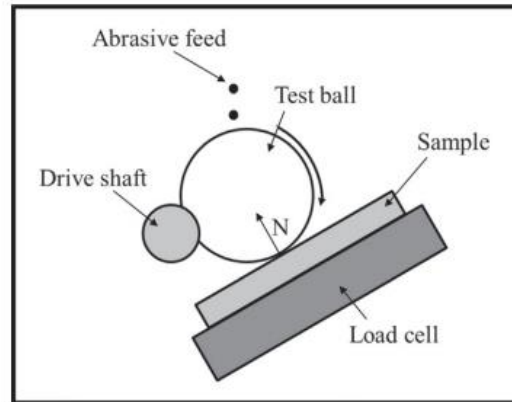


Figure 2.15: Schematic representation of the micro abrasive wear test [70]

Scratch testing is usually performed to evaluate the adhesion resistance of the coatings. After the process of scratching, a metallographic microscope is observing the surface morphology of the tested specimen. The scratch can be spilled into three regions, the first region is the beginning contact zone. The second region that starts directly after the first region is a progressive failure zone. The final region is a complete failure zone, and all these regions are shown in Fig. 2.17. The friction force increases nearly in a linear fashion with increasing the normal load. In the beginning contact zone, the scratch is shallower and there is no acoustic signal at that region. In the second region, the scratch is deeper with also no acoustic signal while there is a sudden decrease of friction force. In the complete failure zone, which is the last region, the coating is completely removed, and the substrate is directly exposed to the atmosphere of the external environment. At this point, there is a sudden drop of friction force, and an acoustic signal is observed. The normal load at this point is the critical load that is considered as the adhesion strength as well [61].

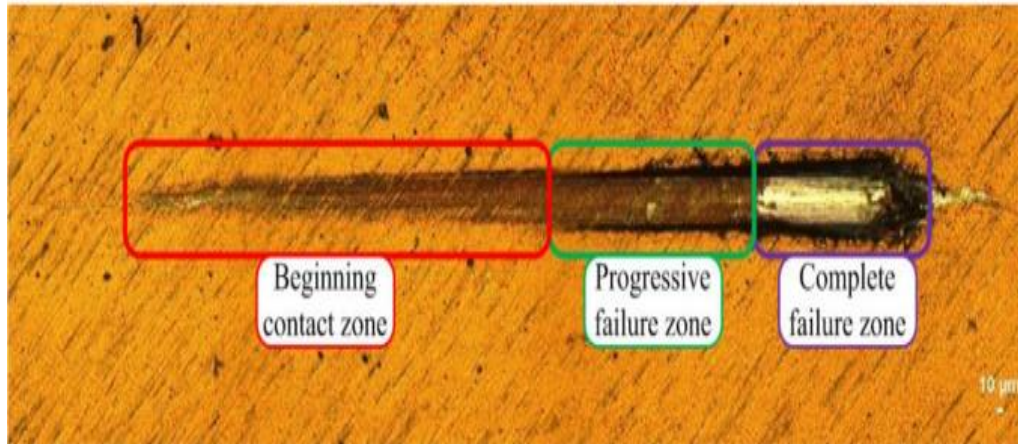


Figure 2.16: Metallographic microscopy of scratches [61]

Hardness test is usually used to define the capability of the material to sustain deformation if load is applied [71]. One of the most famous and universal hard tests is the Rockwell hardness test which uses some scales to determine the hardness. Rockwell hardness can measure various samples from soft materials, such as plastic, to superalloy. The application of Rockwell hardness test is shown in Table 2.3 [72].

Table 2.3: Some applications of Rockwell hardness test [72]

Scale	Indenter	Minor Load (kgf)	Major Load (kgf)	Typical Applications
C	Diamond cone with vertex angle 120° and vertex radius of curvature 0.2 mm	10	150	Hard materials with hardness between B100 and C70
D			100	Materials requiring loads slightly lighter than the C scale loads. (Shallow to medium case hardened steel)
A			60	Superalloys, thin steel and shallow case hardened steel
G	1/16" diameter steel ball	10	150	Materials harder than tested on the B scale
B			100	Steels with hardness between B0 and B100 when annealed.
F			60	Bearing metals, annealed brass, copper, and thin sheet metals
K	1/8" diameter steel ball	10	150	Very soft materials (bearing metals and extremely thin materials)
E			100	
H			60	
P	1/4" diameter steel ball	10	150	Very soft materials (plastic, lead, and extremely thin materials)
M			100	
L			60	
V	1/2" diameter steel ball	10	150	Very soft materials (plastic, lead, and extremely thin materials)
S			100	
R			60	

2.6 Problem statement and motivation

The high rate of wear and friction is the main and critical challenge in IC engines which is an extremely important part of the automotive industry. These challenges lower engine performance and increase the consumption of fossil fuel which causes critical environmental problems around the world. Thus, the increasing trend of using vehicles in recent year in automobiles and the increasing of issues that causes as result, force the automotive industry to tackle the problem and improve the performance of vehicles by increasing the wear resistance and friction resistance.

CA-PVD method is the best option because it provides greater adhesion characteristics and denser layer and it is more stable for refractory metals such as Ti, Cr, and Zr compared to other methods. Also, it is good to synthesize highly hard coatings such as TiN, CrN, TiAlN, AlCrTiN, TiAlSiN for wear resistance.

From the literature review above, the CrAlSiN hard coating exhibited excellent mechanical properties and tribological features. There is an element that can be added for the coating of parts of IC engines because of its good characteristic which is Nickel. Nickel-based composite coatings showed higher friction resistance and better wear resistance. Thus, CrNiAlSiN coating is a promising coating for IC engines.

2.7 Objectives

In this research work, three objectives are targeted:

- 1- Develop hard PVD coating of CrNiAlSiN on cast iron substrate prepared at different surface conditions for internal combustion engine application.
- 2- Investigate the effect of substrate surface conditions on the coating for higher wear-resistant coating.
- 3- Investigate the mechanical and tribological properties of the coating.

CHAPTER 3

METHODOLOGIES

Part one of the experimental procedure is using a cathodic arc evaporation system for applying CrNiAlSiN coatings. The second part is talking about the procedures for the characterization and analysis of the coating. The characterization techniques used for this work are X-ray diffraction (XRD) for crystallographic structure, micro indentation for microhardness, and scanning electron microscopy (SEM) for morphology.

3.1 Coating Process

3.1.1 CA-PVD Equipment

The coating for this work was deposited using a cathodic arc deposition system in the Advanced Coating Laboratory at the Center of Research Excellence in Corrosion, King Fahd University of Petroleum and Minerals, Saudi Arabia. The manufacturer of this system is Sulzer Metaplas located in Germany. The internal schematic drawing for the machine that will be used is shown in Fig. 3.1. Figure 3.2 shows CA-PVD equipment that was used in this work.

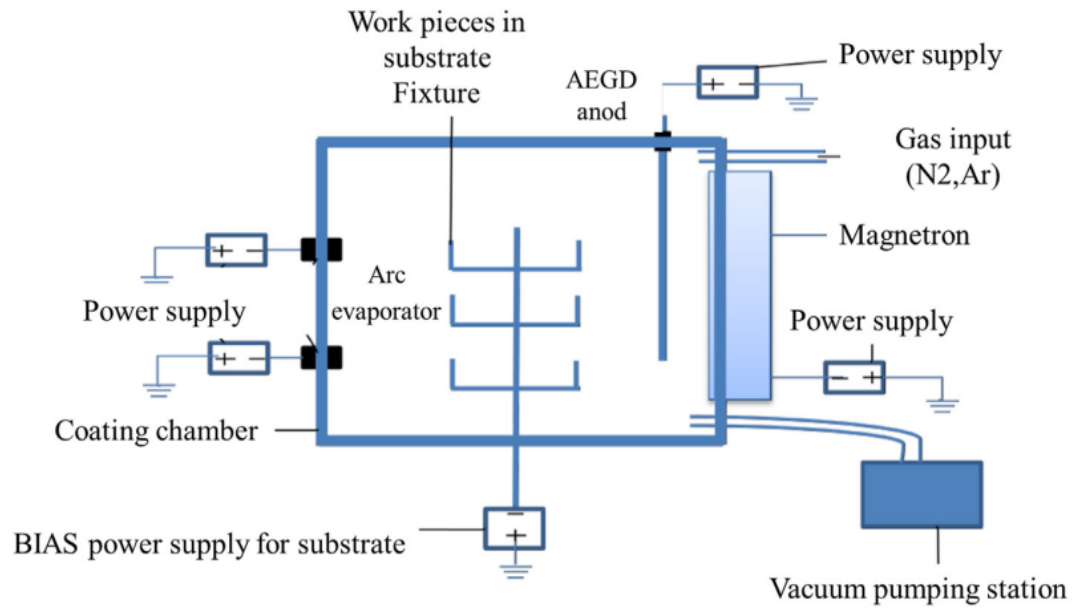


Figure 3.1: Schematic of used cathodic arc-physical vapor deposition [73]



Figure 3.2: The image of the cathodic arc evaporation equipment

3.1.2 Material and sample preparation

The substrate material investigated during this work is cast iron. A plate of cast iron was cut into pieces or samples with a width of 30 mm and length of 30 mm each. A hole with a diameter of 4 mm was made in the upper left corner of all samples. The Cast iron has a percentage composition of 0.40–0.70% Mn, 1.85–2.10% Si, 3.00– 3.25% C. To attain different substrate surface roughness, sandpaper (SP) is used with different grits. In the beginning, samples were polished with a 0.5 μm Al_2O_3 solution and then, they were grouped into five sets. The first set contains four samples lifted as received with no changes. The second, third, fourth, and fifth sets were grounded using SiC with different grit sizes which are 60-grit, 240-grit, 480-grit, and 800-grit sandpaper. Then the samples were cleaned with ethanol and dried with N_2 followed by ethanol in the ultrasonic bath to remove any contamination from the surface. Then, they dried with N_2 and loaded into the cathodic arc chamber as shown in Fig. 3.3.



Figure 3.3: The loaded samples inside the chamber of the cathodic arc evaporation

3.2 Cathodic Arc Deposition Procedure

All samples were loaded into the deposition chamber using the planetary lift car which is shown in Fig. 3.4. After that, the chamber is evacuated to a pressure of 4×10^{-5} mbar. The heater inside the chamber was set to 500o C and the planetary rotated at 2rpm clockwise direction. The loaded samples were heated for one hour. Before the operation of deposition starts, oxide layers must be separated from the surfaces of the coupons to prevent any adherence with the surface after polishing. Arc-enhanced glow discharge (AEGD) method was used to do this etching process. In (AEGD) method, argon gas was inserted into the chamber with a pressure of 1 Pa which is equivalent to 1×10^{-2} mbar. As a result, almost 400 nm oxide layers were removed. After the AEGD etching, coating deposition started with the bond layer. The bond layer is a thin metallic layer deposited on the substrate in a limited nitrogen pressure to enhance the adhesion of the coating to the substrate. During the process of bond layer deposition, the charge on the evaporator was set to a value of 20-ampere hours (Ah) and a nitrogen pressure of 8.5×10^{-2} mbar. The evaporators were supplied with a current of 130 A. The evaporator charge (ampere-hours) was increased to 200 Ah at a nitrogen pressure of 6.5×10^{-2} mbar. The parameters of the complete deposition are shown in Table 3.1. The chemical composition of the coating material of CrNiAlSi (in wt%) is 91 Cr, 3 Al, 3 Si, and 3 Ni. Finally, the cooling down of the substrate and the chamber takes place for one hour.



Figure 3.4: Samples loaded in the planetary lift car

Table 3.1: Deposition parameters for the coating

Parameters	
IR Heater (°C)	500
Evaporator (wt%)	91 Cr, 3 Al, 3 Si, and 3 Ni
Evaporator Current (A)	150
Substrate bias (V)	-80
Duration (min)	60

3.3 Characterization and tests

In this section, some characterization techniques were applied to evaluate the quality and performance of the coating.

For microstructure examination, the coated samples were cut using an abrasive grinding cutting machine. The samples cross sections were polished using 150 to 4000-grit SiC paper under a running stream of water, then polished to a mirror-like surface using cloth disc and alumina particles that are suspended in ethanol. Finally, the sample cross sections were cleaned using deionized water followed by ethanol in the ultrasonic bath to ensure particles and dirt-free surface. The polished surfaces were etched using Linsenätzmittel solution for 30 seconds.

The phase analysis of the coatings was studied by using XRD with a current of 30 mA and voltage of 40 kV. All samples were scanned from 20° and 90° at a scanning rate of 1.2° for each minute.

The morphologies of the surfaces for both the top surface and cross sections of the coating were characterized by (SEM) (FEI Quanta 250). An electron microscope bombards the sample surface with a focused beam of electrons that interact with the sample structure and topography and then scattered away from the sample surface. These electrons are called back-scattered electrons (BS). The incident electron beam also produces X-ray emissions which have characteristic wavelengths dependent on the elemental composition of the coated sample. These X-ray emissions were used in energy dispersive spectroscopy (EDS) to provide information about the elemental composition. AFM (Agilent 5500) was used to

characterize the surface roughness and topography of all samples of the substrate before and after surface treatment and the coated and uncoated.

Scratch resistance was performed with an indenter which has a tip radius of 100 μm . The speed of the scratch will be 5 mm/min. The load was set to increase in a linear fashion until the failure happened to the coating. The failure was detected by using an acoustic emission sensor along with an optical microscope.

In order to determine the hardness of the coated and uncoated specimens, CSM Micro Combi Tester (CSM, Switzerland) fitted with a diamond tip Vickers indenter V-H 86 was utilized. The load that is applied is 200 mN for a short period of 10 seconds. The Vickers indenter was plastically deforming the sample using a four-sided square-based diamond pyramid tip. Hardness Vickers (HV) is calculated from the equation below.

$$HV = \frac{F_{max}}{A_p}$$

Whereas A_p is the projected contact area and F_{max} is the maximum test force. Figure 3.5 shows a schematic representation of indenter - sample contact.

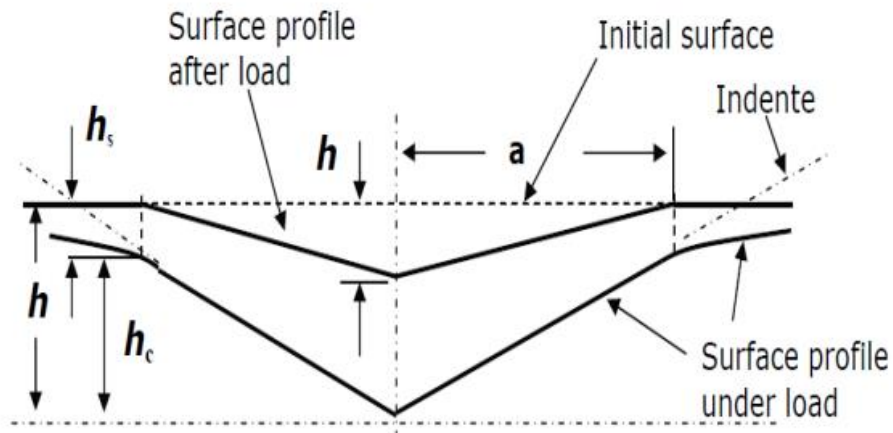


Figure 3.5: Schematic representation of indenter - sample contact [74]

Wear tests were conducted using a tribometer (UMT-3, Bellerica, MA, USA) that uses Ball-on-disk technique to determine the friction and wear characteristics of the composites. The counterface used was a 440C stainless steel ball. Wear tests were conducted at a normal load of 15 N and the bath was circular with a diameter of 2mm for 5000 cycles corresponding to a sliding distance of almost 31.4 m. The track of wear was pictured using an optical profilometer (GTK-A, Bruker, Bellerica, MA, USA).

The wear rate was calculated by the following formula:

$$\text{Wear rate} = \text{Wear volume} / (\text{Load} \times \text{Sliding distance})$$

Where: Wear volume = Wear track area * Stroke length

CHAPTER 4

RESULTS, ANALYSIS, AND DISCUSSION

4.1 Microstructural Characterization

4.1.1 Morphology Analysis

Morphology The qualitative information on the morphologies of the coating is provided by SEM. Whereas the quantity of the coating's elemental composition is illustrated by Energy Dispersive Spectroscopy (EDS). The morphology of the polished coating sample is shown in Fig. 4.1. Cross sections of all coated samples with a magnification of 700x and 1500x are illustrated in Fig. 4.2 - 4.6.

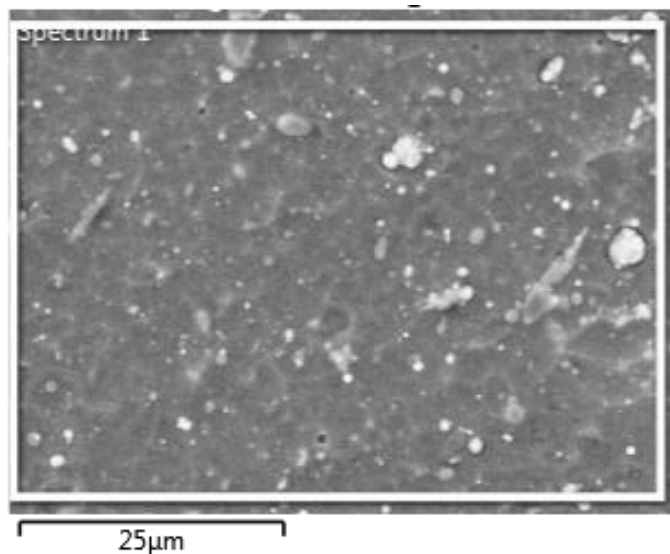


Figure 4.1: SEM micrographs showing the morphologies of CrNiAlSiN

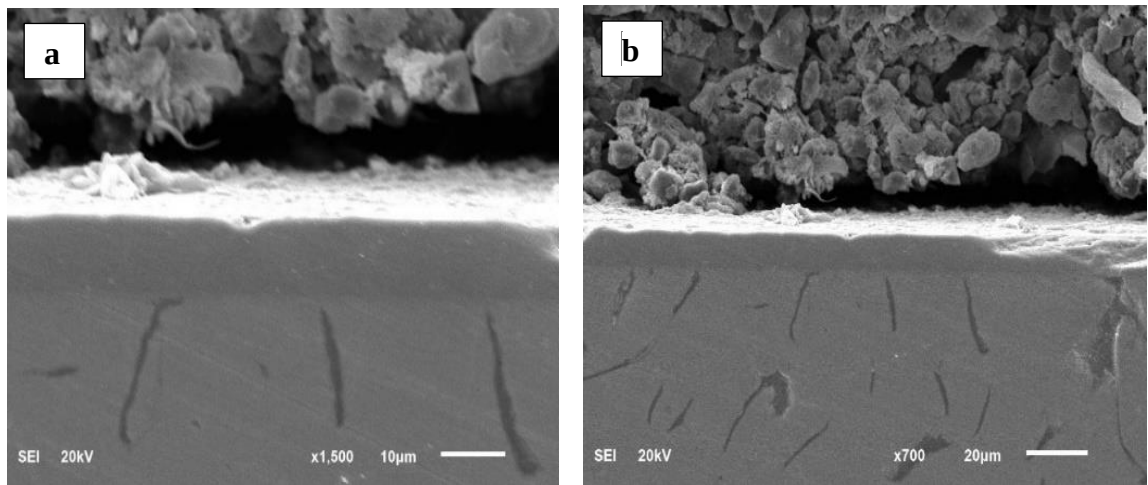


Figure 17.2: CrNiAlSiN coating on polished substrate with a magnification of: a) 1500x and b) 700x

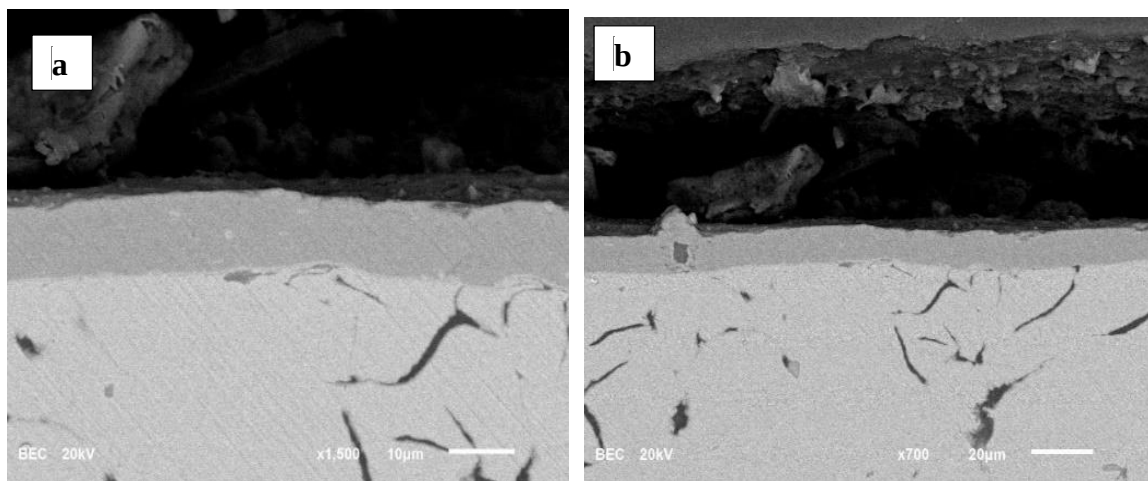


Figure 4.3: CrNiAlSiN coating on substrate that exposed to sandpaper with a size of 60 grit with a magnification of: a) 1500x and b) 700x

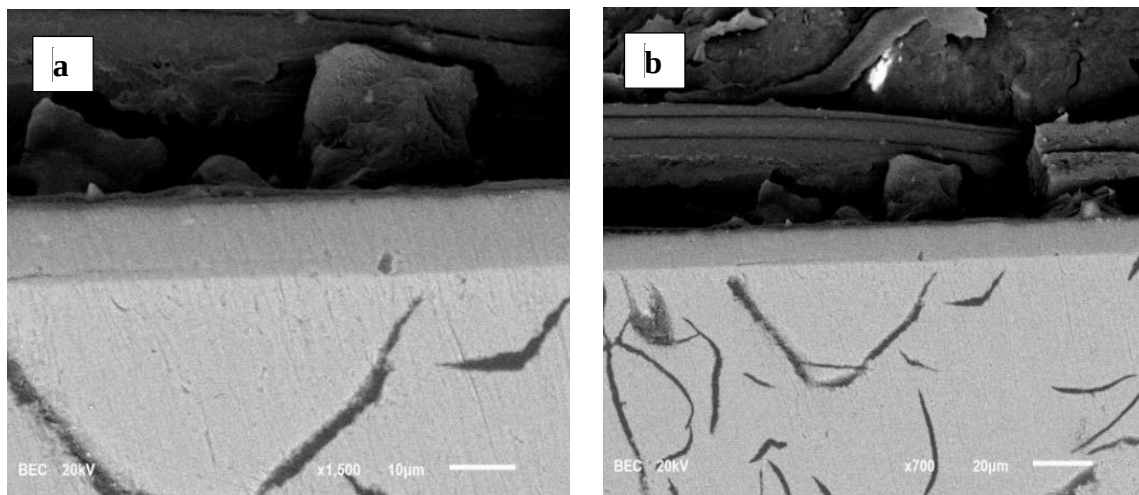


Figure 4.4: CrNiAlSiN coating on substrate that exposed to sandpaper with a size of 240 grit with a magnification of: a) 1500x and b) 700x

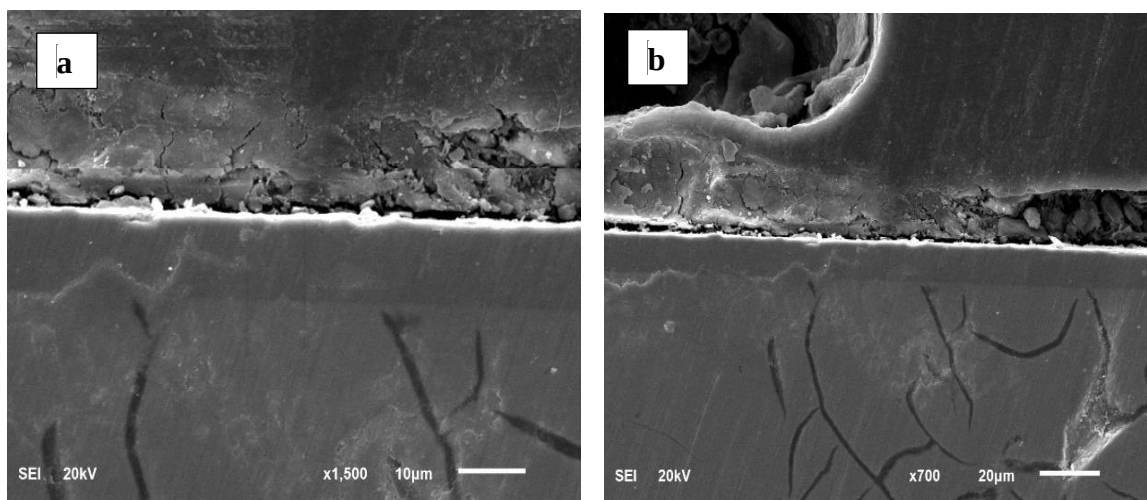


Figure 4.5: CrNiAlSiN coating on substrate that exposed to sandpaper with a size of 400 grit with a magnification of: a) 1500x and b) 700x

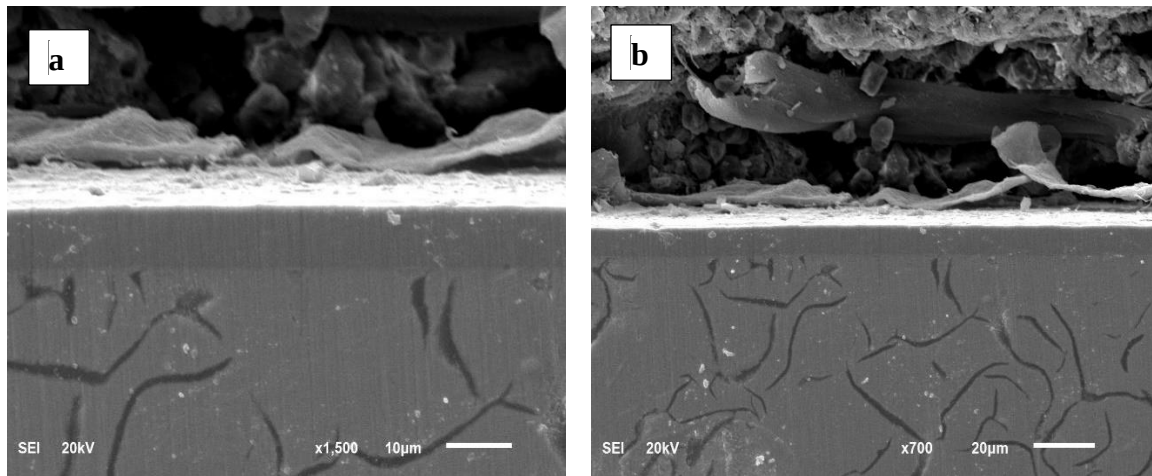


Figure 4.6: CrNiAlSiN coating on substrate that exposed to sandpaper with a size of 800 grit with a magnification of: a) 1500x and b) 700x

EDX cross-sectional line scanning technique or line mapping was used to detect the chemical composition and the distribution of Chromium and Iron in the cross-section of the thin film coating. Figures 4.7 – 4.11 are the EDX lines scanning spectrums of Chromium and Iron in the cross-sections of the coatings for the polished sample, 60 grit-size, 240 grit-size, 400 grit-size, and 800 grit-size respectively.

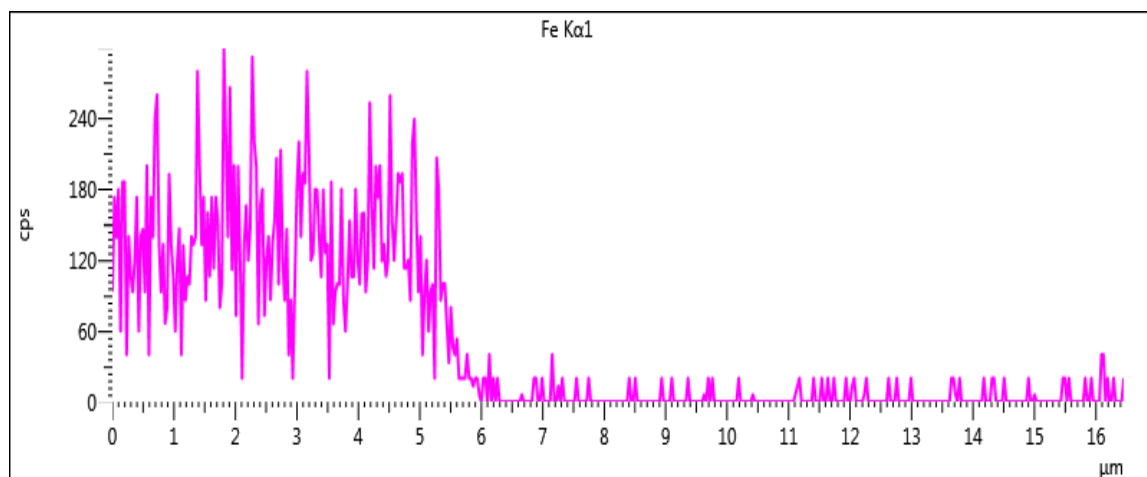
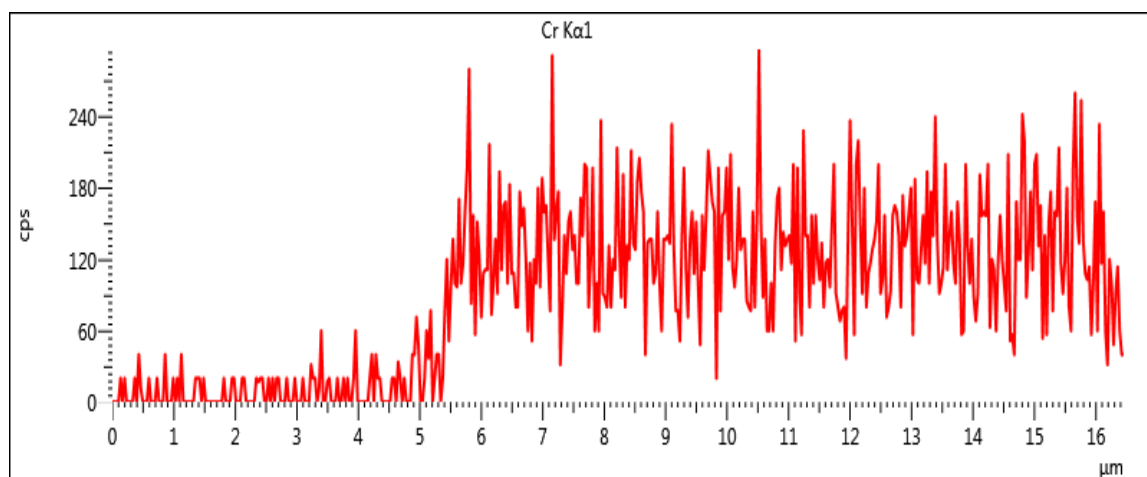
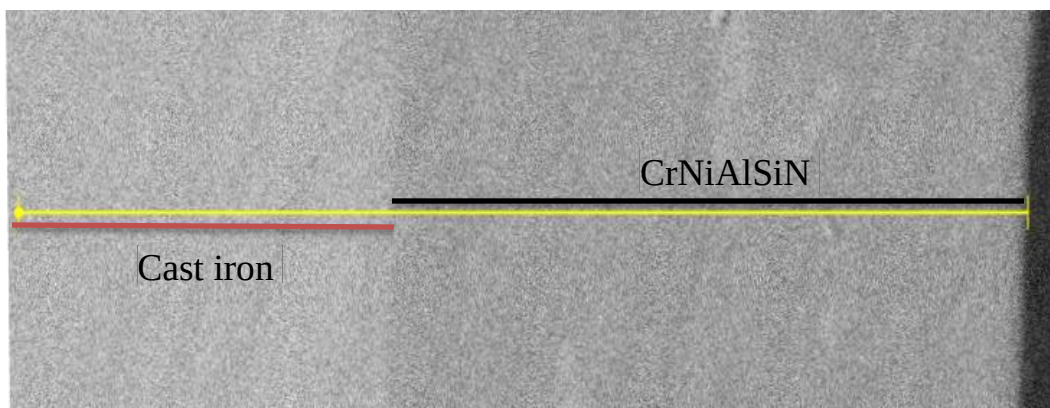


Figure 4.7: EDX line scanning spectra of Chromium and Iron in the cross-section of the coating for the polished sample

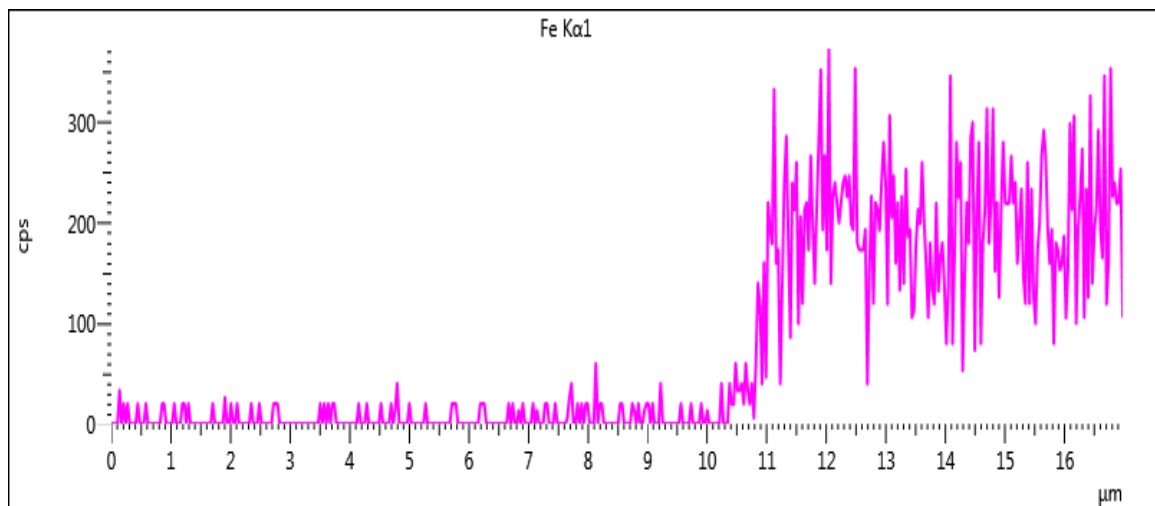
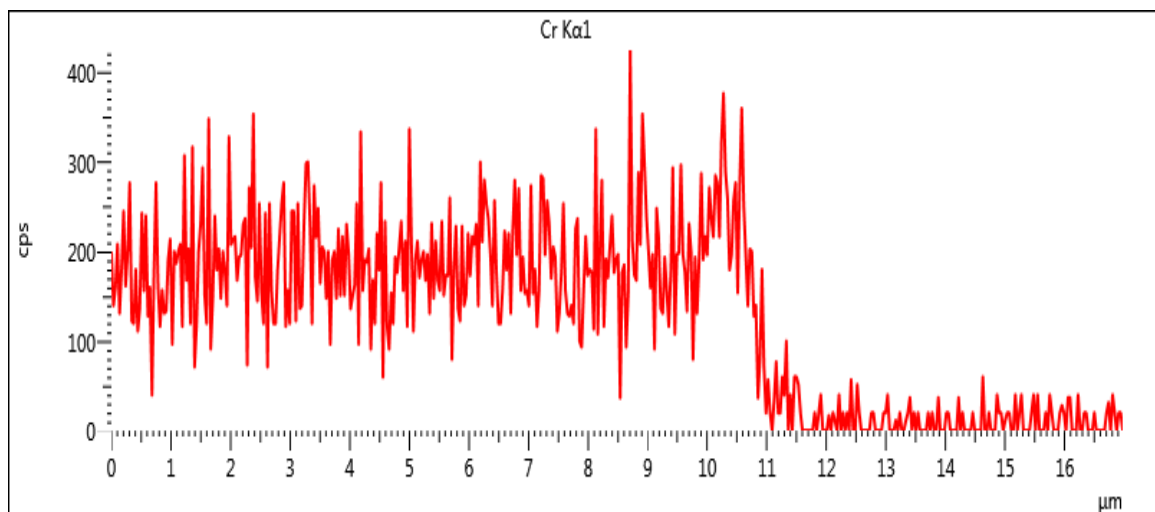
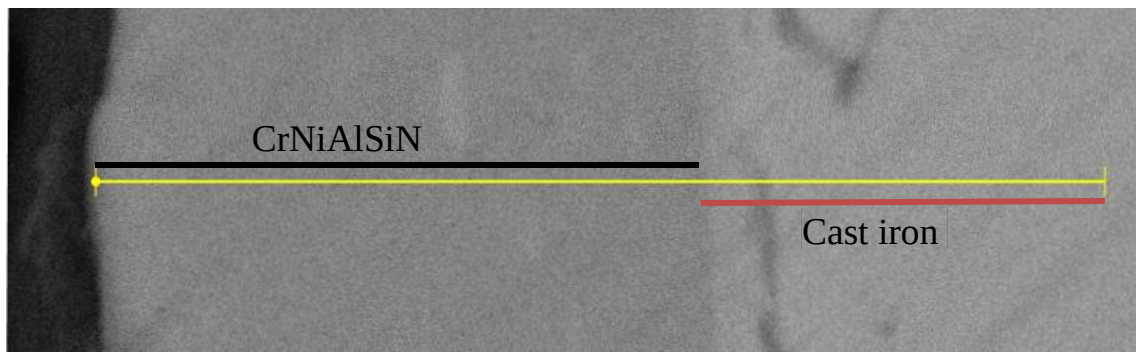


Figure 4.8: EDX line scanning spectrums of Chromium and Iron in the cross-section of the coating for the 60 grit-size sample

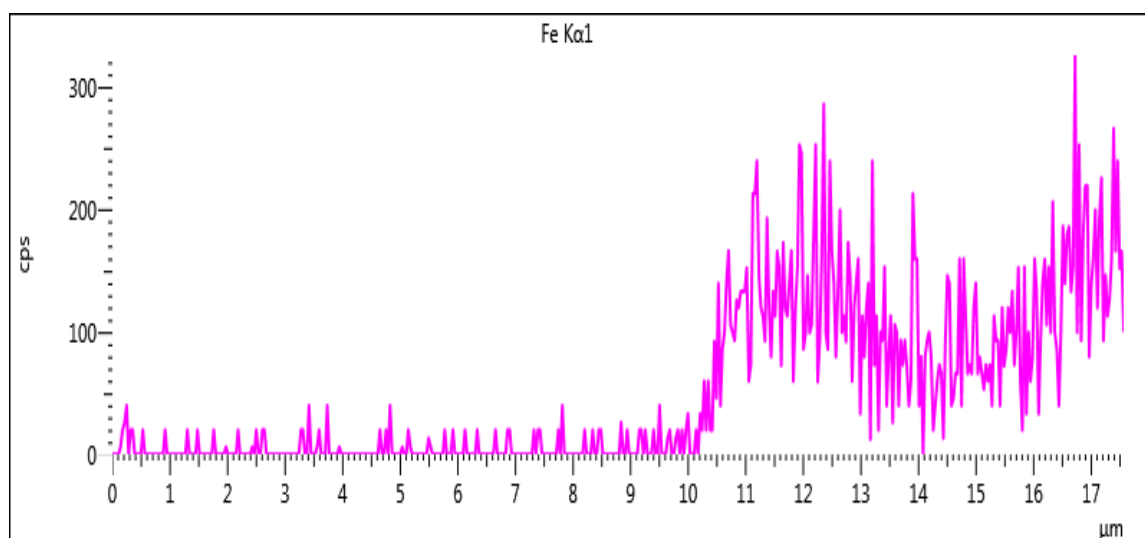
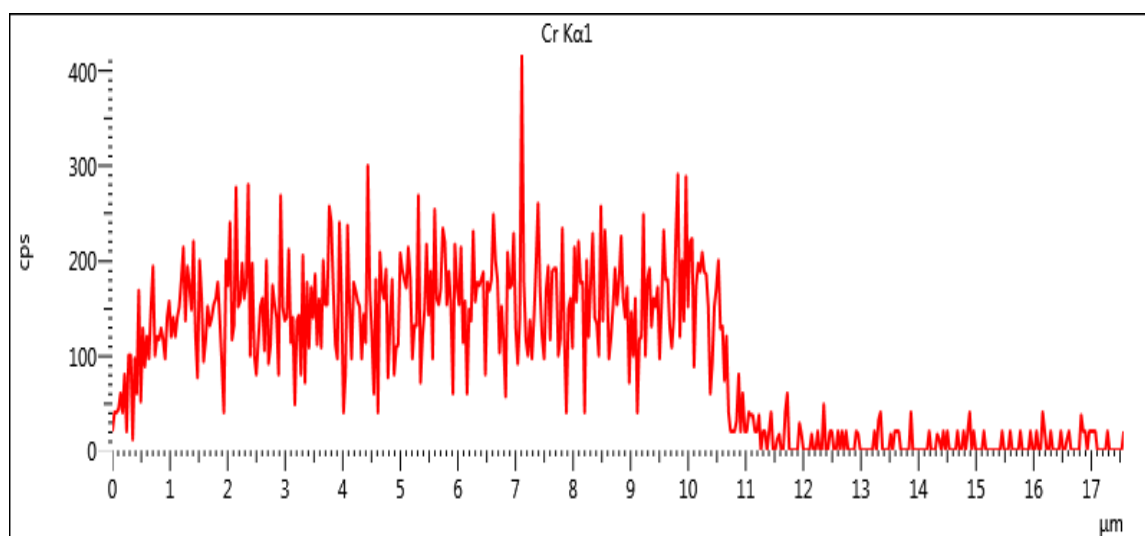
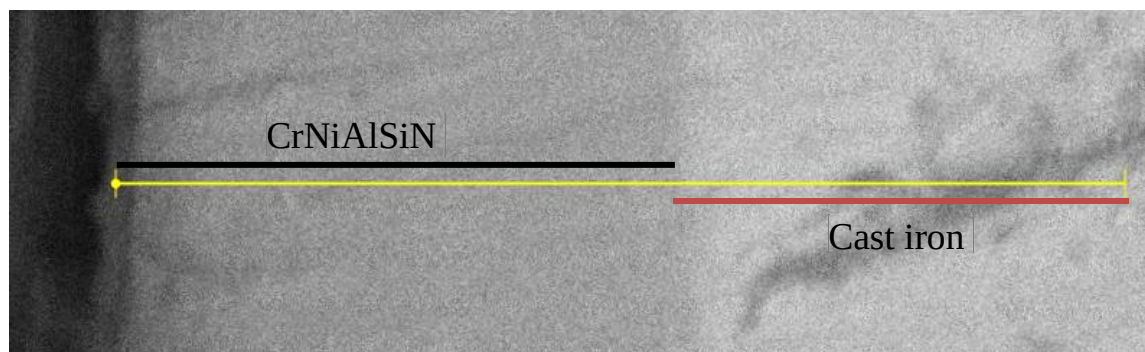


Figure 4.9: EDX line scanning spectrums of Chromium and Iron in the cross-section of the coating for the 240 grit-size sample

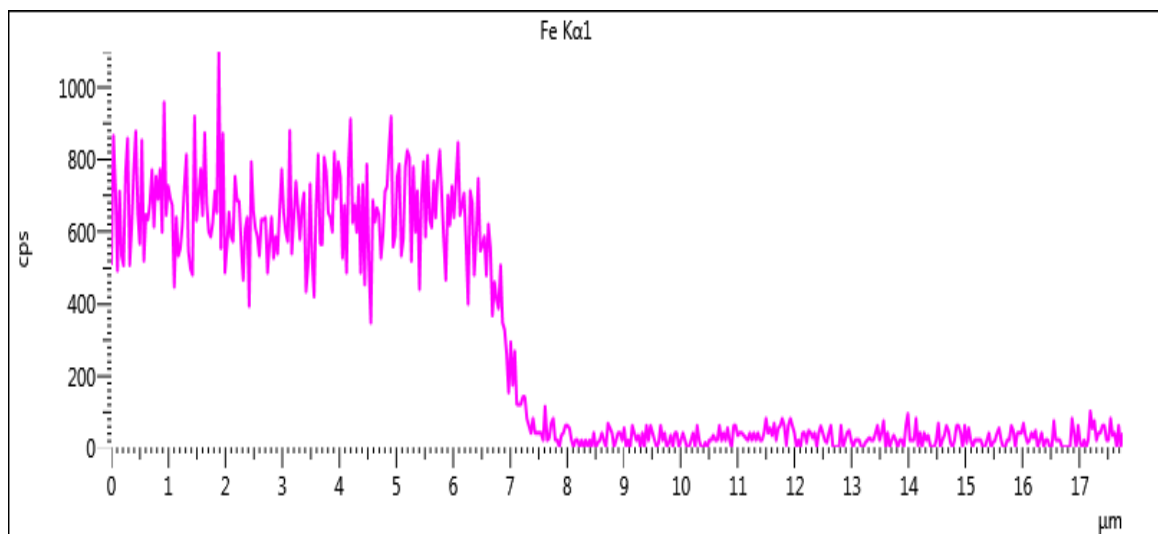
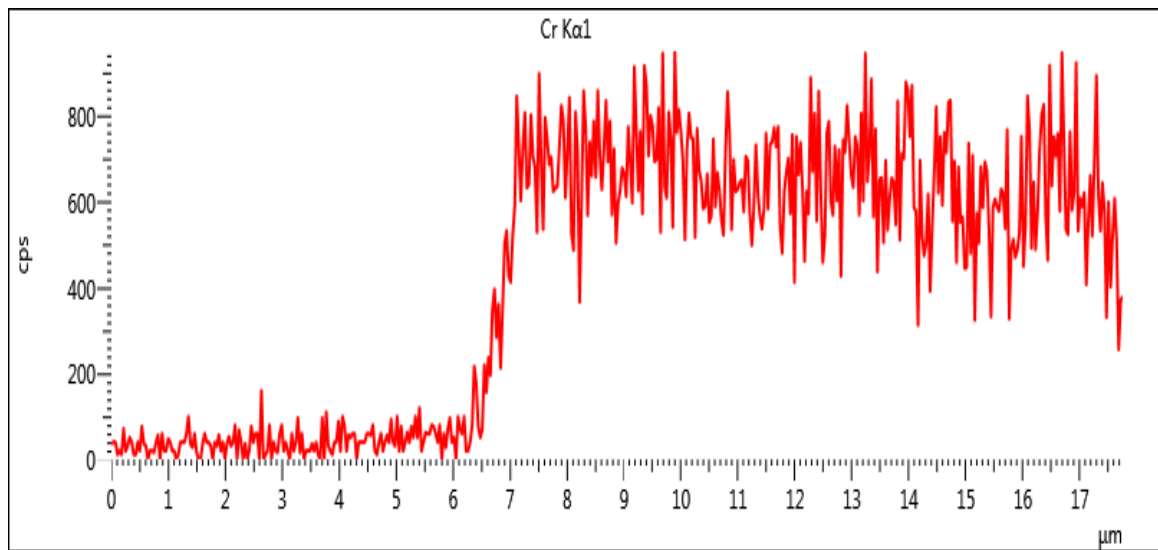
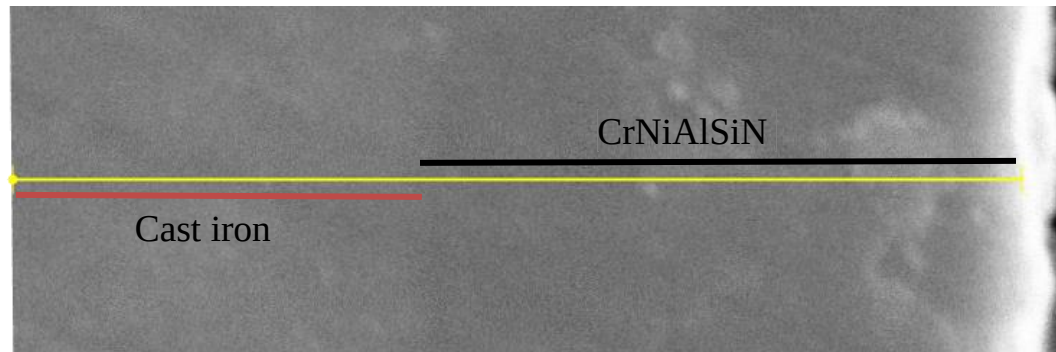


Figure 4.10: EDX line scanning spectrums of Chromium and Iron in the cross-section of the coating for the 400 grit-size sample

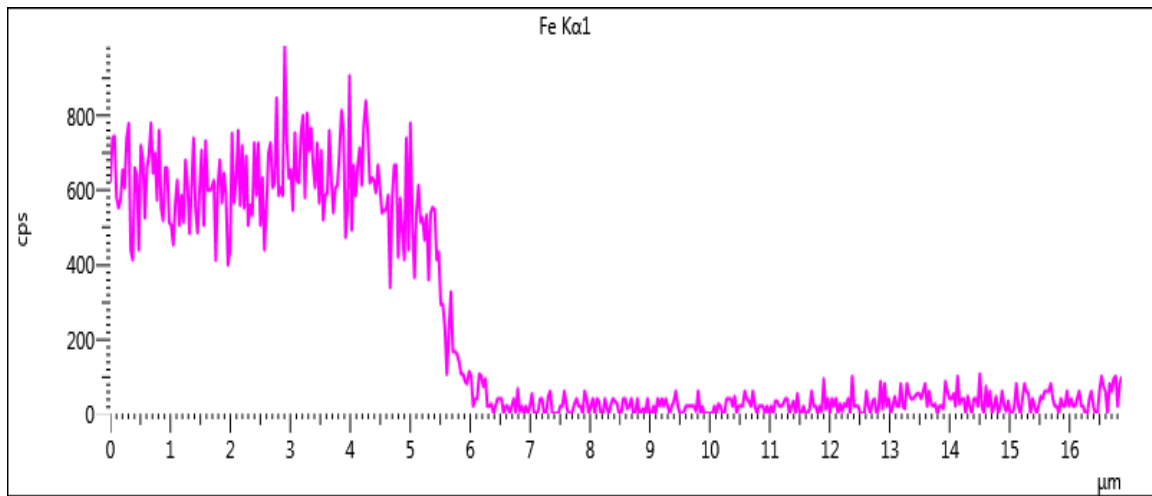
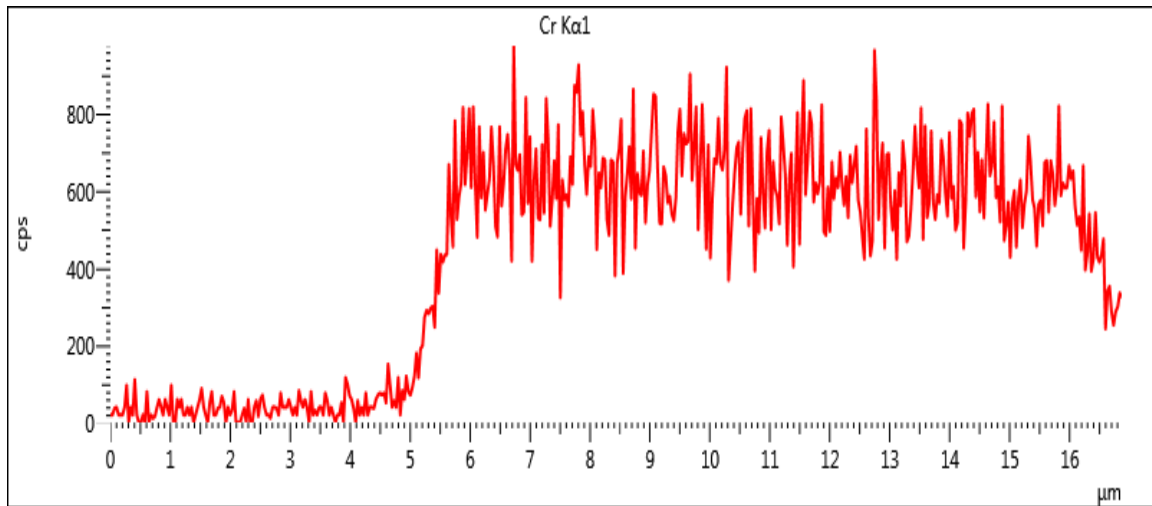
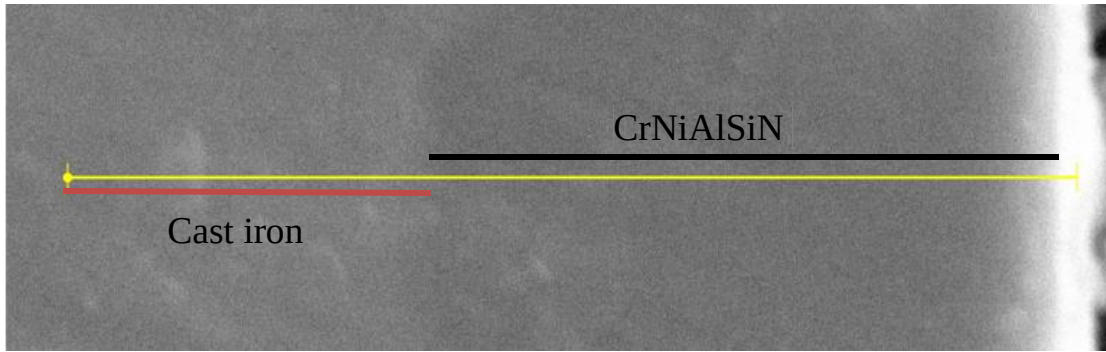


Figure 4.11: EDX line scanning spectrums of Chromium and Iron in the cross-section of the coating for the 800 grit-size sample

SEM micrographs of the polished coated surface are shown in Fig. 4.1. The mean residence time of the cathodic arc spot is very instrumental in macroparticle emission. Low resident meantime of the cathodic spot owing to the higher arc spot velocity causes individual evaporation events on the target surface to have insufficient time for any significant localized heating of the material to be melted and thus emitted in the form of macro droplets. This is consistent with an observed pattern in the performance of the arc source. Cross-section images (Figs. 4.2 – 4.6) showed that the coating is compact and homogeneous with a laminar structure. This was a result of the dense nucleation of depositing materials. Also, those Figs. illustrate that the layers of the coatings were bonded with the substrate closely without delamination and porosity either within the coatings or at the substrate-coating contact area.

Figures 4.7 – 4.11 show the diffusion rate of the Chromium, which is the base of the coating, and Iron in the substrate for all samples. It demonstrates a pretty good diffusion between the coating and the substrate. Also, from Figs. 4.7 – 4.11, the average thickness of the layer of the coating is almost 9 μm .

4.1.2 Elemental Composition (EDS analysis)

EDS was used to examine the elemental composition of the coating. The elemental compositions are shown in Fig. 4.12 and Table 4.1. The distribution of all materials on the surface of the coated sample is shown in Fig. 4.13. Whereas Fig. 4.14 demonstrates the distribution of each element, Cr, N, Si, Al and Ni on the surface of the coated sample.

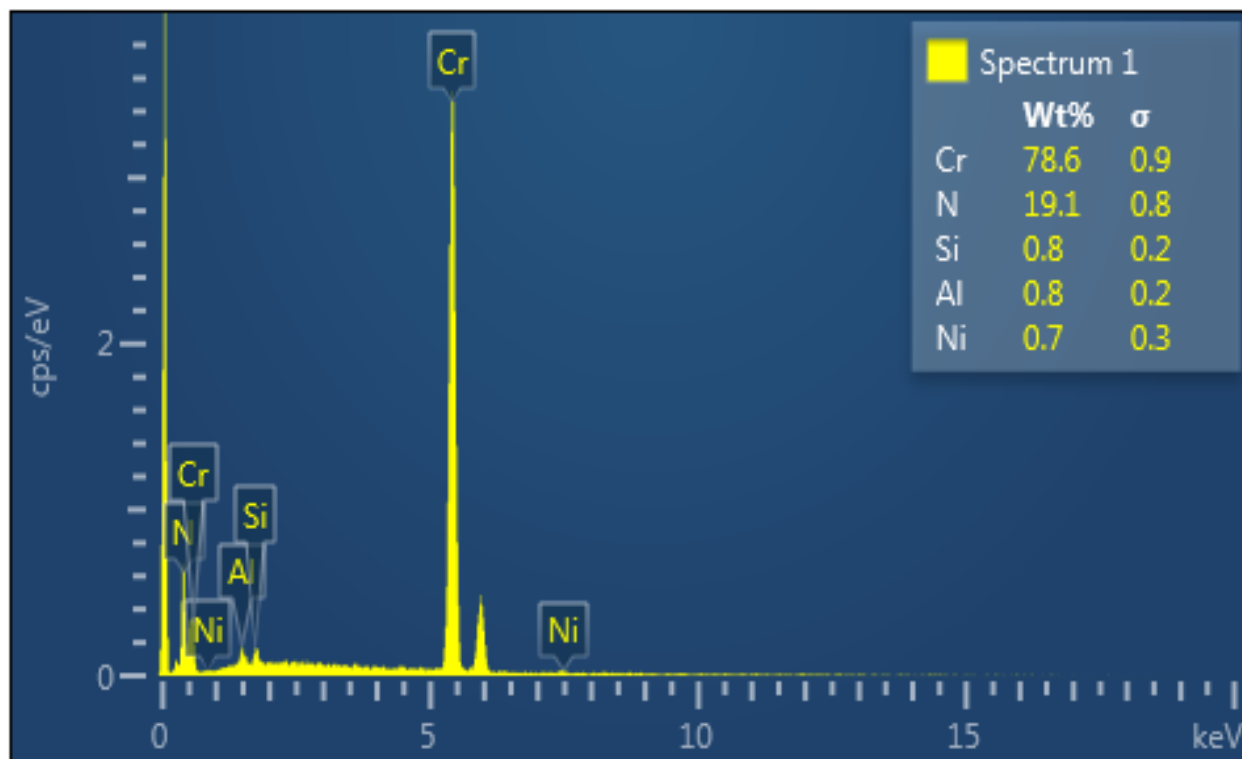


Figure 4.12: EDS for the used coating

Table 4.1: The elemental compositions of each element of the coating

Element	Wt%
N	19.06
Al	0.81
Si	0.83
Cr	78.56
Ni	0.74
Total:	100.00

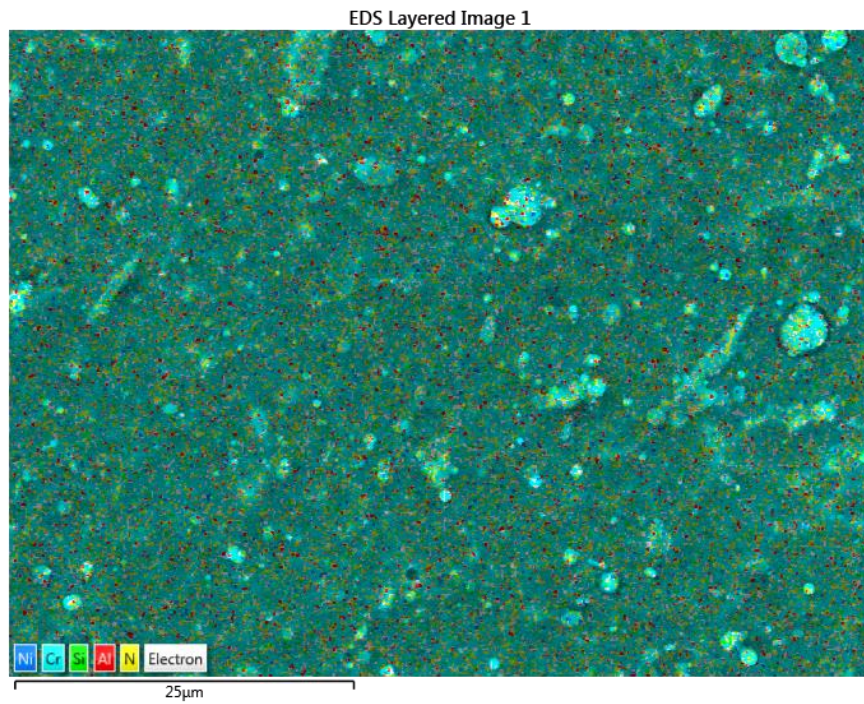


Figure 4.13: The distribution of all elements on the surface of the coating

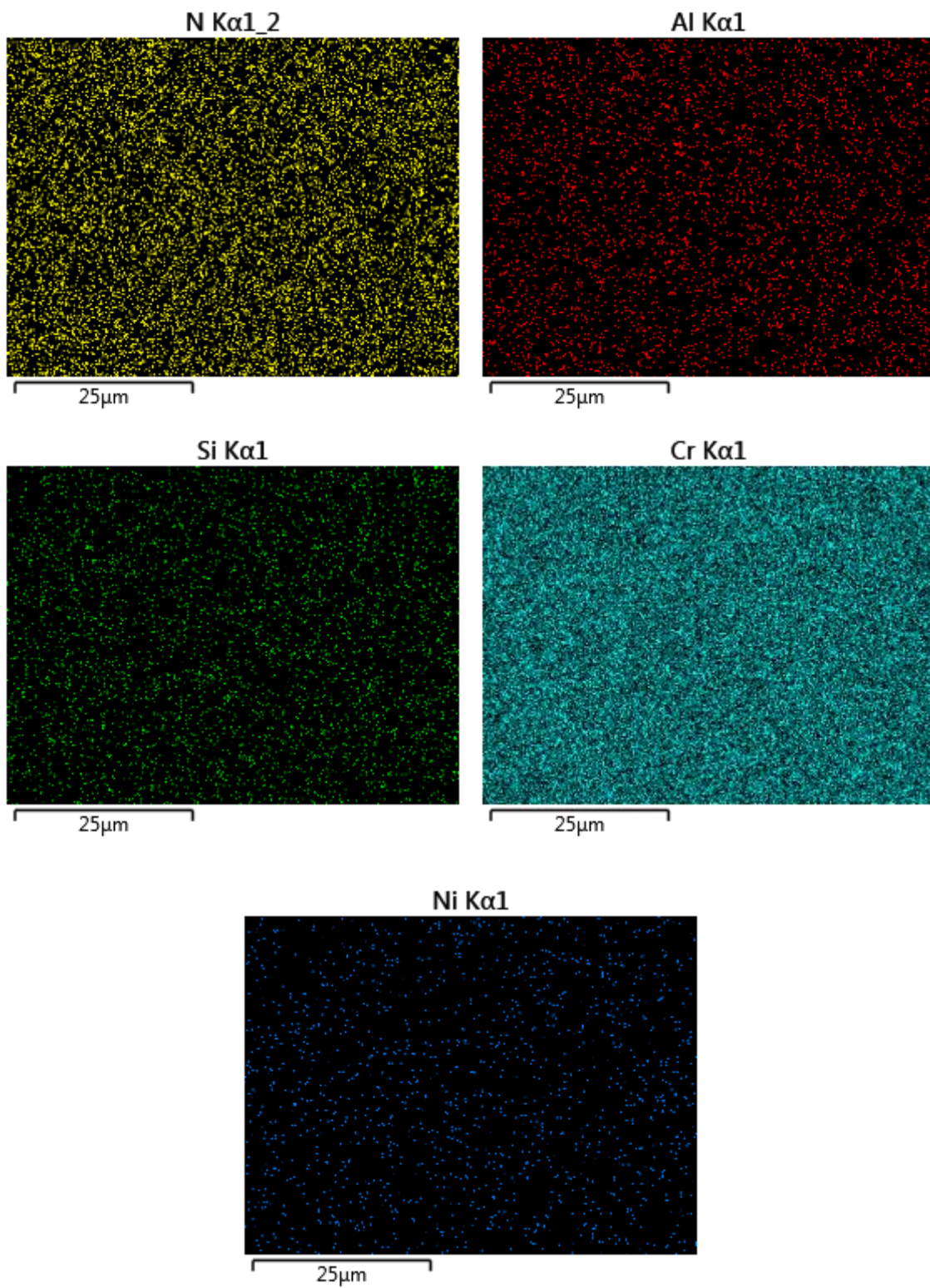


Figure .4.14: The distribution of each element on the surface of the coating

The average elemental compositions of the coatings are presented in Table 4.1. The percentage ratio of Cr is almost 79% while the N is almost 20% and slightly more than 2% for the rest Al, Si and Ni. The resulting coating showed a lower ratio as compared to their respective target materials and this was attributed to sputtering during deposition and growth.

4.1.3 Crystallographic Structure

$\theta/2\theta$ XRD scans were performed to determine the crystallographic structure of the coating and compared to the Powder Diffraction Files published by the International Centre for Diffraction Data (ICDD). In addition, an XRD pattern of cast iron substrate was obtained and illustrated in Fig. 4.15 [73]. The $\theta/2\theta$ diffraction pattern for the CrNiAlSiN coating is shown in Fig. 4.16.

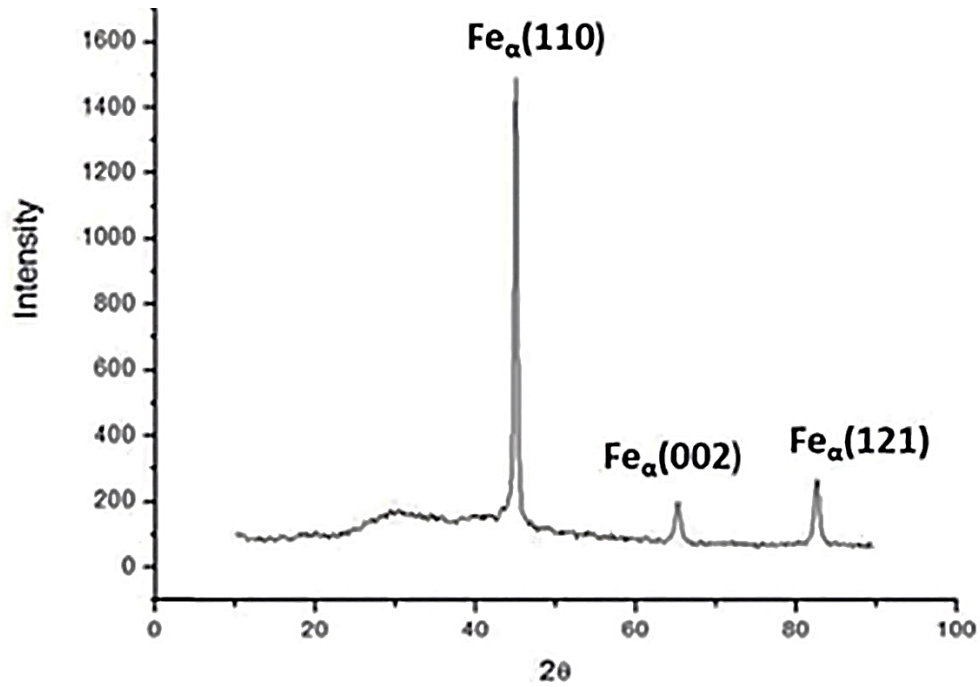


Figure 4.15: XRD for cast iron [75]

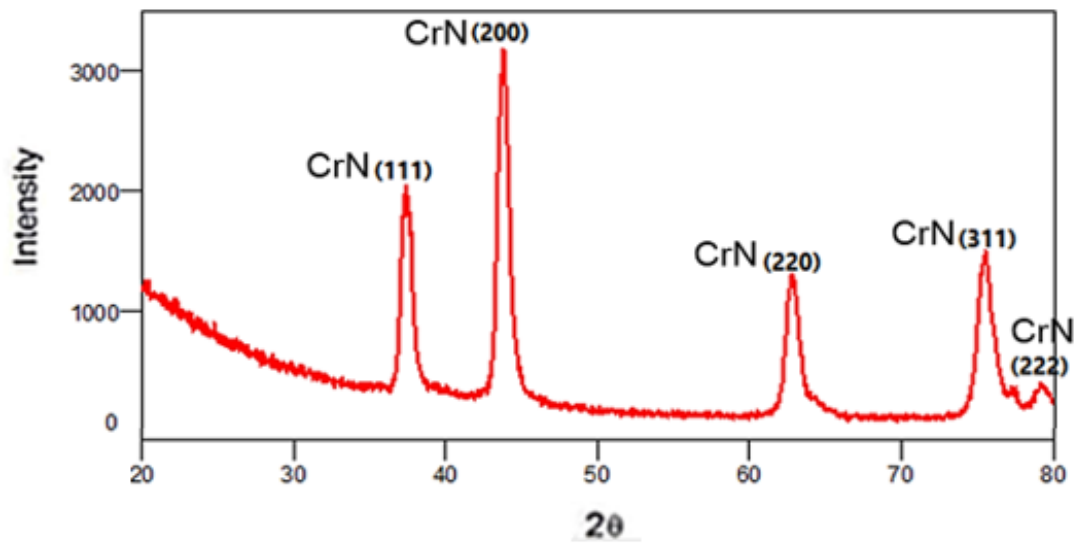


Figure 4.16: XRD for the CrNiAlSiN coating

This pattern shows a very similar crystallographic orientation for CrN that was found in the literature [74, 75]. Si, Al, and Ni elements did not appear due to the very small content

of those elements compared to CrN in the alloy, and this made deducting their peaks very difficult for the instrument. The texture of (111), (200), (220) and (311) reflections, while the (222) reflection is diminished. The diffraction peaks are slightly shifted relative to the standard data of CrN. Peak shifts in spectra occur when there is residual stress in a sample that generates strain in the coatings by stretching or compressing bonds between the atoms resulting in changes of the spacing of crystallographic planes. When the spacing of the crystallographic plane changes, the Braggs angle should either increase or decrease. The residual stress, tensile in nature increases the atomic spacing thereby shifting the 2θ to a lower value whereas compressive residual stresses decrease the atomic spacing thereby shifting the 2θ to a higher value [76]. The high intensity peak centered at 43.69° was indexed to cubic CrN (200) plane, the peak with a lower intensity at 78.54° was indexed to cubic CrN (222), plane. Other high angle reflections such as (111), (220) and (311) were clearly shown. The high bias voltage during deposition process resulted in high atom mobility and increased surface diffusion, which could facilitate alignment of the growth along the (200) direction for CrN [77].

4.2 Mechanical and Tribological

This section presents the results of the micro indentation test and the wear test of the coatings.

4.2.1 Microhardness

The nano-indentation was utilized to study the surface hardness of the coated samples. The software associated with the machine was used to calculate the hardness and to graph the penetration depth as the indentation load changes for all the samples. More than one experiment was done for the samples and then averaged. Graph in Fig. 4.17 demonstrates the behavior of the penetration depth and the load-displacement as the normal force changes for the sample that treated with 240 grit-size sandpaper. The graphs of the rest of all trails and samples are in appendix A. Table 4.2 shows the mean and of each level of roughness. The hardness for cast iron that had been used is 211.9 HV. The results of the average microhardness values in Vickers scale for the coated samples and substrate are illustrated in Table 4.3.

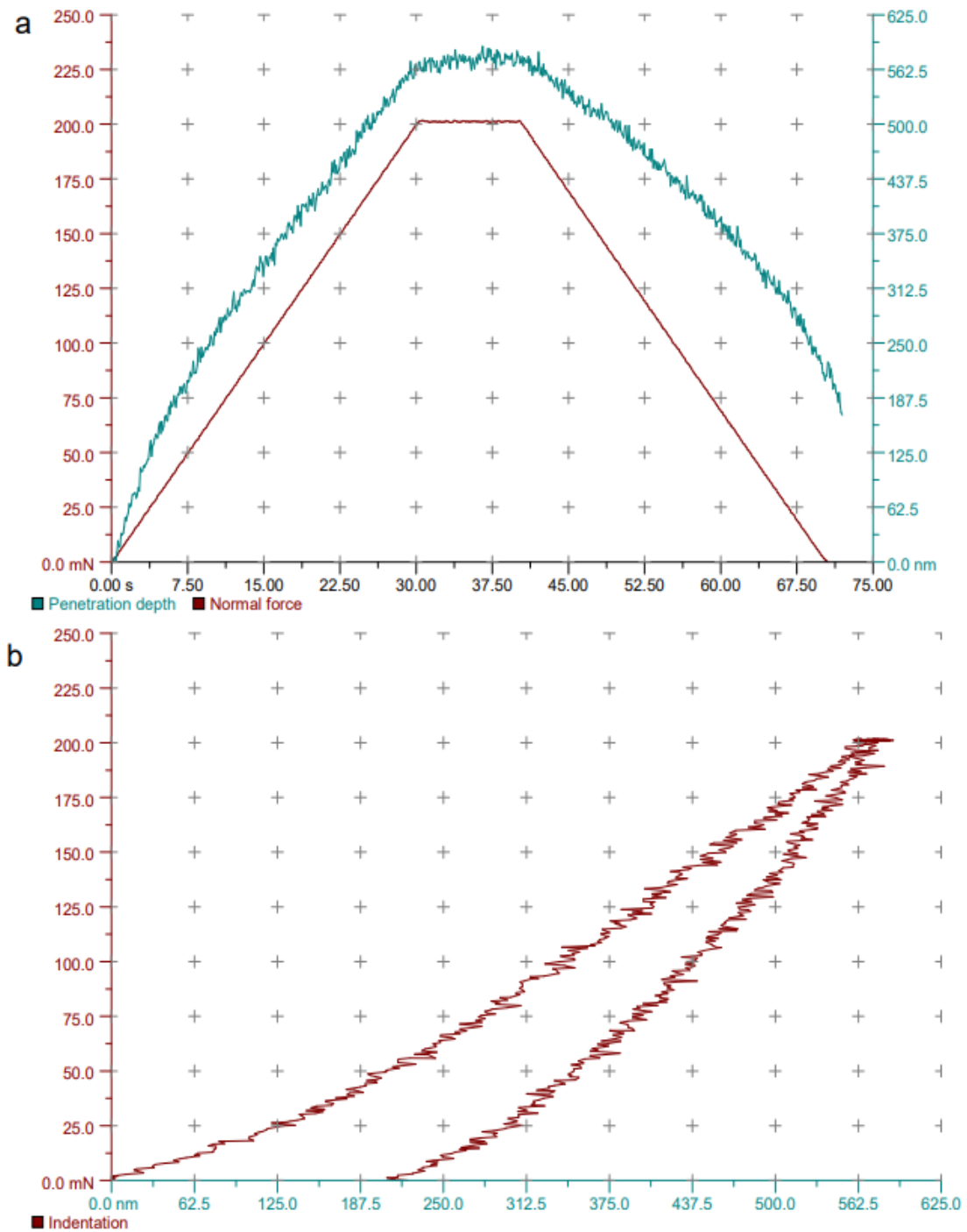


Figure 4.17: The behavior of the penetration depth and load-displacement as the normal force changes for 240 grit-size sample

Table 4.2: Hardness of all trails in each sample with the mean

	Uncoated	Coated				
	Substrate (HV/GPa)	Polished (HV/GPa)	60 grit-size (HV/GPa)	240 grit-size (HV/GPa)	400 grit-size (HV/GPa)	800 grit-size (HV/GPa)
Hardness 1	222.9 (HV) 2.2 (GPa)	2868 (HV) 28.1 (GPa)	2333 (HV) 22.9 (GPa)	3874 (HV) 38 (GPa)	3100 (HV) 30.4 (GPa)	2448 (HV) 24 (GPa)
Hardness 2	206.1 (HV) 2 (GPa)	3195 (HV) 31.3 (GPa)	2150 (HV) 21.1 (GPa)	3971 (HV) 39 (GPa)	2095 (HV) 20.2 (GPa)	3252 (HV) 31.9 (GPa)
Hardness 3	206.7 (HV) 2 (GPa)	2715 (HV) 26.6 (GPa)	2334 (HV) 22.9 (GPa)	3682 (HV) 36.1 (GPa)	4203 (HV) 41.2 (GPa)	2500 (HV) 24.5 (GPa)
Hardness 4		2973 (HV) 29.1 (GPa)		3065 (HV) 30 (GPa)	3763 (HV) 36.9 (GPa)	2457 (HV) 24.1 (GPa)
Hardness 5		2652 (HV) 26 (GPa)		3072 (HV) 30.1 (GPa)	3308 (HV) 32.4 (GPa)	3119 (HV) 30.6 (GPa)
Mean	211.9 (HV) 2.1 (GPa)	2881 (HV) 28.3 (GPa)	2272 (HV) 22.3 (GPa)	3533 (HV) 34.5 (GPa)	3294 (HV) 32.3 (GPa)	2756 (HV) 27 (GPa)

Table 4.3: Average microhardness values in Vickers scale for the substrate and the coating samples

Sample	HV (Vickers) (GPa)
Cast iron substrate	211.9 HV 2.1 Gpa
Coated cast iron	3115.9 30.5 Gpa

The average measured microhardness for the coatings, which were got from 25 measurements, and for the substrate are 3115.9 HV and 211.9 HV respectively. CrNiAlSiN coating improved the hardness as in Fig. 4.18. Thus, the hardness of the coatings measured at the 20mN load, therefore, reflects the intrinsic property of the film with minimal substrate effect. The average penetration depth of the coatings at 20mN load was 575 nm, which is about 6.4% of the average film thickness. The microstructure and internal stress levels in the coatings could affect the hardness of the coatings [78].

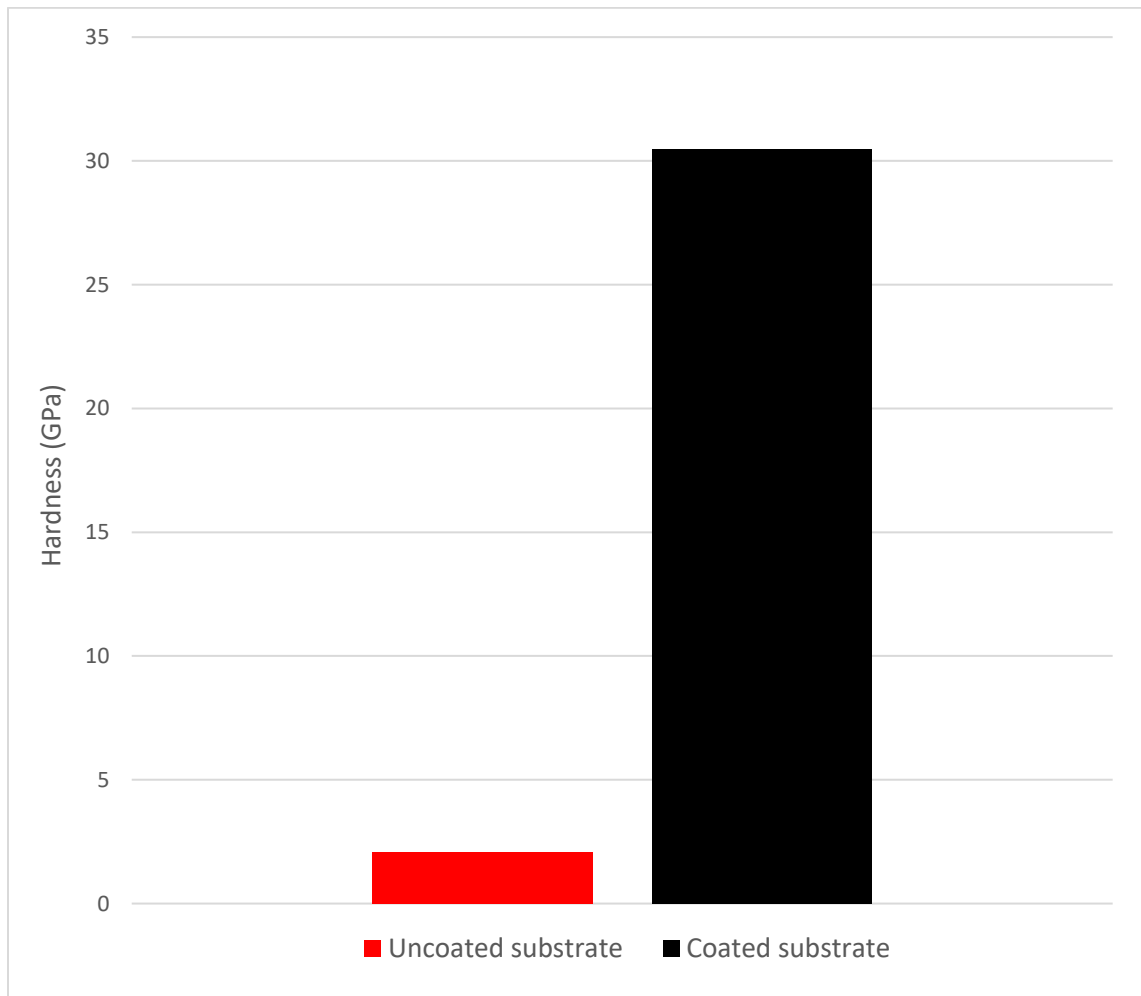
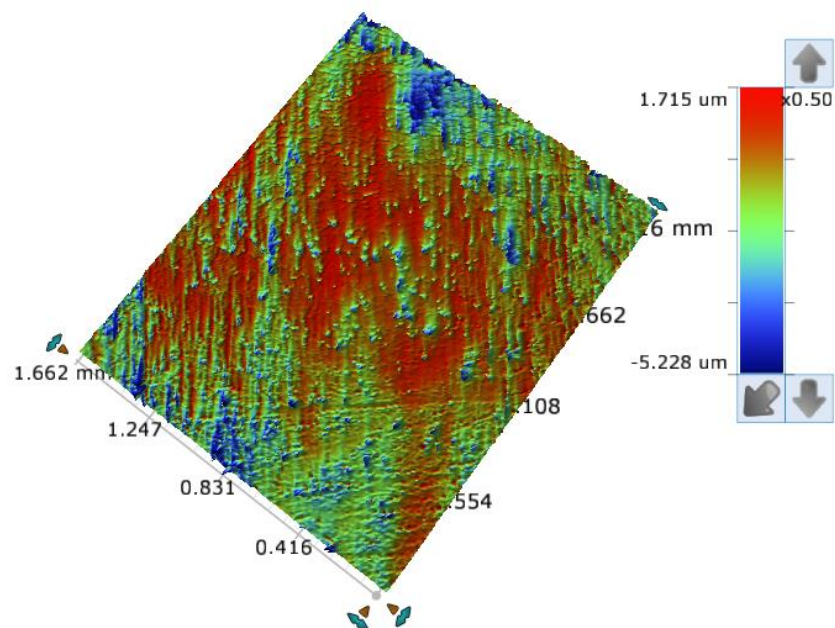
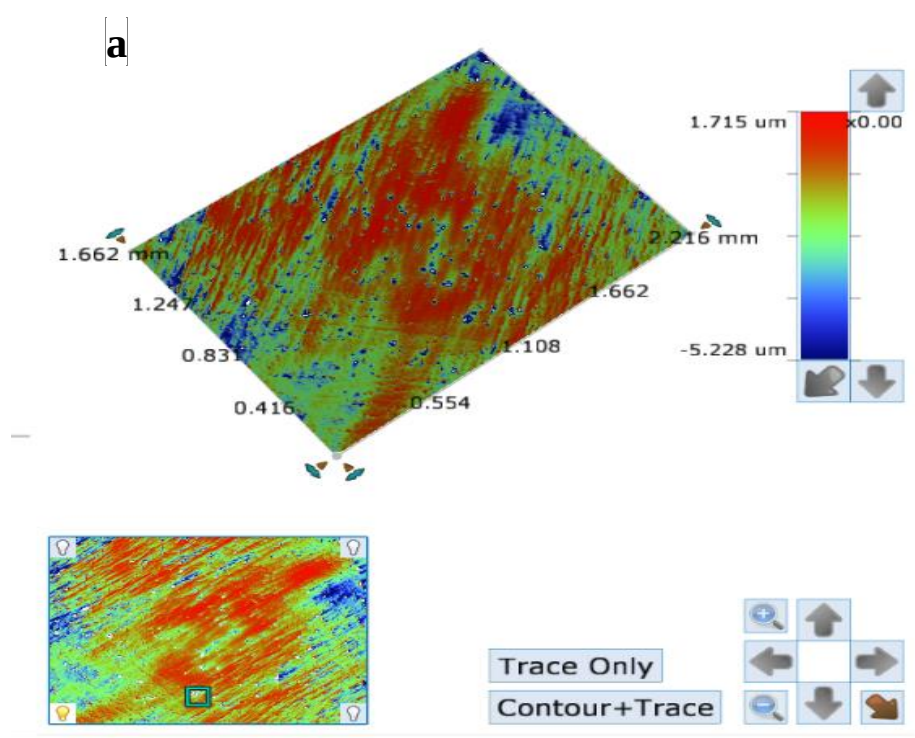


Figure 4.18: The average measured microhardness for the coatings and for the substrate

4.2.2 Surface roughness

The optical profilometer 3-D images of the samples with the different roughness before coating and after the coating are shown in Figs. 4.19 – 4.23. The surface roughness was quantified using the arithmetic average height (R_a). Roughness in more than one location for each sample were taken and then averaged. Table 4.4 demonstrates the average surface roughness of all uncoated and coated samples. Variations of surface roughness of the samples before and after depositing coatings are shown in Fig. 4.24.



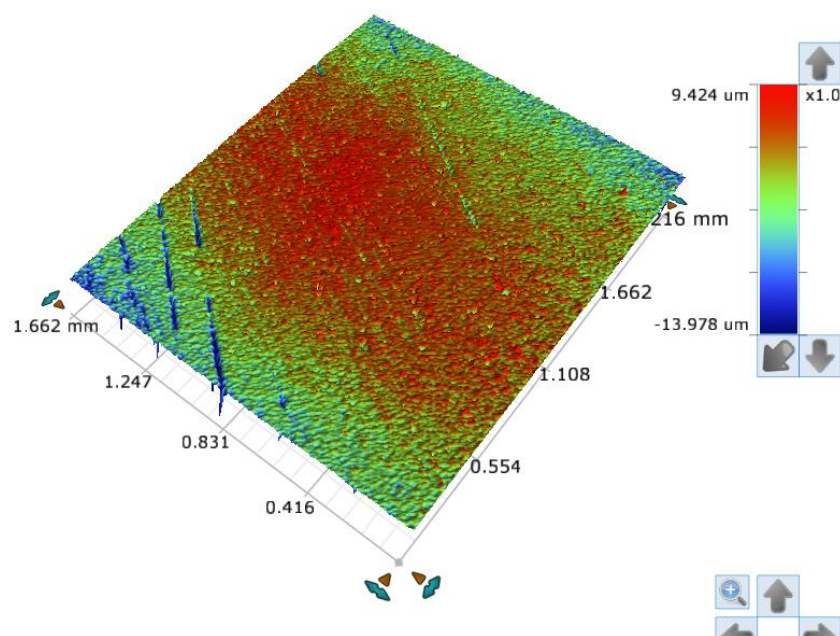
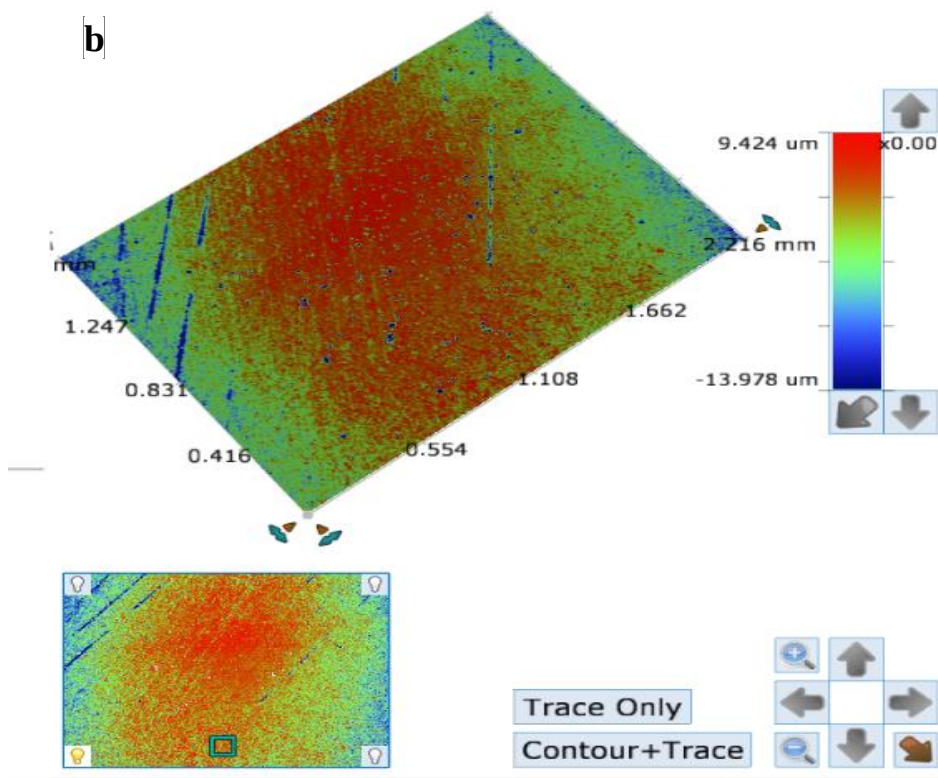
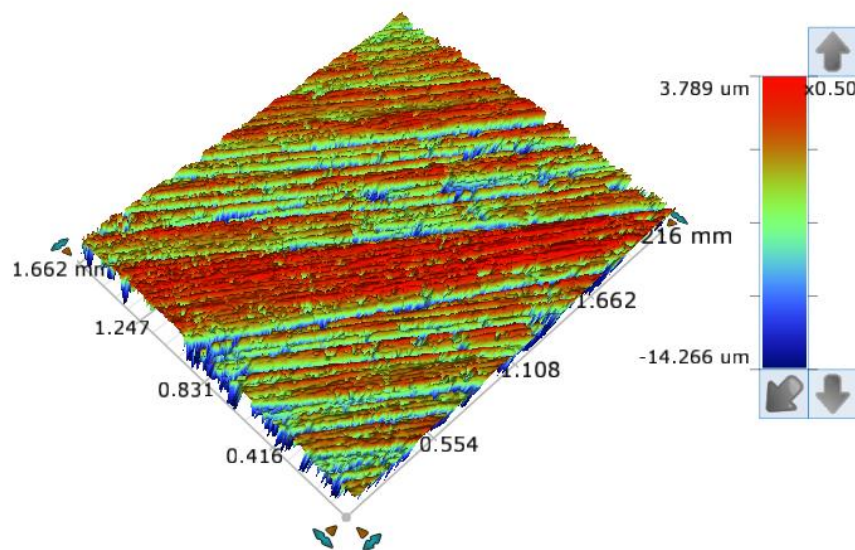
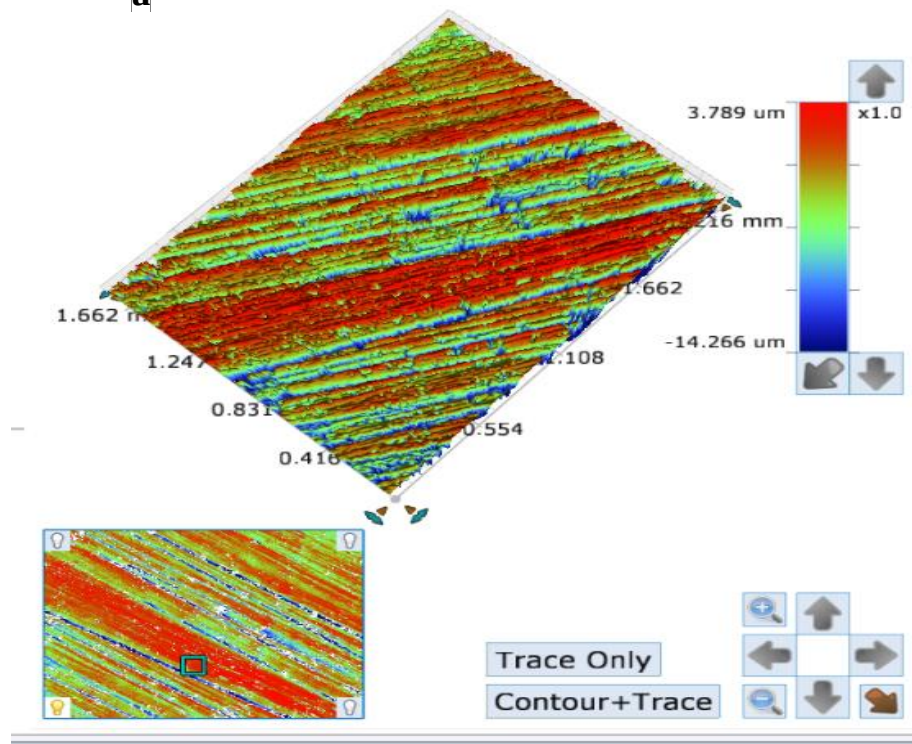


Figure 4.19: Optical profilometer 3-D images of the surface of polished sample a) before coating and b) after the coating

a



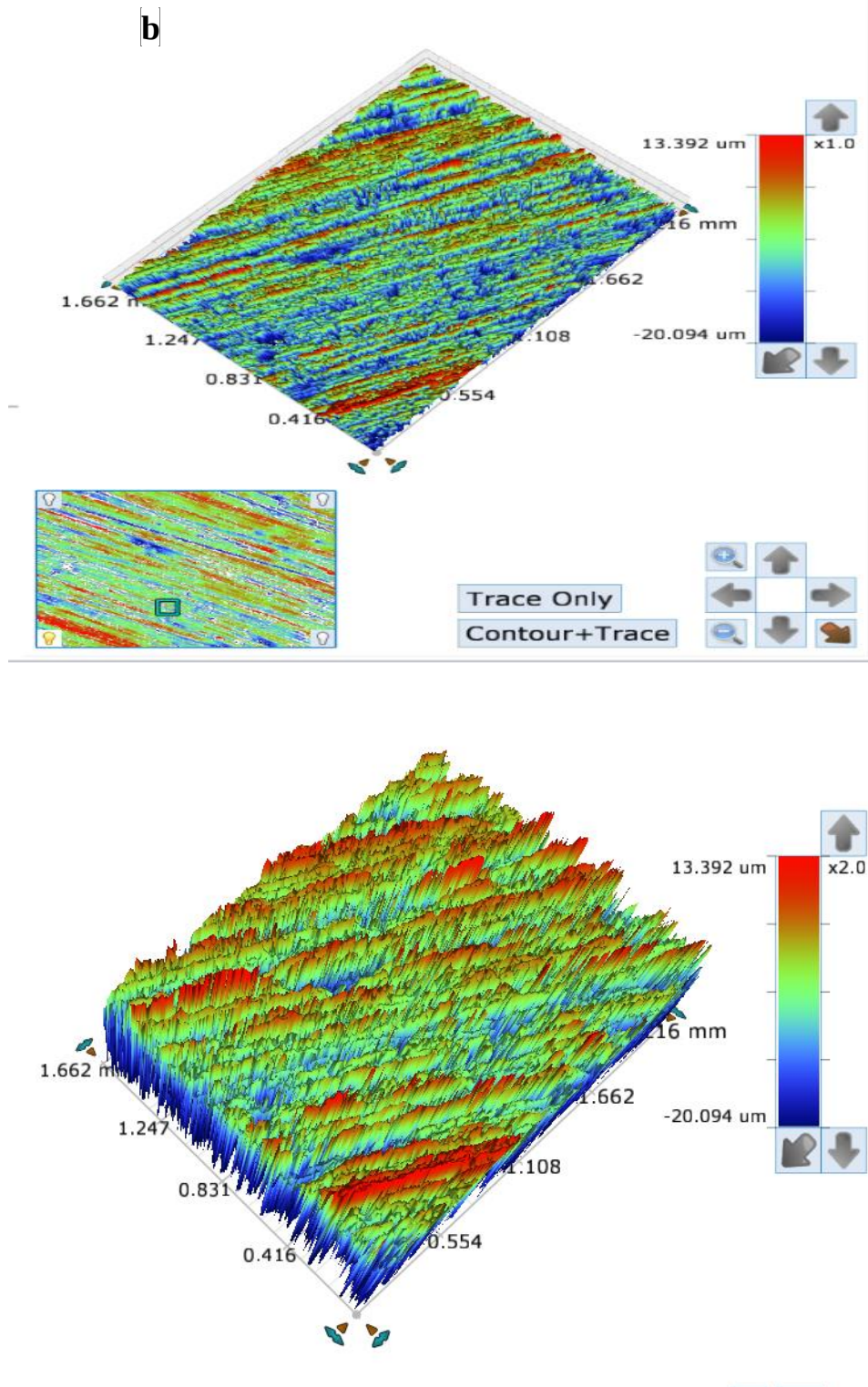
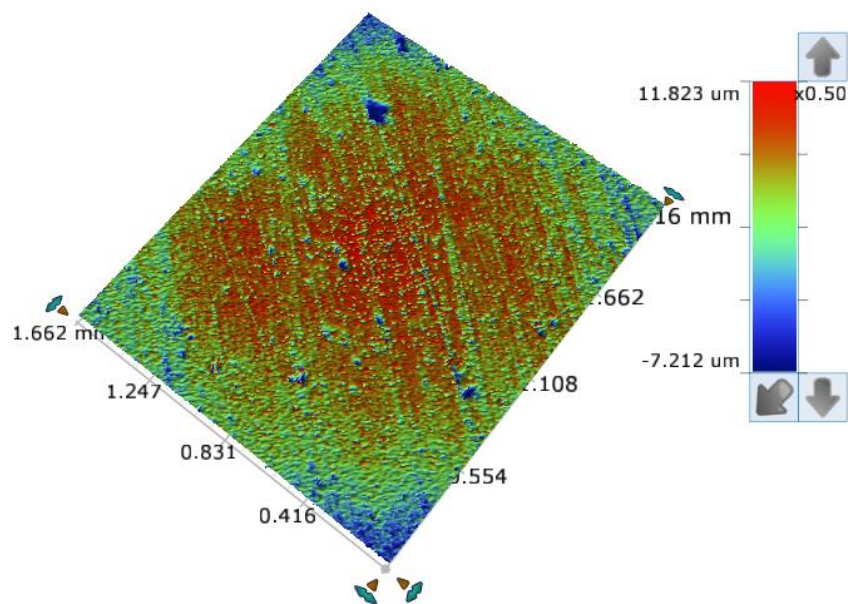
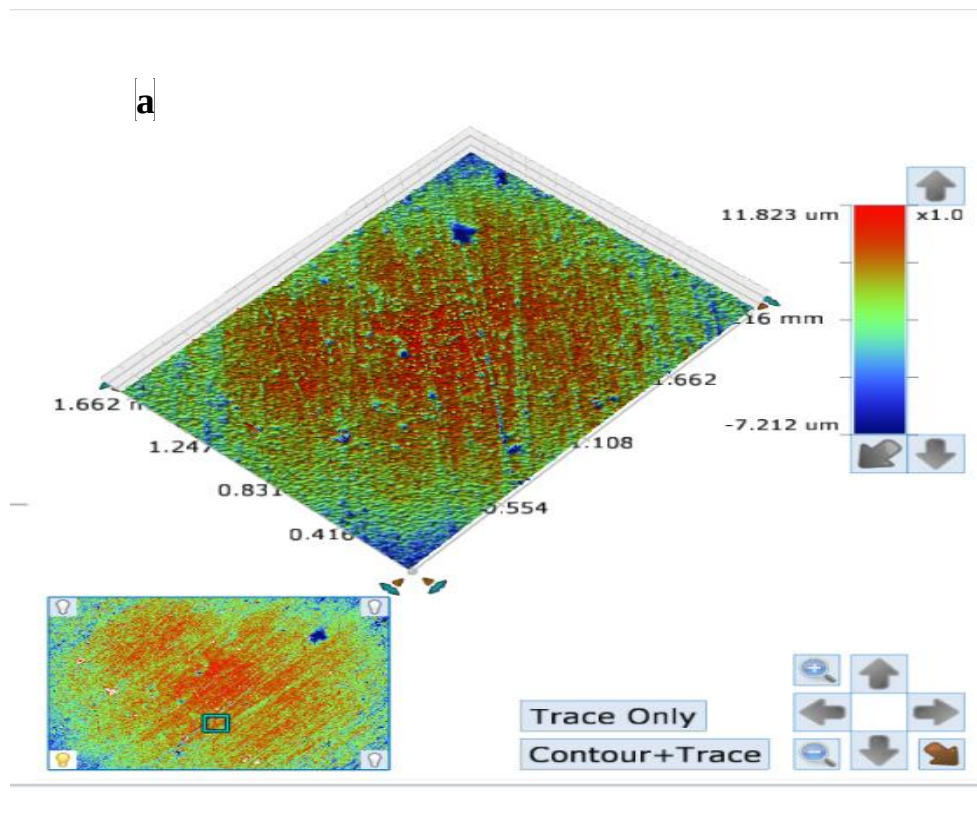


Figure 4.20: Optical profilometer 3-D images of the surface of 60 grit-size sample a) before coating and b) after the coating



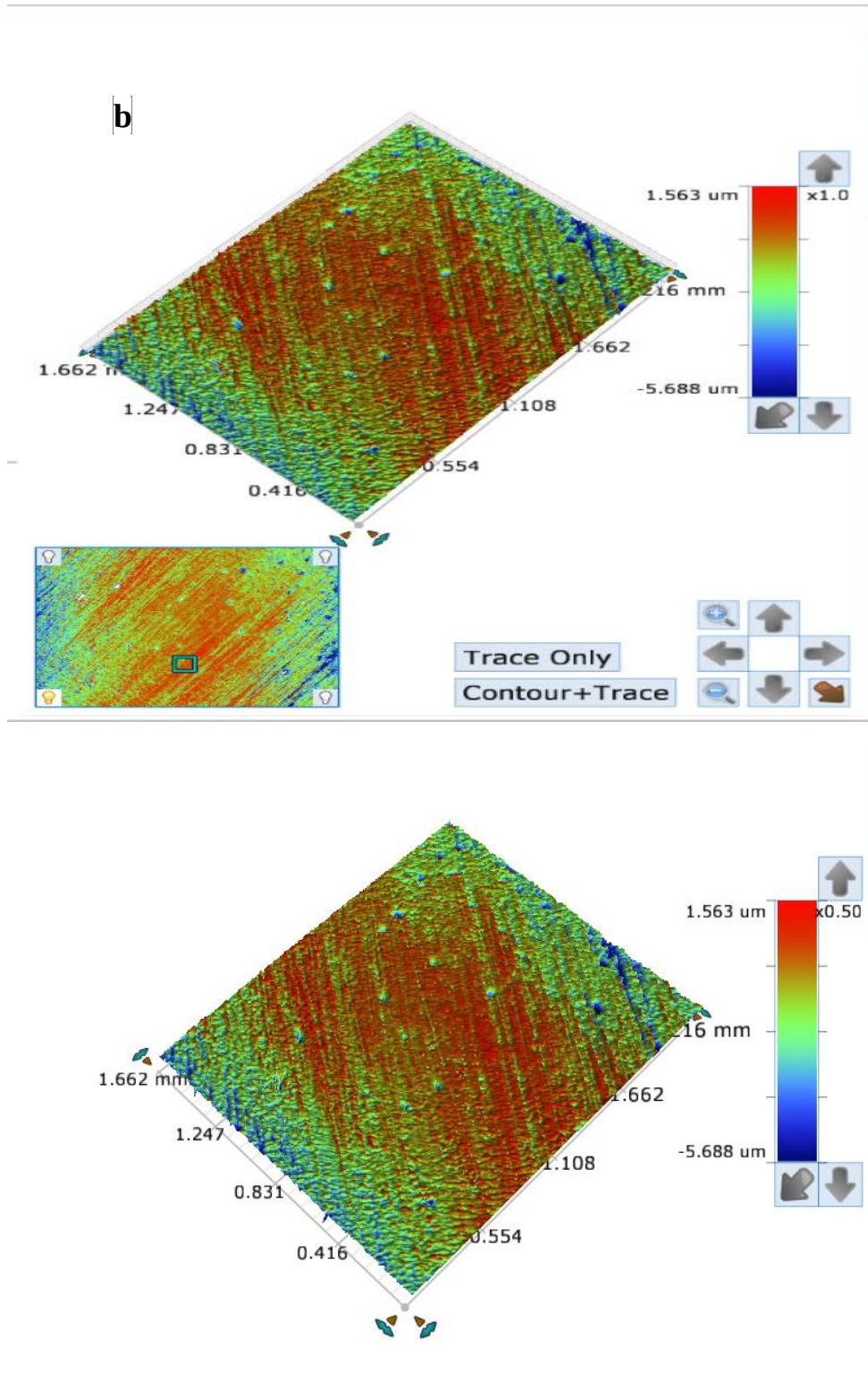
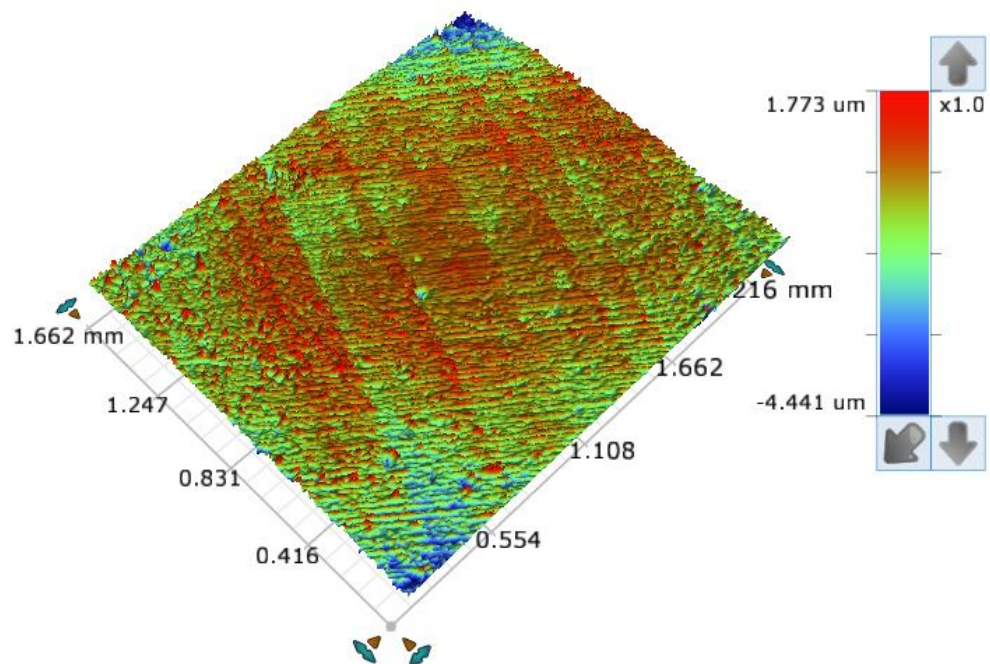
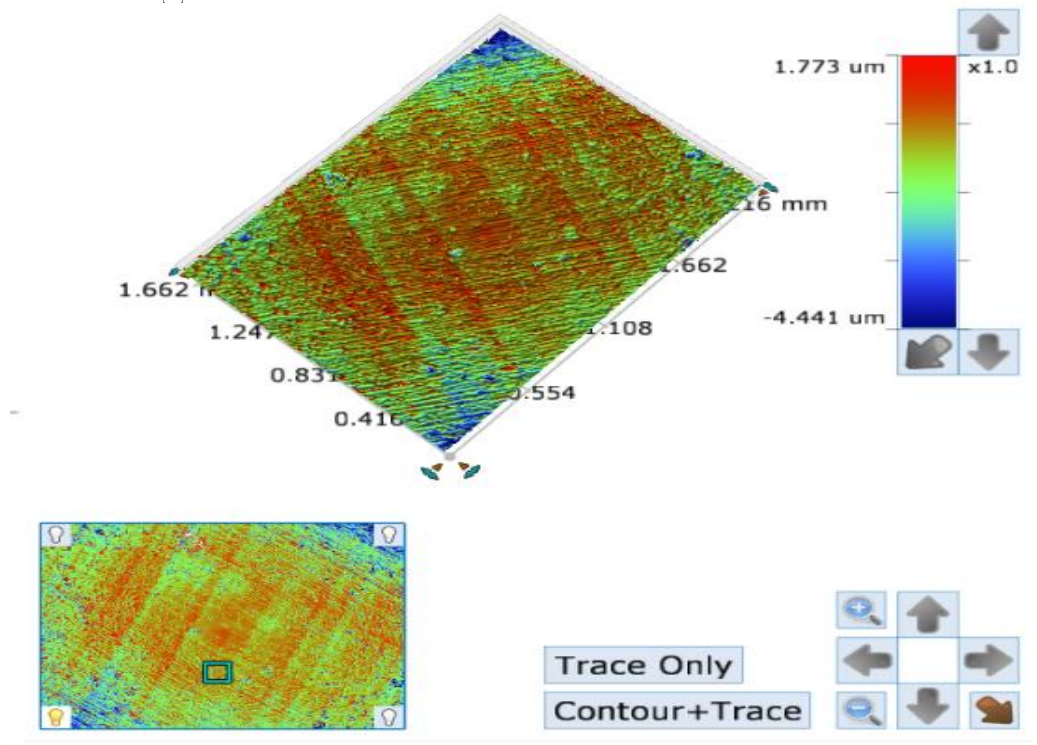


Figure 4.21: Optical profilometer 3-D images of the surface of 240 grit-size sample a) before coating and b) after the coating

a



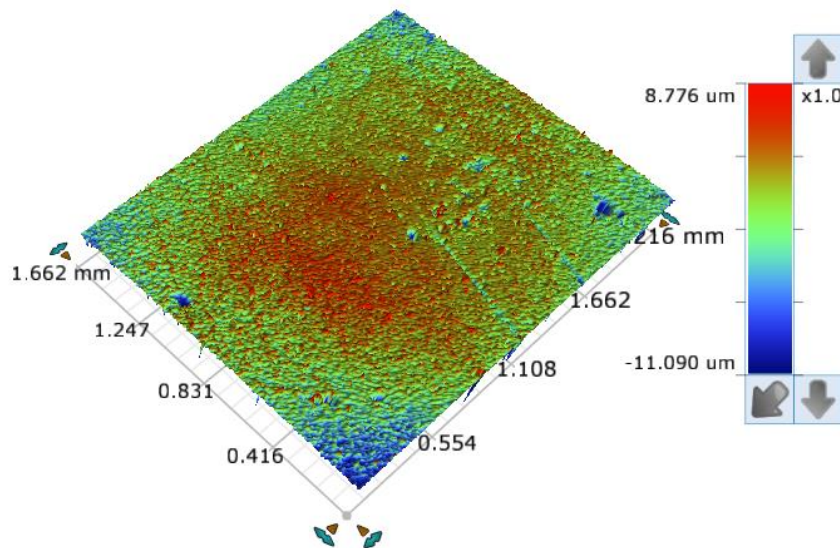
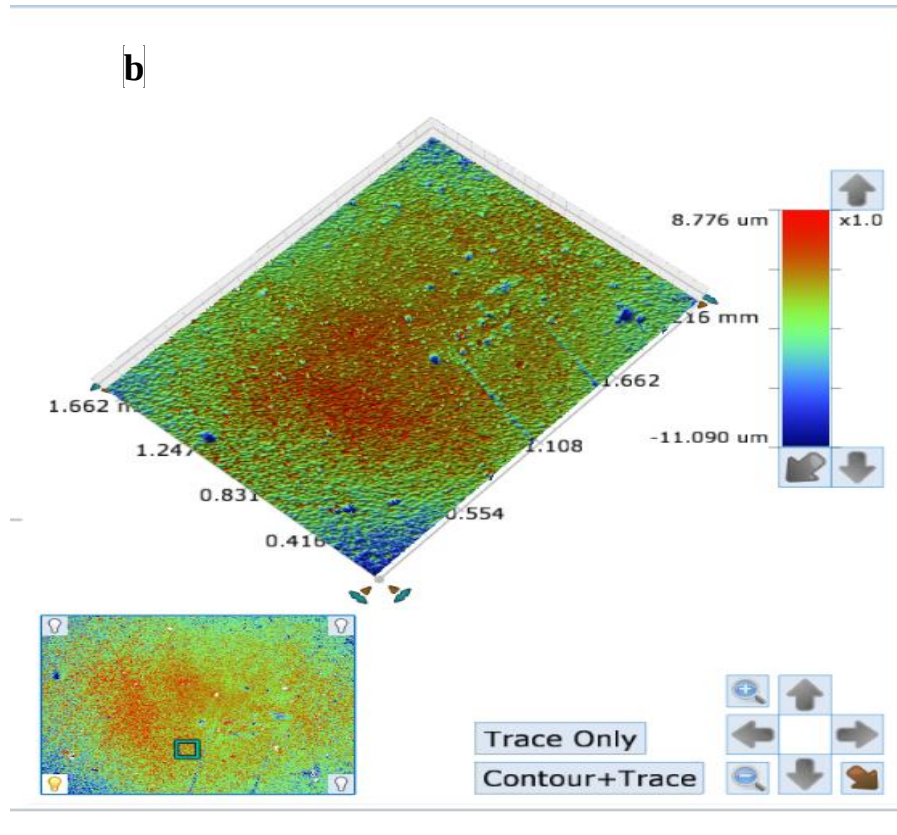
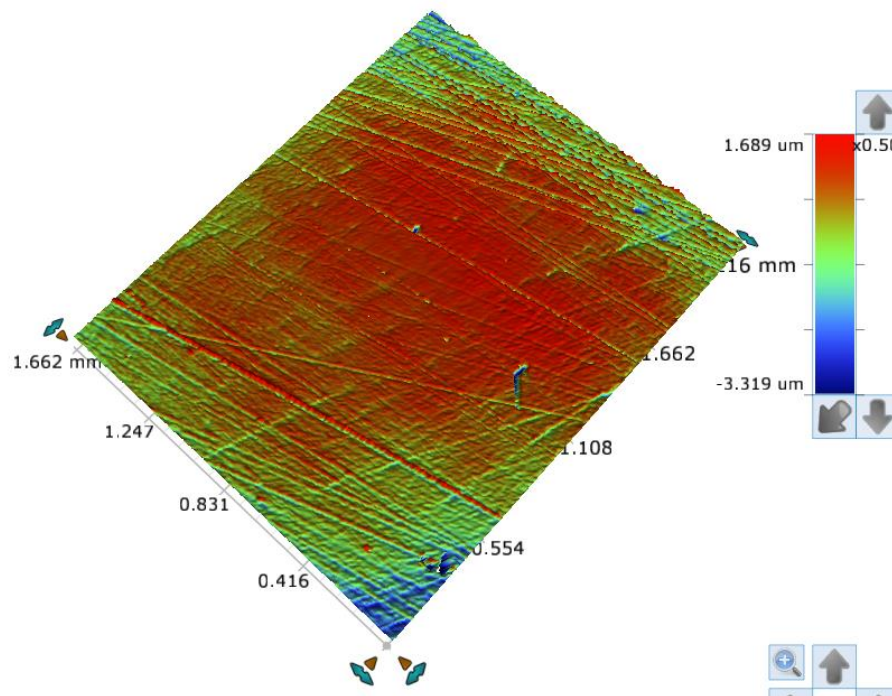
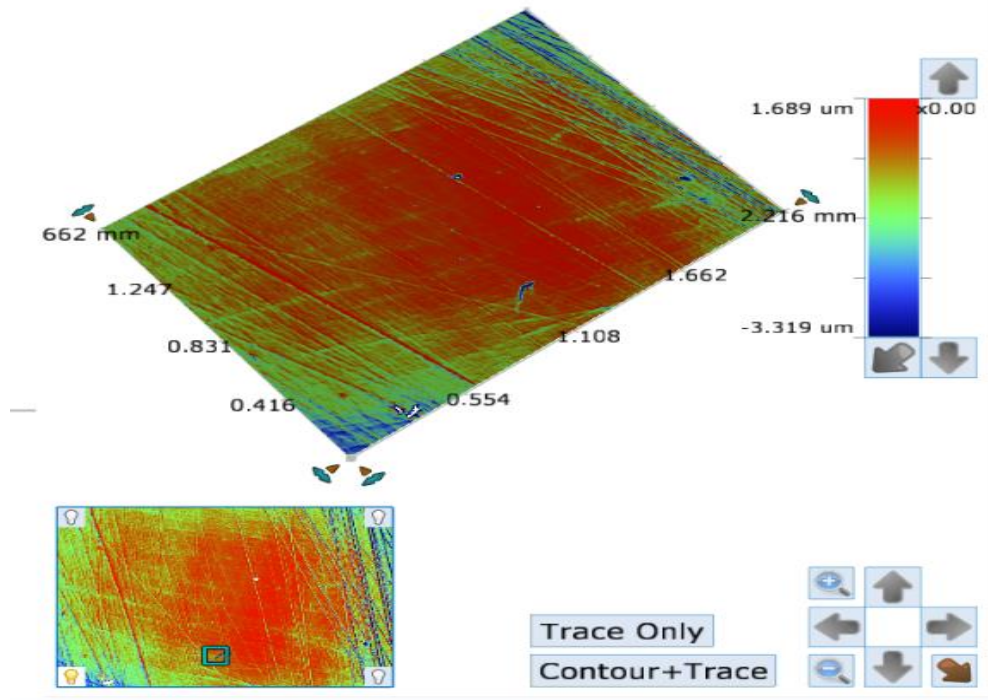


Figure 4.22: Optical profilometer 3-D images of the surface of 400 grit-size sample a) before coating and b) after the coating

a



b

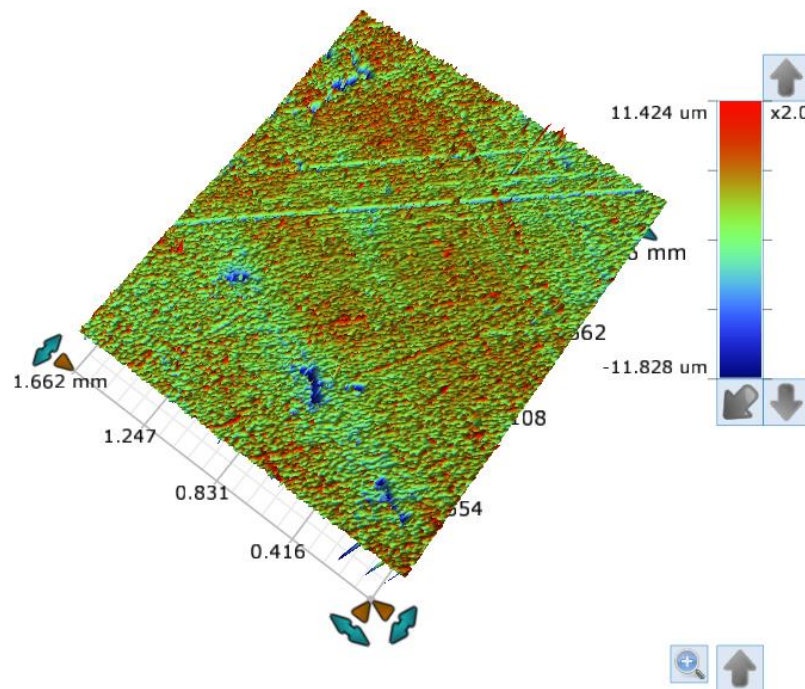
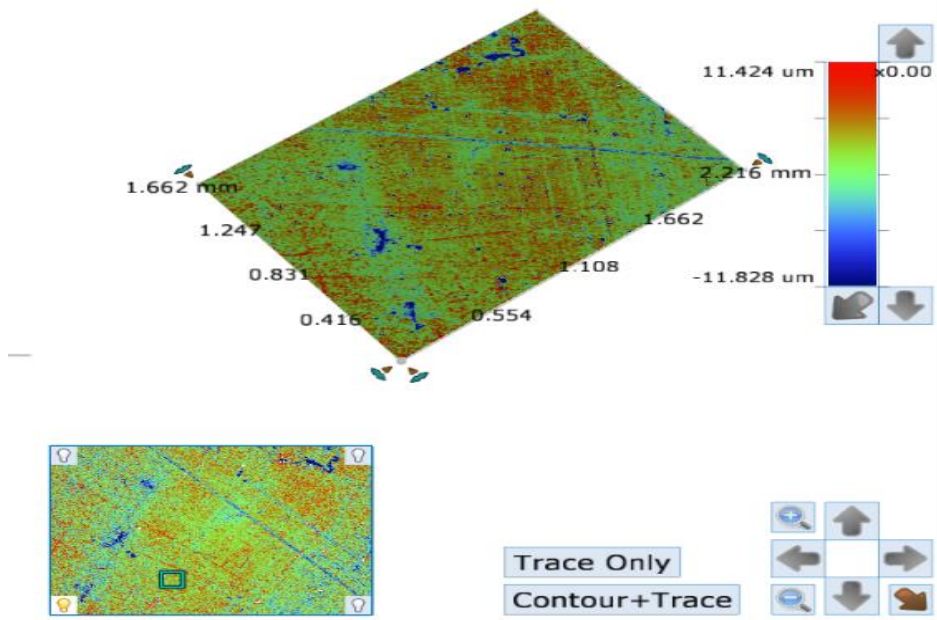


Figure 4.23: Optical profilometer 3-D images of the surface of 800 grit-size sample a) before coating and b) after the coating

Table 4.4: Average surface roughness of all uncoated and coated samples

Sample	Polished	60	240	400	800
Coated (Ra μm)	0.4	2	0.4	0.25	0.3
Uncoated (Ra μm)	0.2	0.95	0.3	0.19	0.14

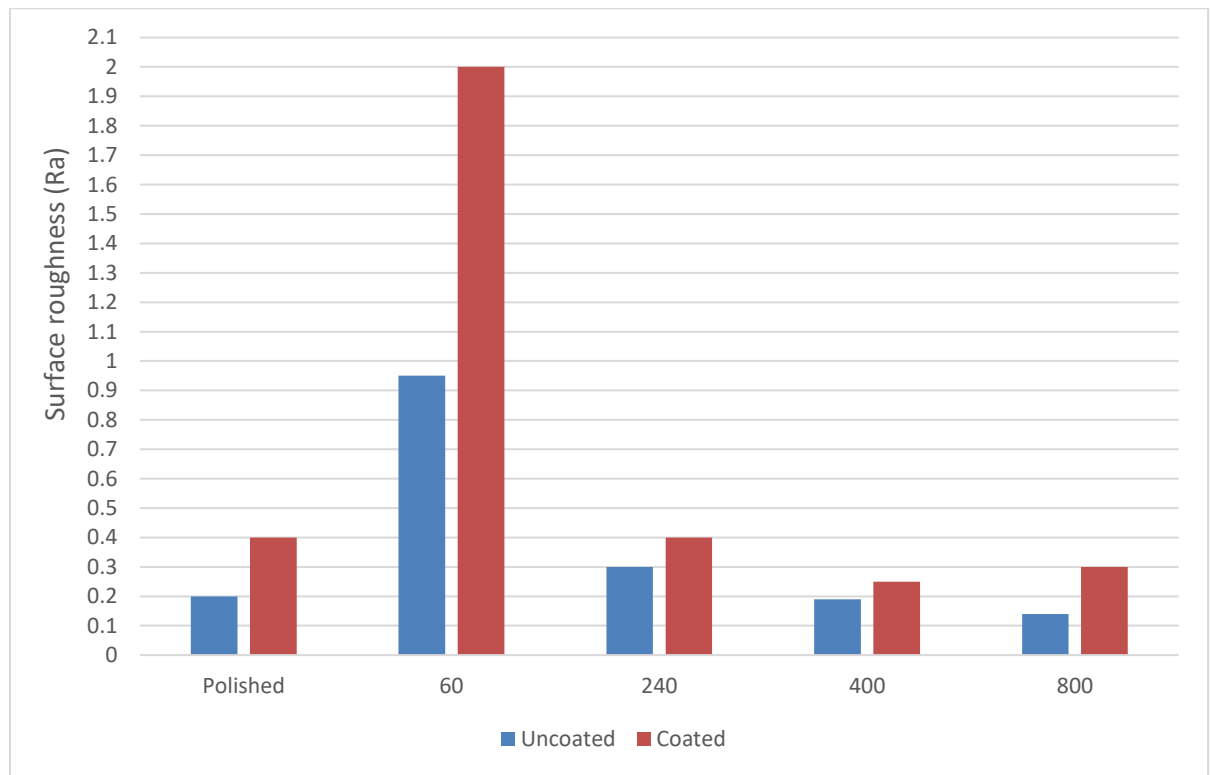


Figure 4.24: Variations of surface roughness of the samples before and after the deposition

Variations of surface roughness of the samples before and after depositing coatings are shown in Fig. 4.24. According to Fig. 4.24, the 60 grit-size demonstrated a rough surface,

while the 400 and 800 grit-sizes samples had smooth surfaces. The rougher uncoated sample has a roughness that is almost 15 times more increasing than the smoother one. The polished sample has a roughness that is near to the sample with 400 grit-size. The surface roughness value of all coated samples was higher than that of the substrates because of the characteristics of microparticles and pits observed in the coatings deposited using CA-PVD. That means that as the substrate roughness decreases, the surface of the obtained coatings becomes smoother. This observation is because the coating surface roughness results from the sharps of the initial nucleus, from substrate roughness, and from preferential growth.

4.2.3 Wear test

Wear test was performed using Tribometer to evaluate the wear rate in addition to the coefficient of friction and the depth of wear. The wear track was observed using an optical profilometer. Figures 4.25 – 4.29 illustrate the 2-D and 3-D of the wear track for substrate, 60, 240, 400, and 800 grit-size samples respectively.

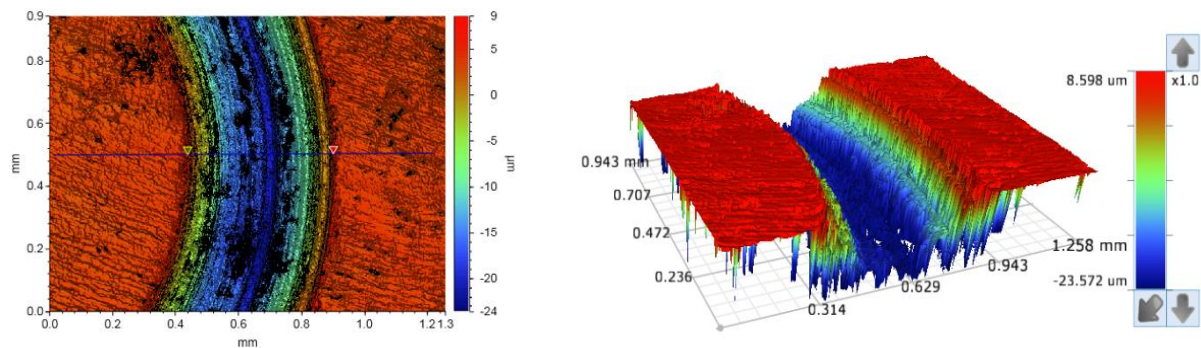


Figure 4.25: 2-D and 3-D of the wear track for the substrate

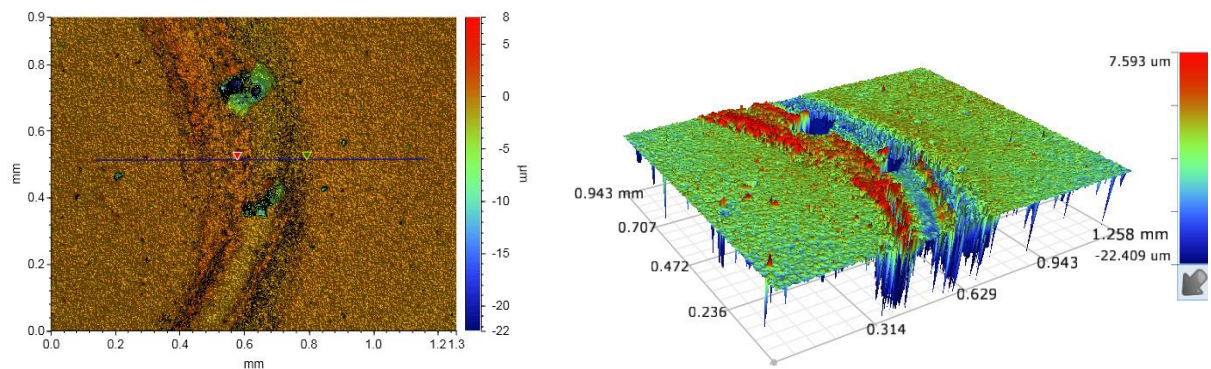


Figure 4.26: 2-D and 3-D of the wear track for the sample that treated with 60 grit-size sandpaper

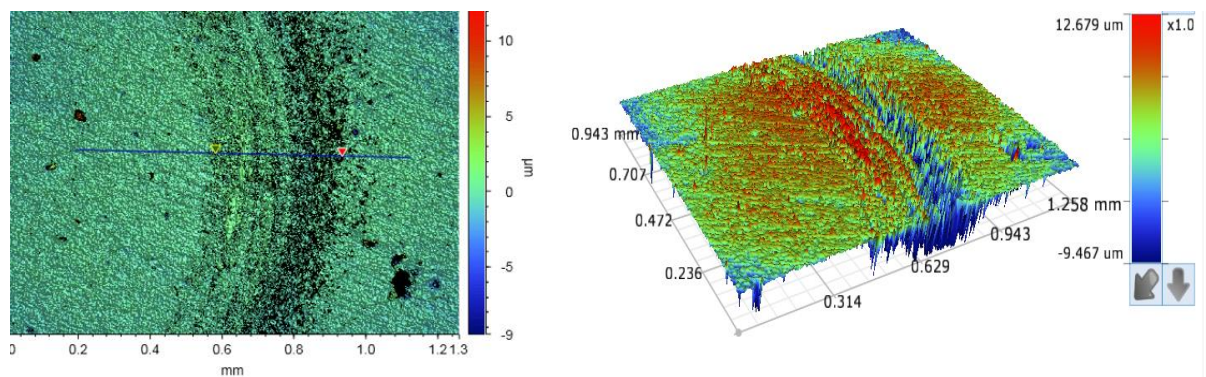


Figure 4.27: 2-D and 3-D of the wear track for the sample that treated with 240 grit-size sandpaper

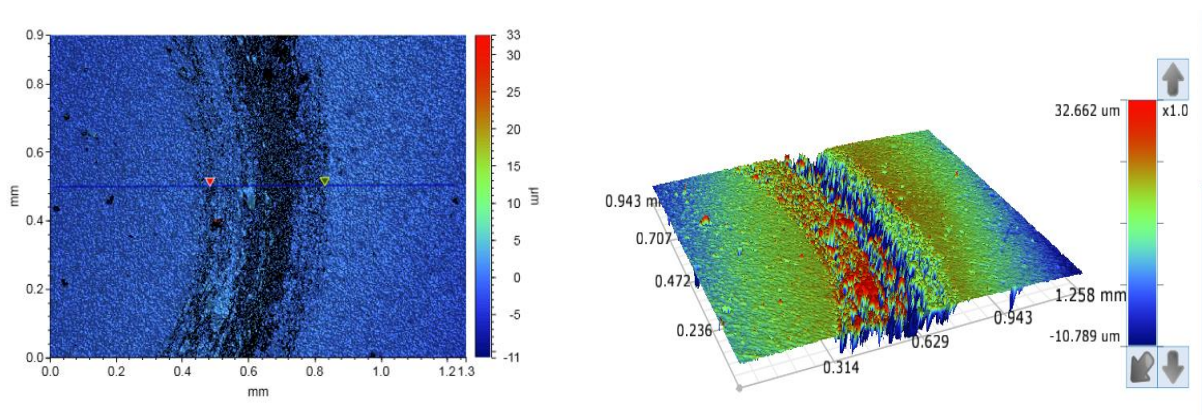


Figure 4.28: 2-D and 3-D of the wear track for the sample that treated with 400 grit-size sandpaper

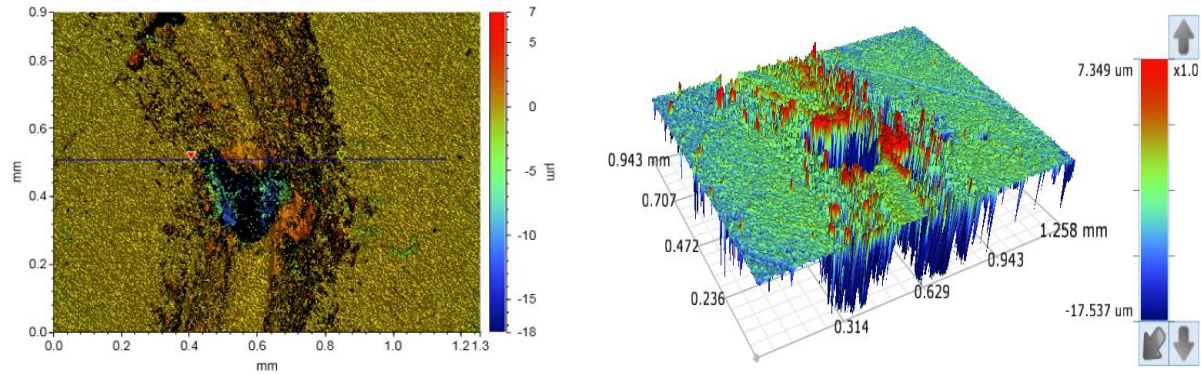


Figure 4.29: 2-D and 3-D of the wear track for the sample that treated with 800 grit-size sandpaper

The CrNiAlSiN coating was beneficial for significantly reducing the wear depth from 25 μm for substrate, to 1 μm for the 60 grit-size coated sample. The wear rate of the cast iron was found to be significantly greater than all coated samples, concluding that all coatings noticeably improved the wear resistance of the cast iron as in Fig. 4.30. The coated sample treated with 60 grit-size sandpaper before the coating has the best result in terms of wear depth and wear resistance. This result agreed with Zemian and T.D. Atmani experiments. This sample reduces the wear rate from 26.67×10^{-9} to $0.69 \times 10^{-9} \text{ mm}^2/\text{N}$ which is a great reduction by 38 times.

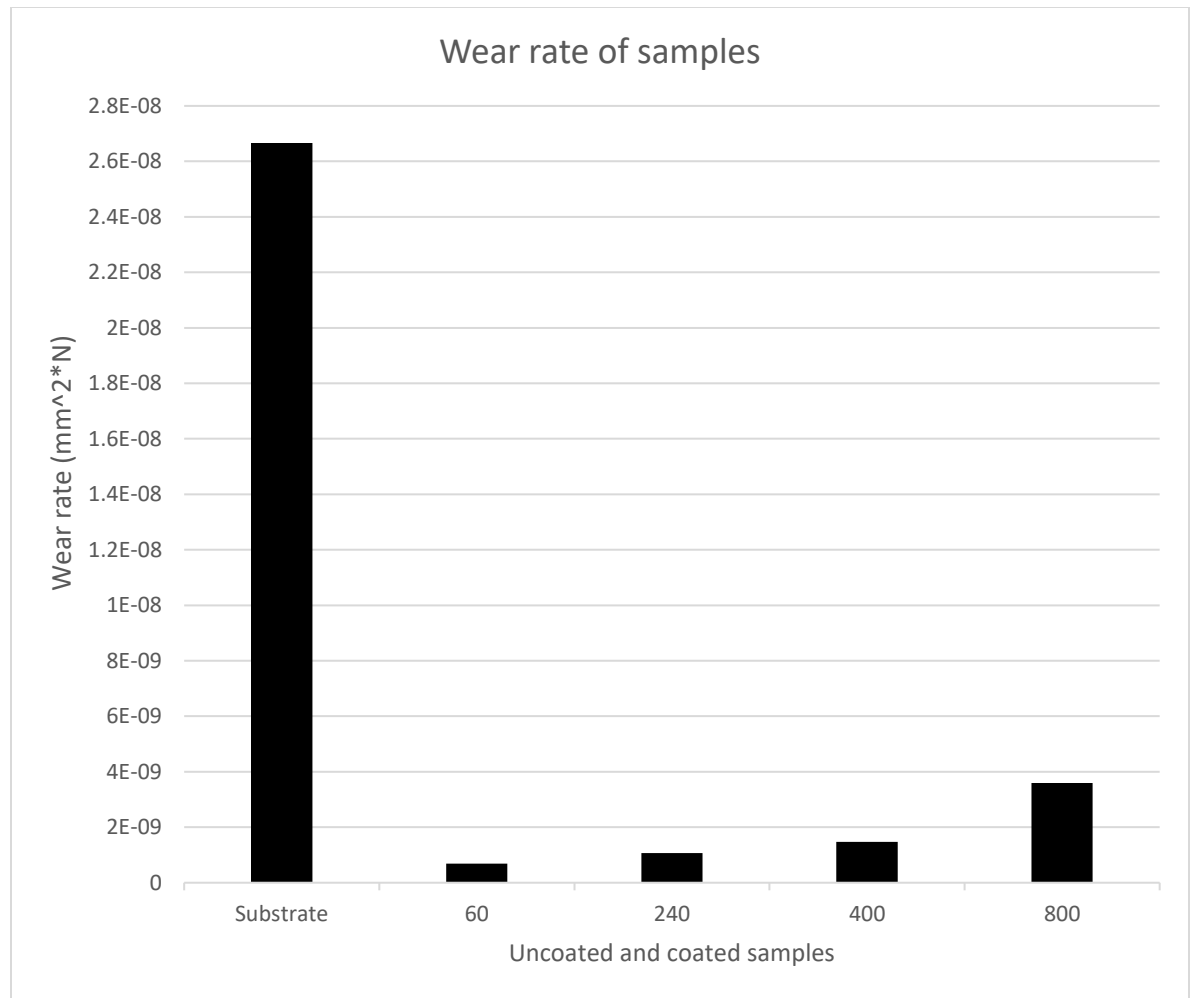


Figure 4.30: Chart for wear rate of coated and uncoated samples

4.2.4 Coefficient of friction

The coefficient of friction (COF) for 600 seconds was also evaluated by using the wear test. Figure 4.31 illustrates COF vs time for the sample that treated with 240 grit-size sandpaper while the rest of samples are in appendix B. COF keeps increasing and then fluctuates until it reaches almost to steady state.

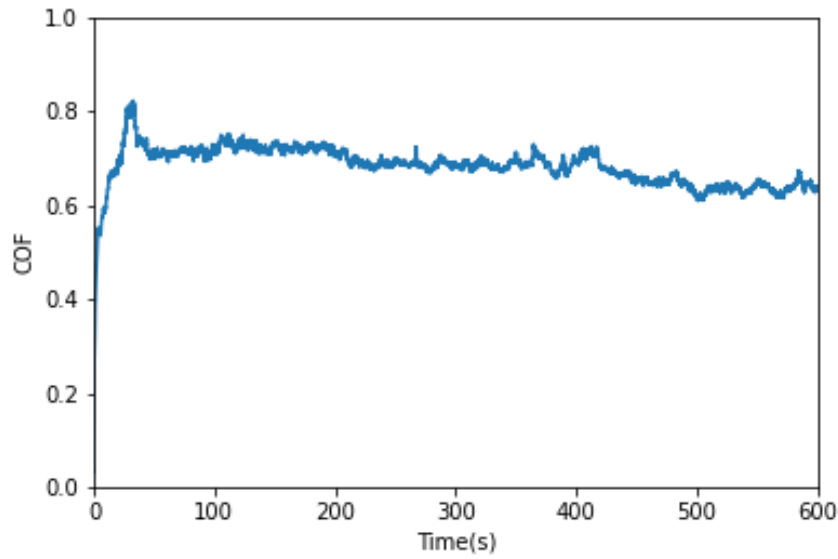


Figure 4.31: COF vs Time for the sample that treated with 240 grit-size sandpaper

From the equations in the Methodology section, wear rates were calculated. The steady-state friction coefficient along with the wear rate and depth of the wear for the substrate and the coated samples are presented in Table 4.5.

Table 4.5: Wear rate with the steady-state friction coefficient and depth of wear for coated and uncoated samples

Sample	Wear rate (mm ² /N)	Steady-state friction coefficient	The depth of wear (um)
Substrate	26.67 * 10⁻⁹	0.38	25
60	0.69 * 10⁻⁹	0.6	1
240	1.07 * 10⁻⁹	0.7	1.25
400	1.47 * 10⁻⁹	0.87	2
800	3.6 * 10⁻⁹	0.9	2.6

CHAPTER 5

CONCLUSIONS

IC engines are an essential part of the automobile industry. Improving its performance will improve the performance of the whole vehicle. However, high friction is the main challenge in the IC engine that must be tackled. To overcome this challenge, first, a hard PVD coating of CrNiAlSiN was developed on a grey cast iron substrate prepared at different surface conditions for IC engine application. CrAlSiN hard coating exhibits pretty good mechanical properties that result in good tribological properties. Nickel element has good wear resistance which is the main feature needed for the components of IC engine. So, the coating of CrNiAlSiN is a promising solution to the problem. SEM was used to visualize the morphology and the cross-sectional view, while EDX was used to provide elemental analysis and the distribution of the elements at the surface. Roughness before and after the coating and 3-D images of the surfaces were illustrated by the profilometer. In general, the roughness of the coatings increased when the surfaces of the substrate increased. The hardness of the coatings measured using 20mN load revealed that CrNiAlSiN coating enhances the hardness. The wear resistance in 60 coated samples is higher than the uncoated one by 25 times. The wear resistance was higher in the sample with 60 grit-size, followed by 240, 400, and 800 grit-size. In a similar way, the wear depth was significantly reduced from 25 μm for the substrate, to an average of 3.4 μm for all

coated samples. Also, the steady-state friction coefficient of all coated samples had values greater than that for the uncoated one. The improvement of the surface hardness by depositing the CrNiAlSiN coating enhances the wear resistance, thereby increasing the lifetime of the IC engines.

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Appendix A

November 2022

Polished - 200mN

Sample specifications

Reference	:	Client	:
Operator	:		
Poisson's ratio	0.3		
Substrate	:		

Indentation # 1

Indentation parameters

Standard

Standard

+ Instrument : MHTX S/N: 01-04300

+ Hardware settings

Fn contact : 10 mN

Approach speed : 16600.001 nm/min

Dz sensor in standard range

Load in fine range

X Position :96.89 mm

Y Position :97.75 mm

+ Measurement

Acquisition Rate : 10.0 [Hz]

Linear Loading

Max load : 200.00 mN

Loading rate : 400.00 mN/min

Unloading rate : 400.00 mN/min

Pause : 10.0 s

Date : 24/11/2022

Hour : 16:32:38

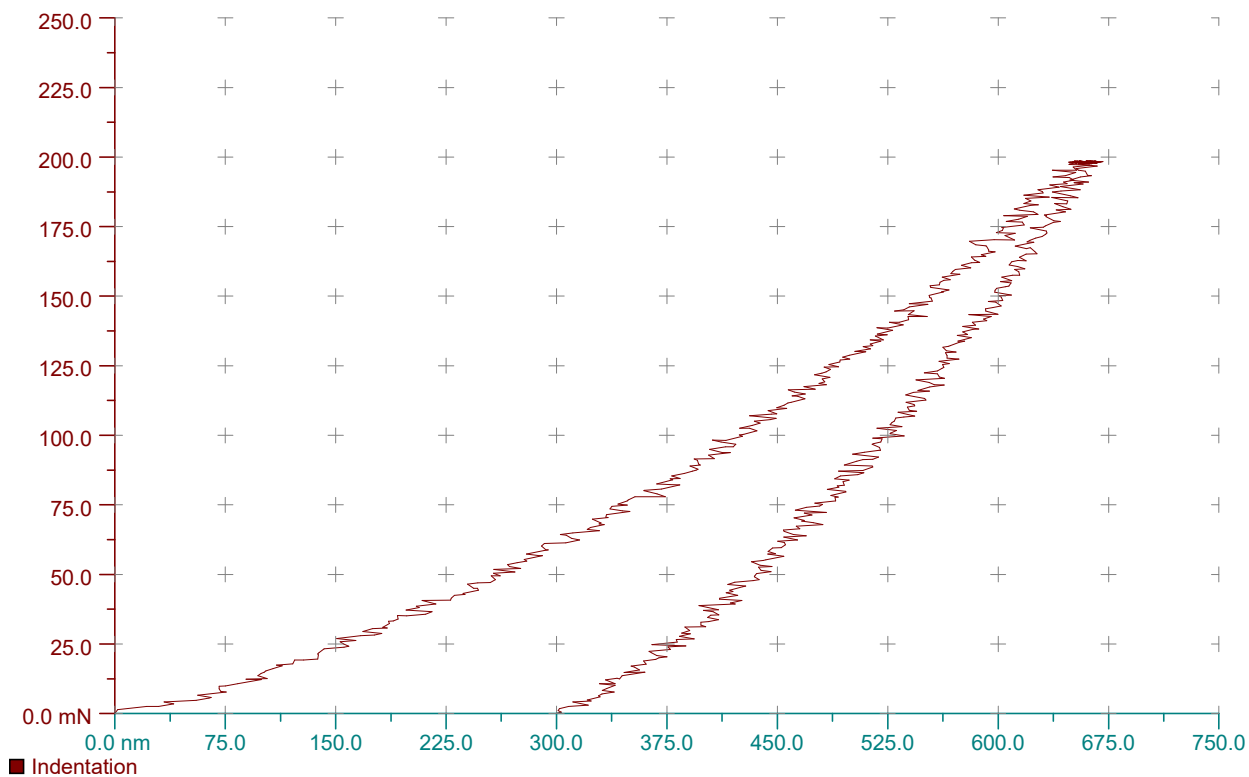
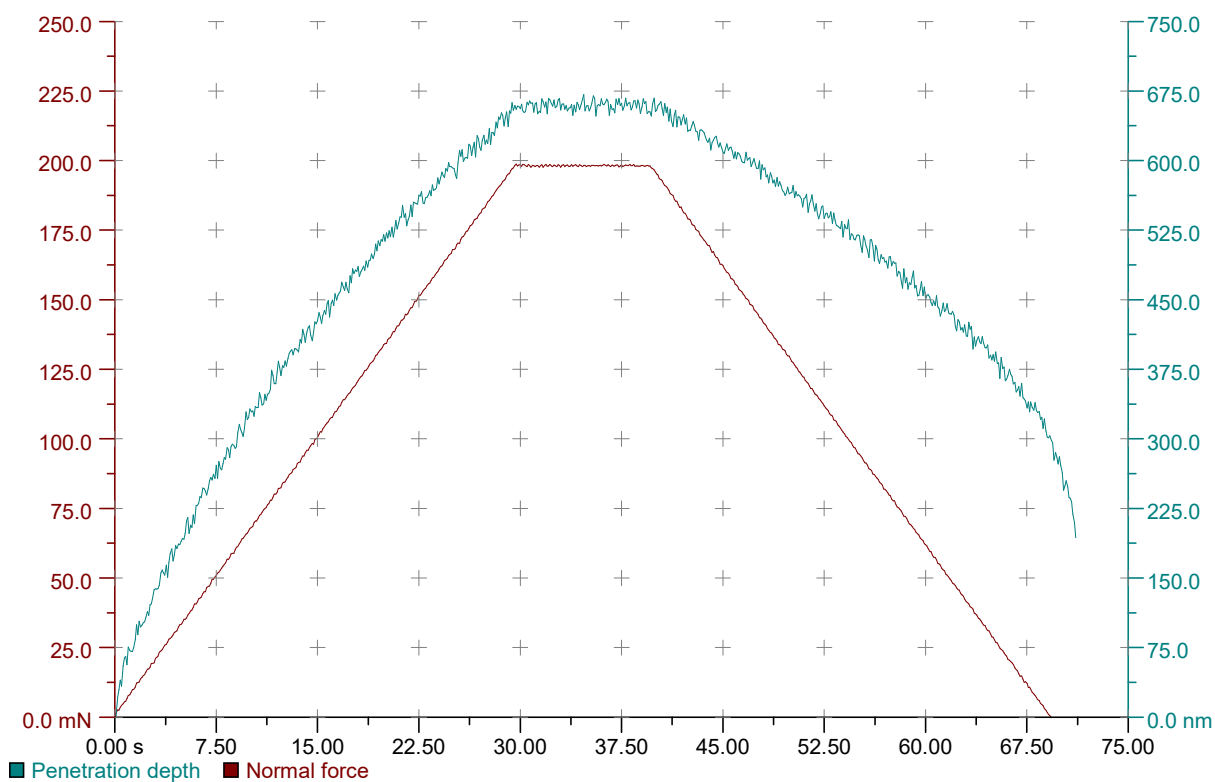
Indenters

Type : Vickers

Serial number : V-H 86

Material : Diamond

Curves



Indentation # 2

Indentation parameters

Standard

Standard

+ Instrument : MHTX S/N: 01-04300

+ Hardware settings

Fn contact : 10 mN

Approach speed : 16600.001 nm/min

Dz sensor in standard range

Load in fine range

X Position :97.39 mm

Y Position :97.75 mm

+ Measurement

Acquisition Rate : 10.0 [Hz]

Linear Loading

Max load : 200.00 mN

Loading rate : 400.00 mN/min

Unloading rate : 400.00 mN/min

Pause : 10.0 s

Date : 24/11/2022

Hour : 16:35:42

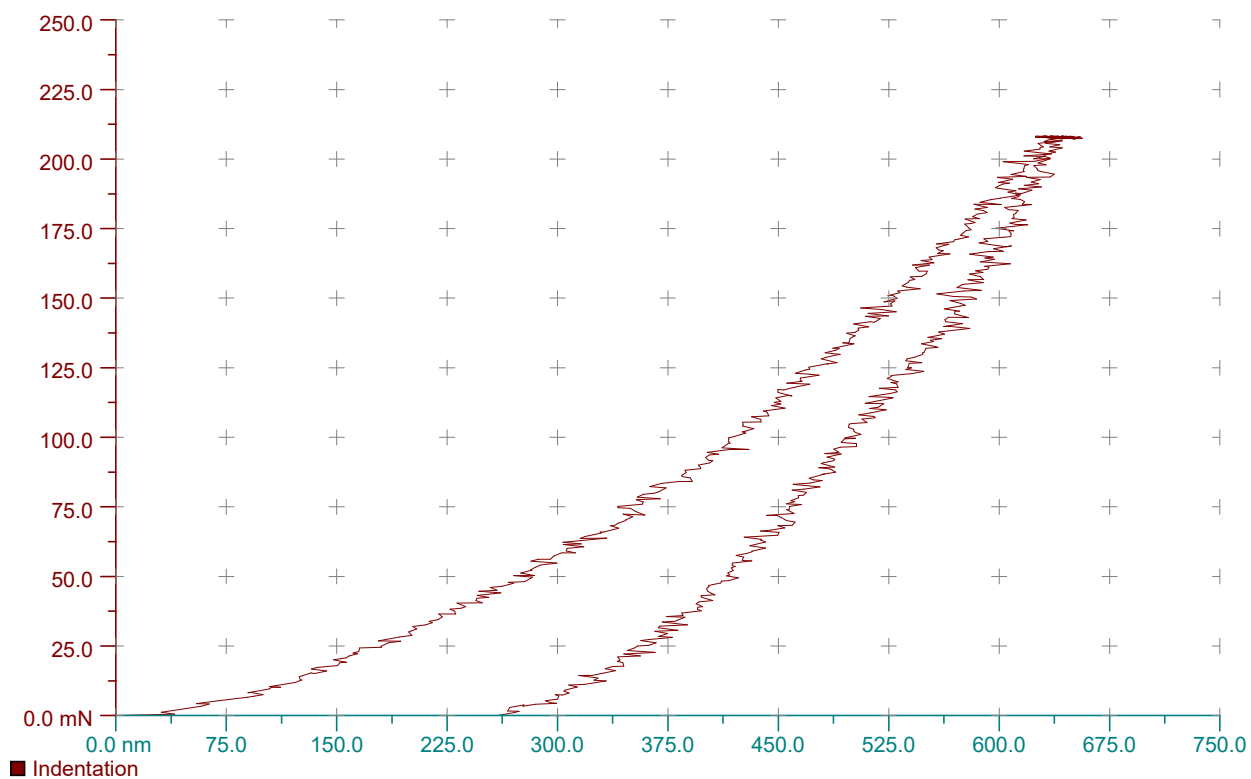
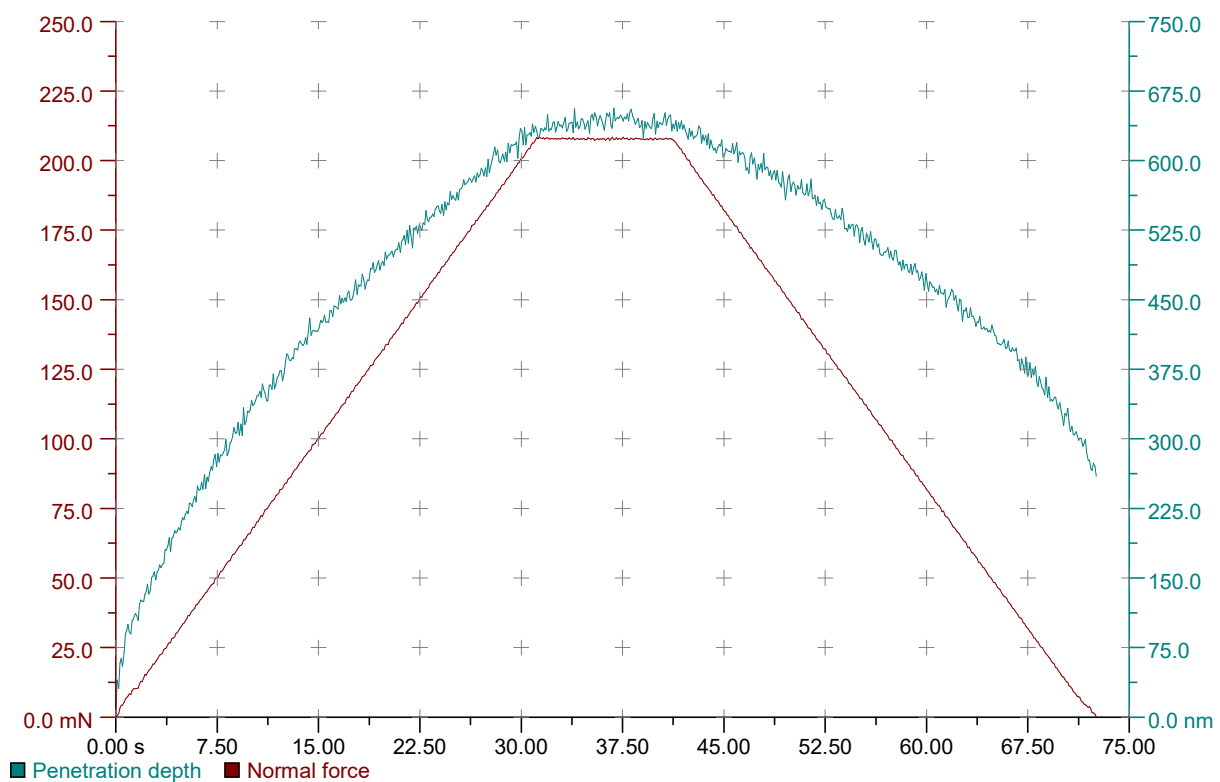
Indenters

Type : Vickers

Serial number : V-H 86

Material : Diamond

Curves



Indentation # 3

Indentation parameters

Standard

Standard

+ Instrument : MHTX S/N: 01-04300

+ Hardware settings

Fn contact : 10 mN

Approach speed : 16600.001 nm/min

Dz sensor in standard range

Load in fine range

X Position :97.89 mm

Y Position :97.75 mm

+ Measurement

Acquisition Rate : 10.0 [Hz]

Linear Loading

Max load : 200.00 mN

Loading rate : 400.00 mN/min

Unloading rate : 400.00 mN/min

Pause : 10.0 s

Date : 24/11/2022

Hour : 16:38:34

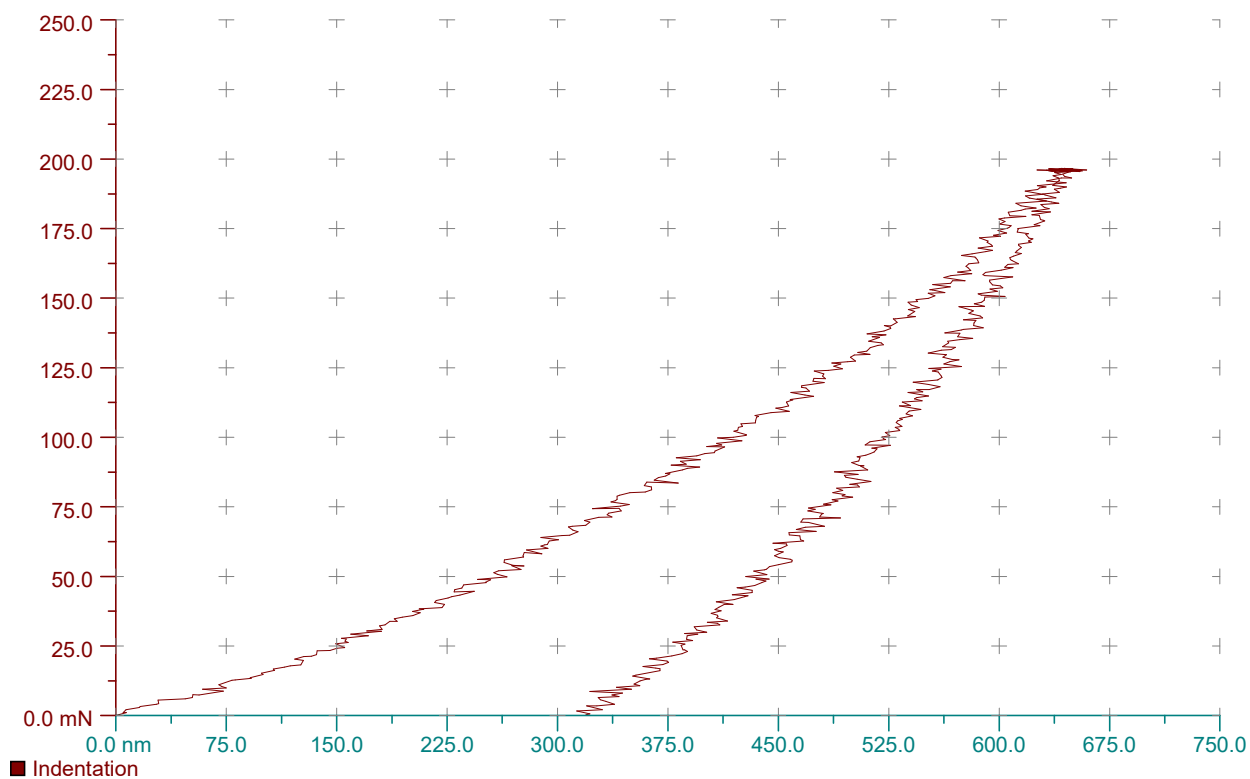
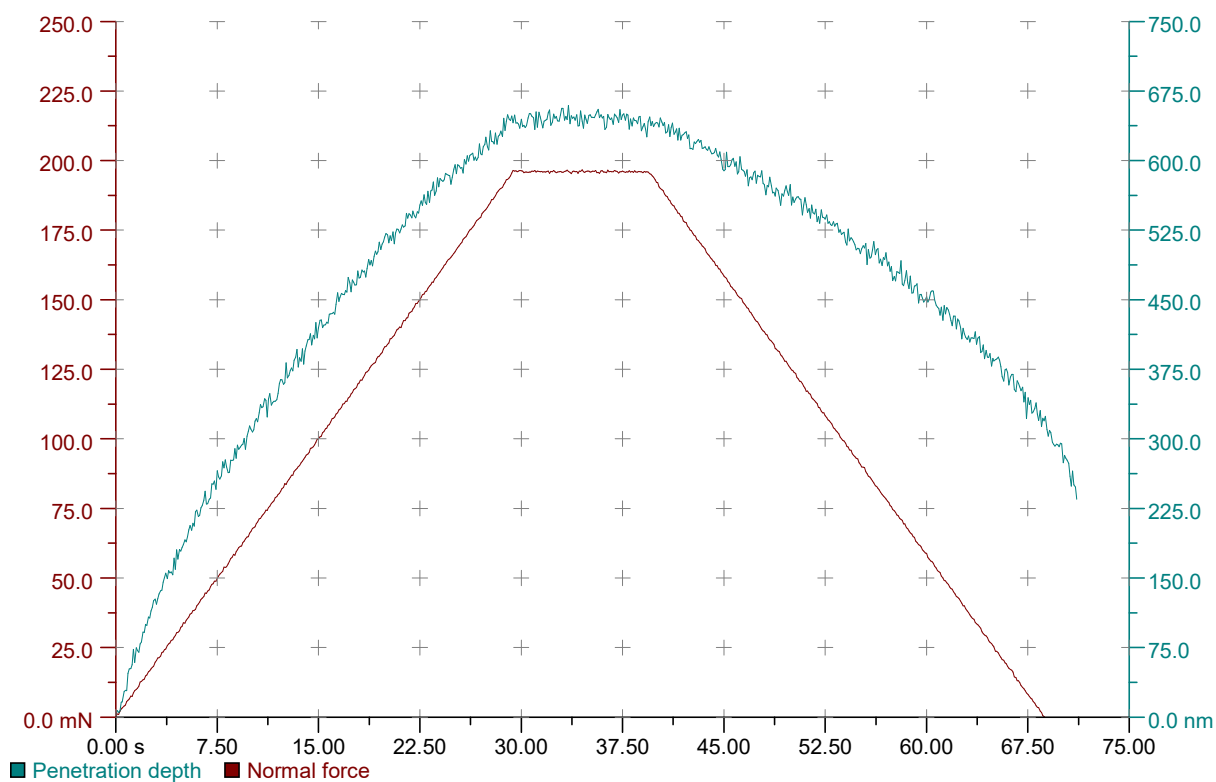
Indenters

Type : Vickers

Serial number : V-H 86

Material : Diamond

Curves



Indentation # 4

Indentation parameters

Standard

Standard

+ Instrument : MHTX S/N: 01-04300

+ Hardware settings

Fn contact : 10 mN

Approach speed : 16600.001 nm/min

Dz sensor in standard range

Load in fine range

X Position :98.39 mm

Y Position :97.75 mm

+ Measurement

Acquisition Rate : 10.0 [Hz]

Linear Loading

Max load : 200.00 mN

Loading rate : 400.00 mN/min

Unloading rate : 400.00 mN/min

Pause : 10.0 s

Date : 24/11/2022

Hour : 16:41:32

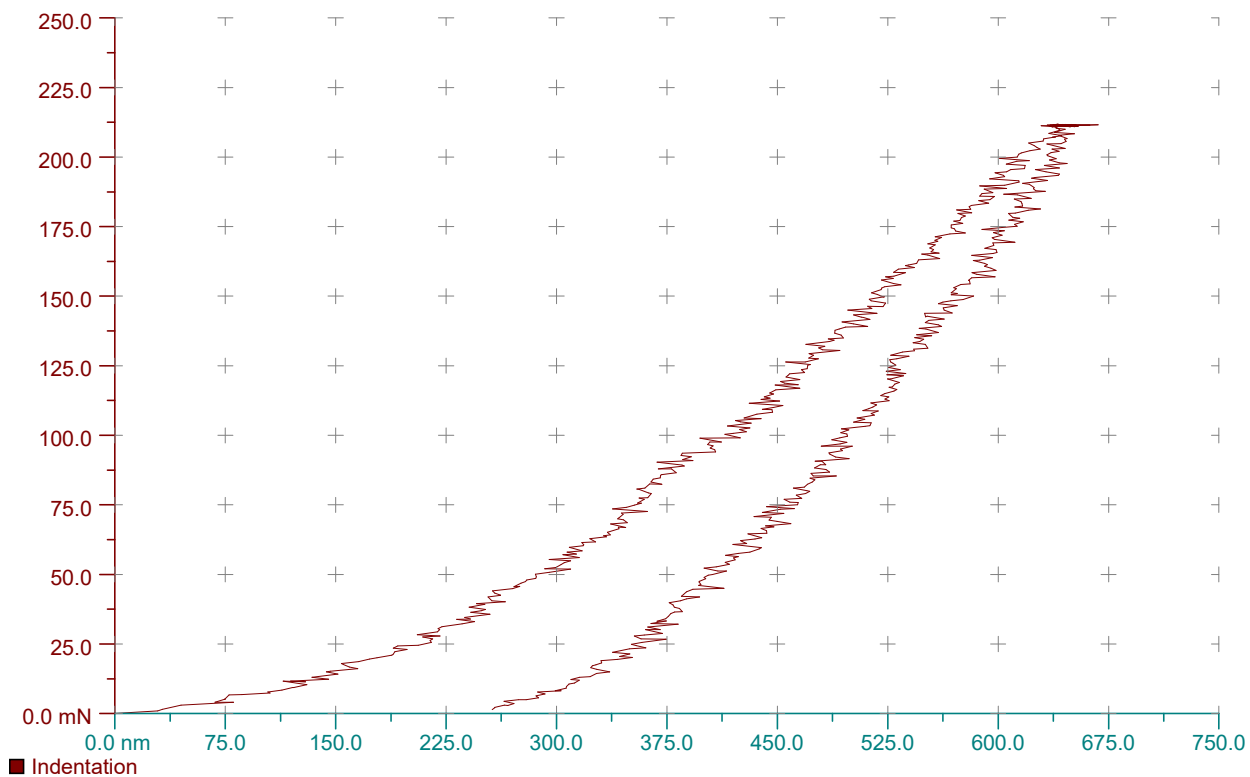
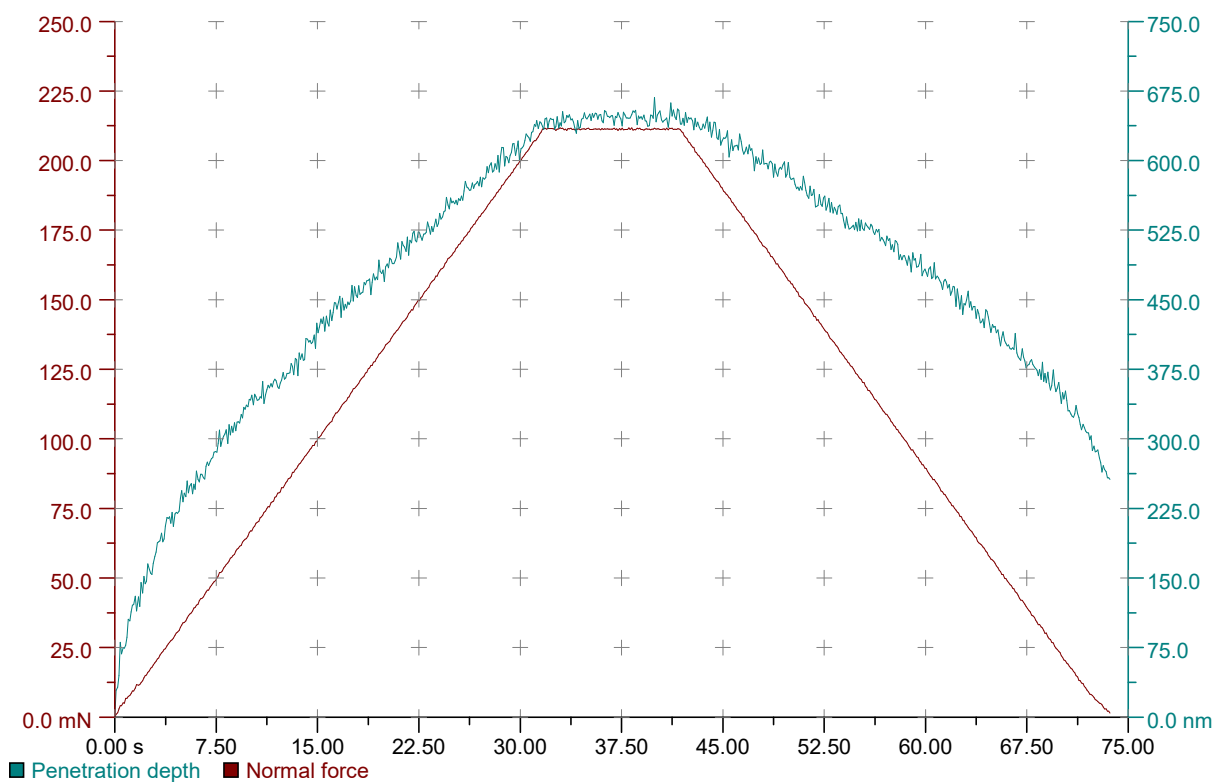
Indenters

Type : Vickers

Serial number : V-H 86

Material : Diamond

Curves



Indentation # 5

Indentation parameters

Standard

Standard

+ Instrument : MHTX S/N: 01-04300

+ Hardware settings

Fn contact : 10 mN

Approach speed : 16600.001 nm/min

Dz sensor in standard range

Load in fine range

X Position :99.39 mm

Y Position :97.75 mm

+ Measurement

Acquisition Rate : 10.0 [Hz]

Linear Loading

Max load : 200.00 mN

Loading rate : 400.00 mN/min

Unloading rate : 400.00 mN/min

Pause : 10.0 s

Date : 24/11/2022

Hour : 16:47:54

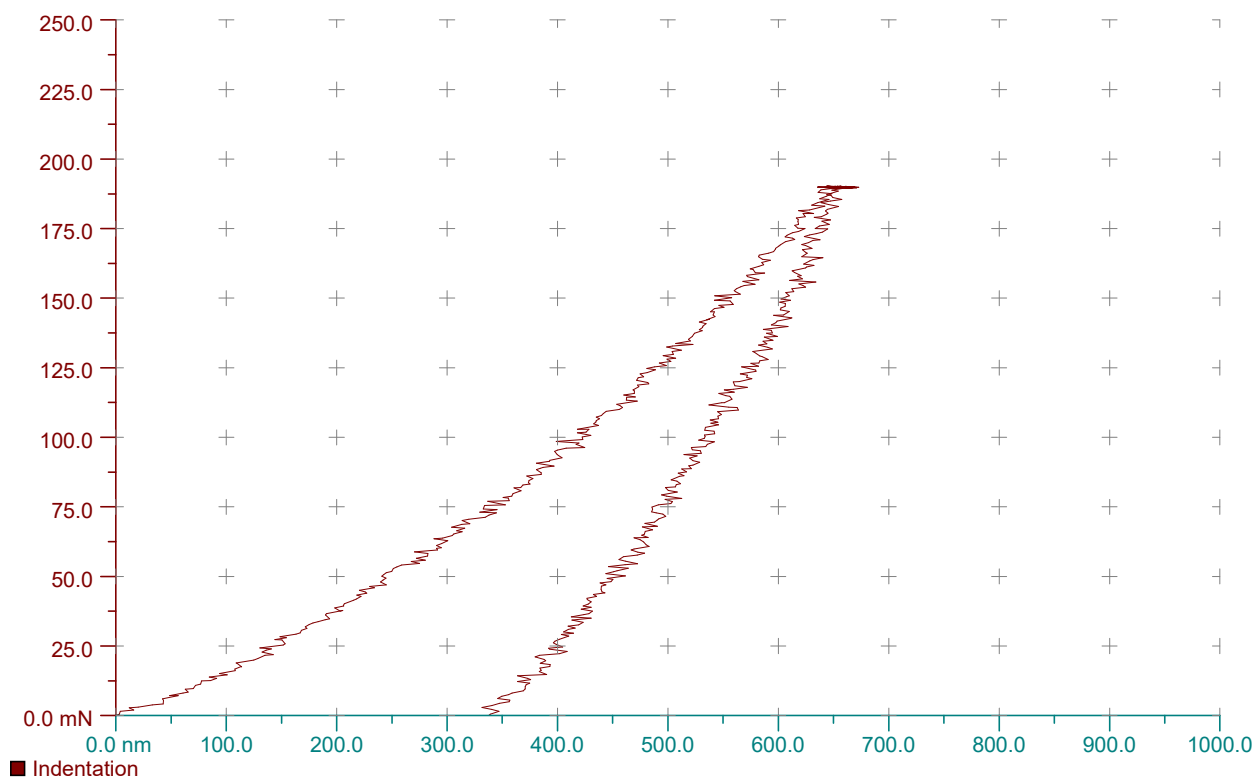
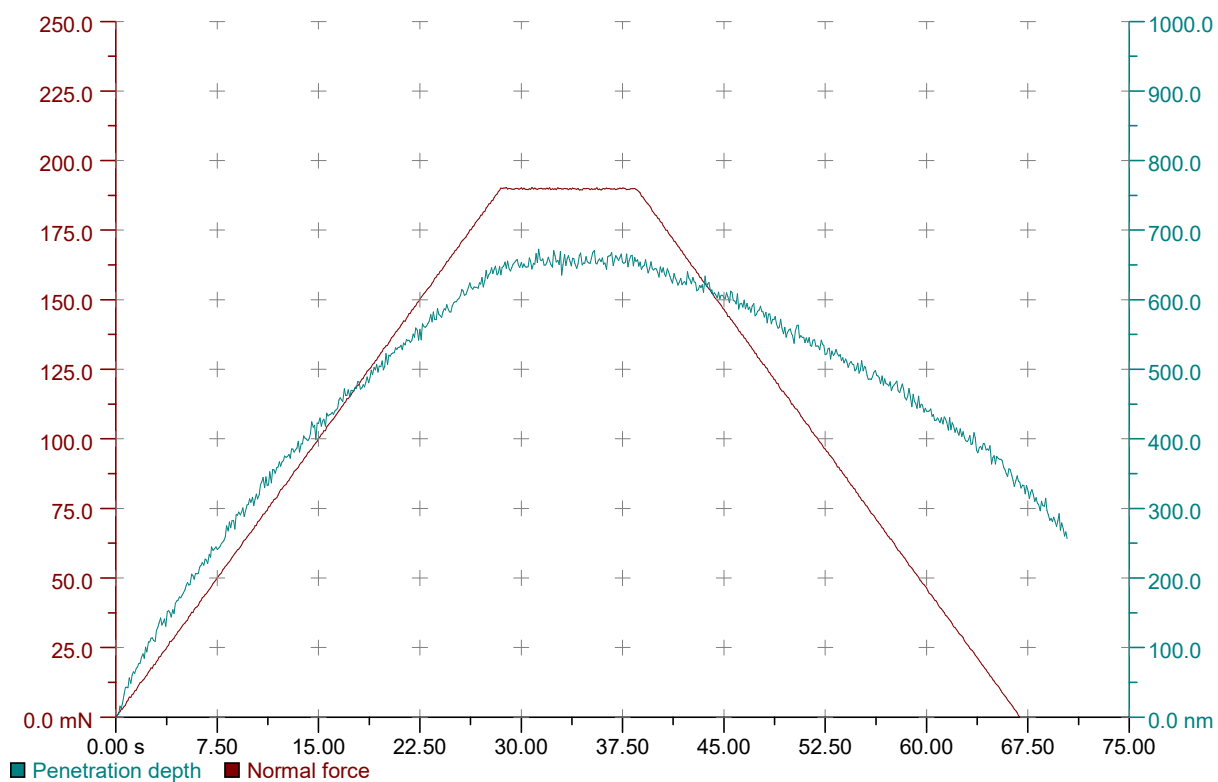
Indenters

Type : Vickers

Serial number : V-H 86

Material : Diamond

Curves



60-200mN

Sample specifications

Reference	:	Client	:
Operator	:		
Poisson's ratio	0.3		
Substrate	:		

Indentation # 1

Indentation parameters

Standard

Standard

+ Instrument : MHTX S/N: 01-04300

+ Hardware settings

Fn contact : 10 mN

Approach speed : 16600.001 nm/min

Dz sensor in standard range

Load in fine range

X Position :97.22 mm

Y Position :96.90 mm

+ Measurement

Acquisition Rate : 10.0 [Hz]

Linear Loading

Max load : 200.00 mN

Loading rate : 400.00 mN/min

Unloading rate : 400.00 mN/min

Pause : 10.0 s

Date : 24/11/2022

Hour : 17:02:39

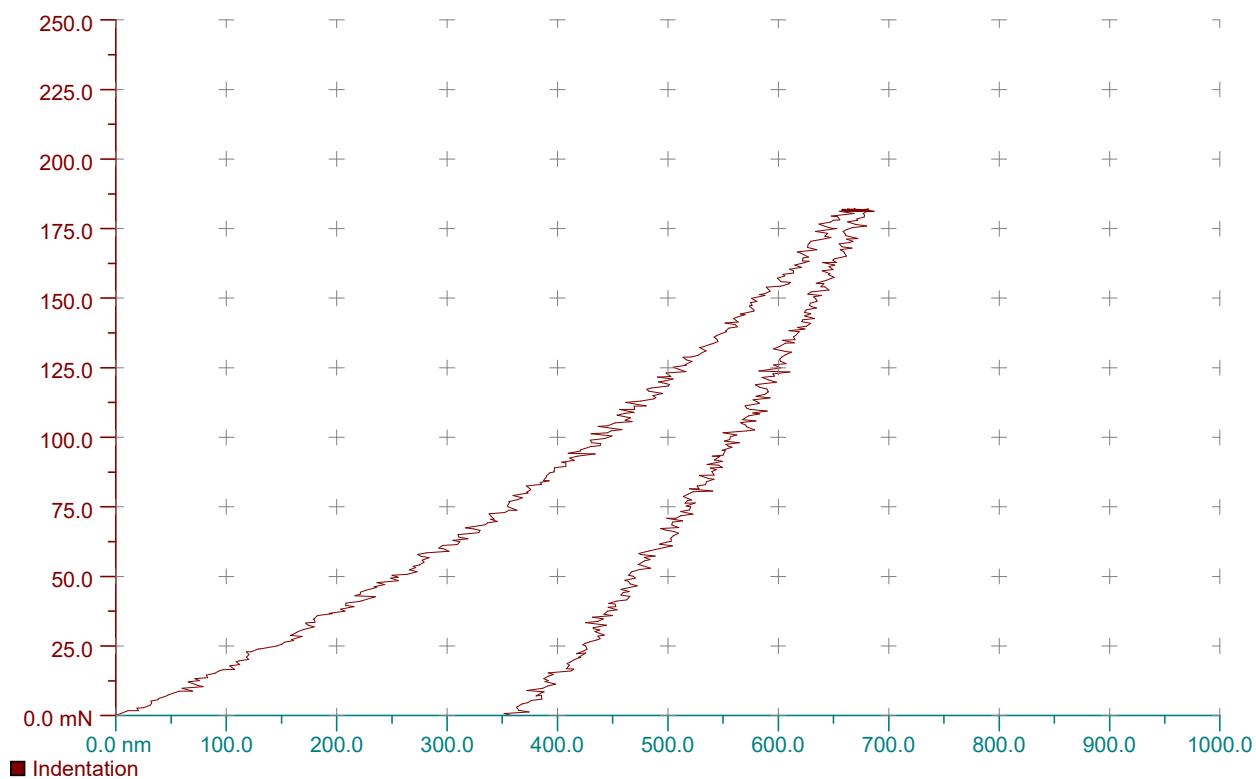
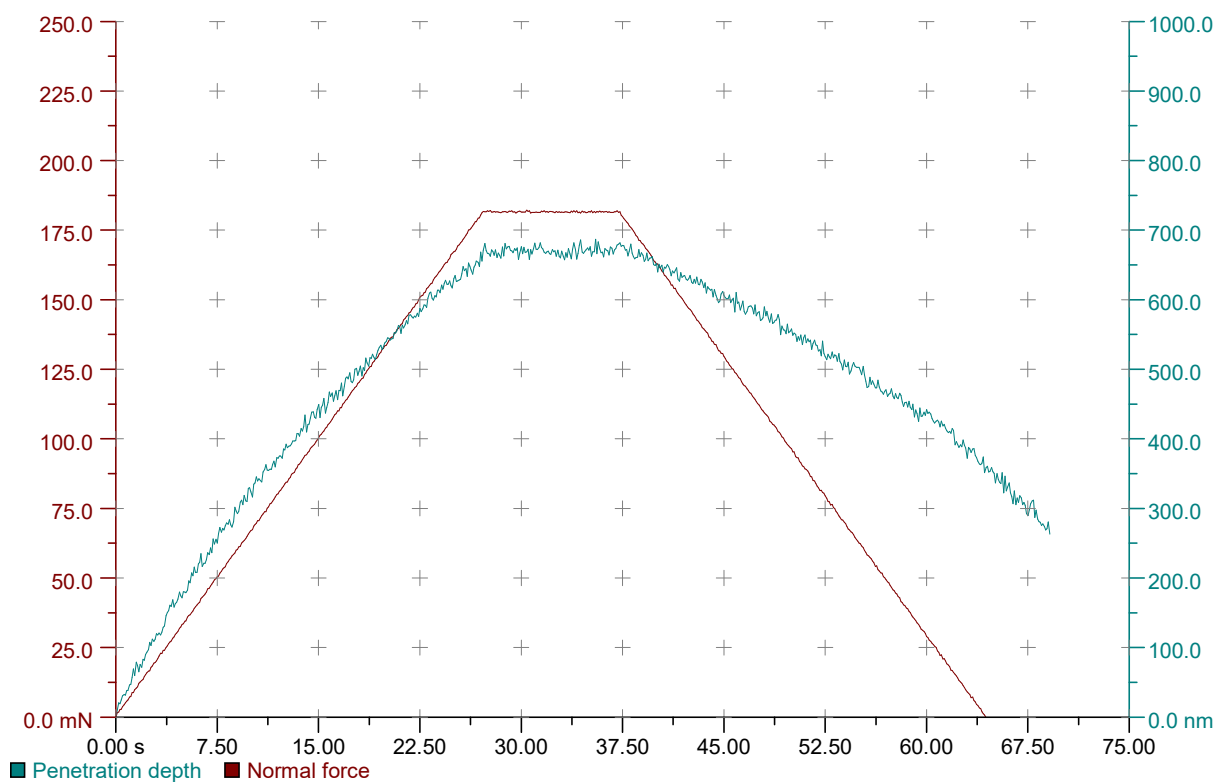
Indenters

Type : Vickers

Serial number : V-H 86

Material : Diamond

Curves



Indentation # 2

Indentation parameters

Standard

Standard

+ Instrument : MHTX S/N: 01-04300

+ Hardware settings

Fn contact : 10 mN

Approach speed : 16600.001 nm/min

Dz sensor in standard range

Load in fine range

X Position :98.22 mm

Y Position :96.90 mm

+ Measurement

Acquisition Rate : 10.0 [Hz]

Linear Loading

Max load : 200.00 mN

Loading rate : 400.00 mN/min

Unloading rate : 400.00 mN/min

Pause : 10.0 s

Date : 24/11/2022

Hour : 17:08:35

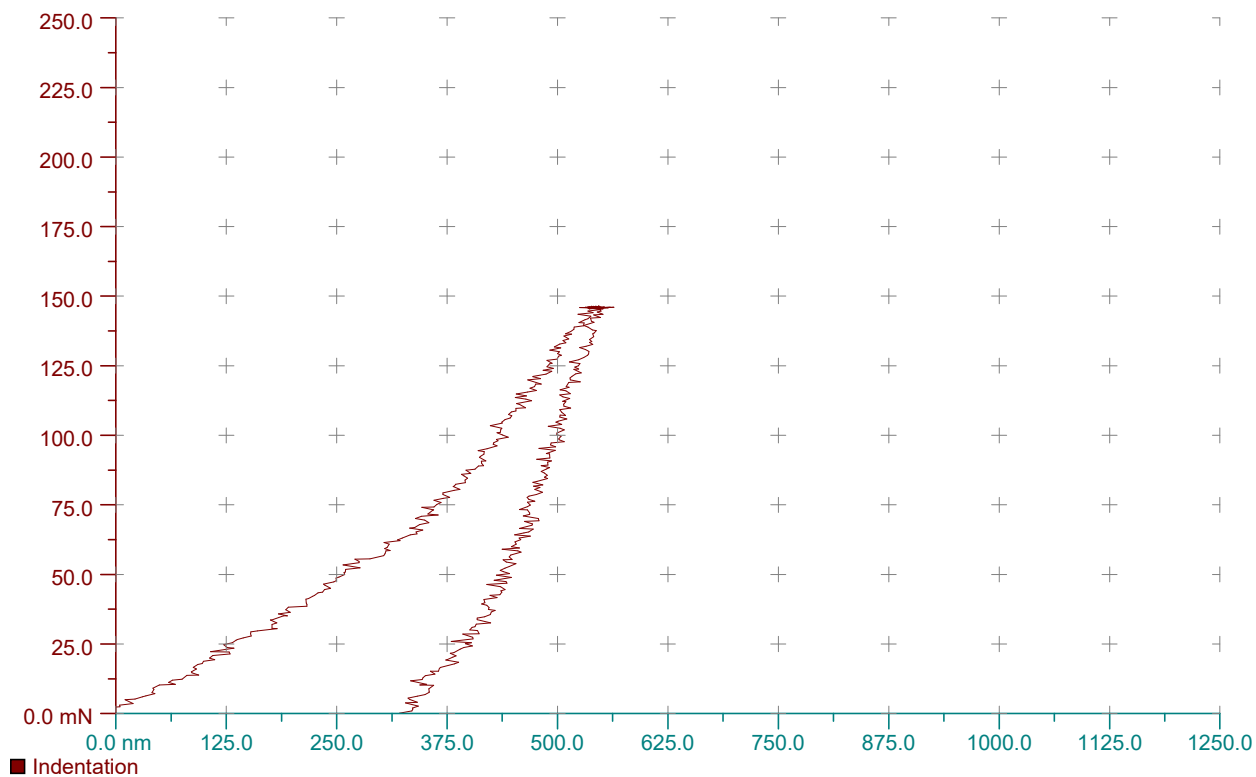
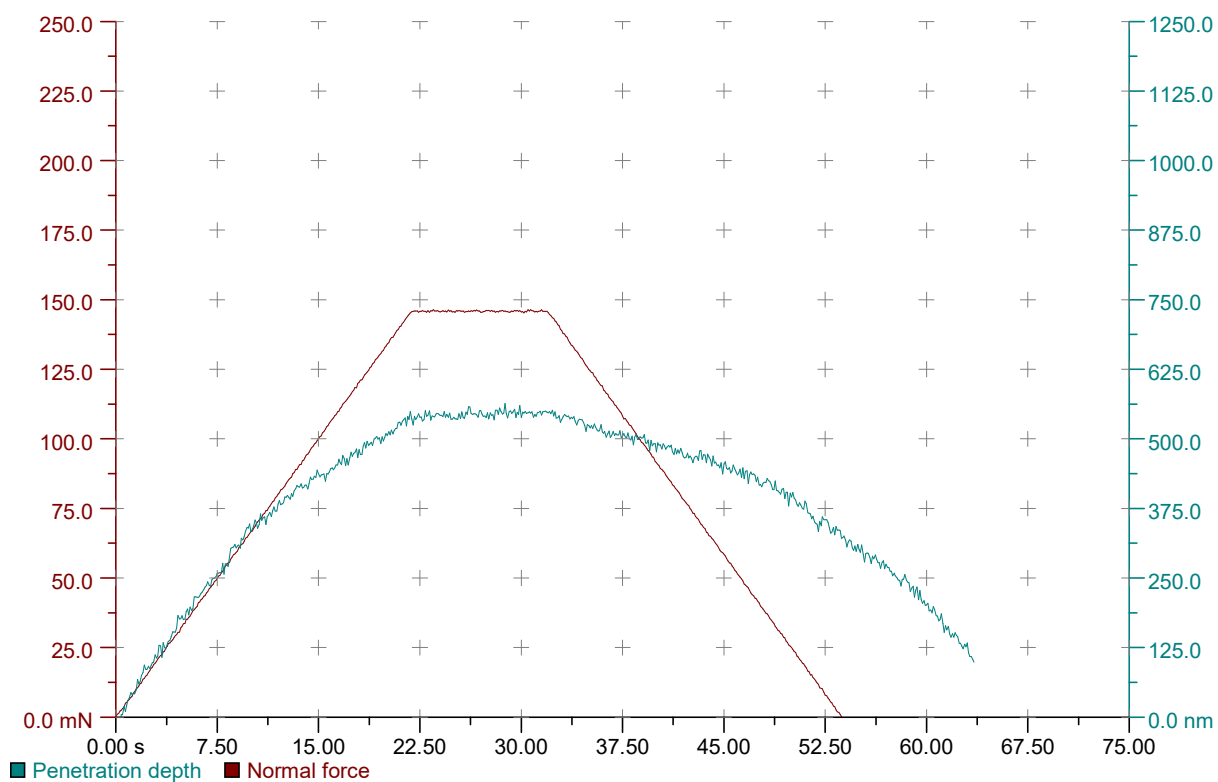
Indenters

Type : Vickers

Serial number : V-H 86

Material : Diamond

Curves



Indentation # 3

Indentation parameters

Standard

Standard

+ Instrument : MHTX S/N: 01-04300

+ Hardware settings

Fn contact : 10 mN

Approach speed : 16600.001 nm/min

Dz sensor in standard range

Load in fine range

X Position :99.22 mm

Y Position :96.90 mm

+ Measurement

Acquisition Rate : 10.0 [Hz]

Linear Loading

Max load : 200.00 mN

Loading rate : 400.00 mN/min

Unloading rate : 400.00 mN/min

Pause : 10.0 s

Date : 24/11/2022

Hour : 17:14:46

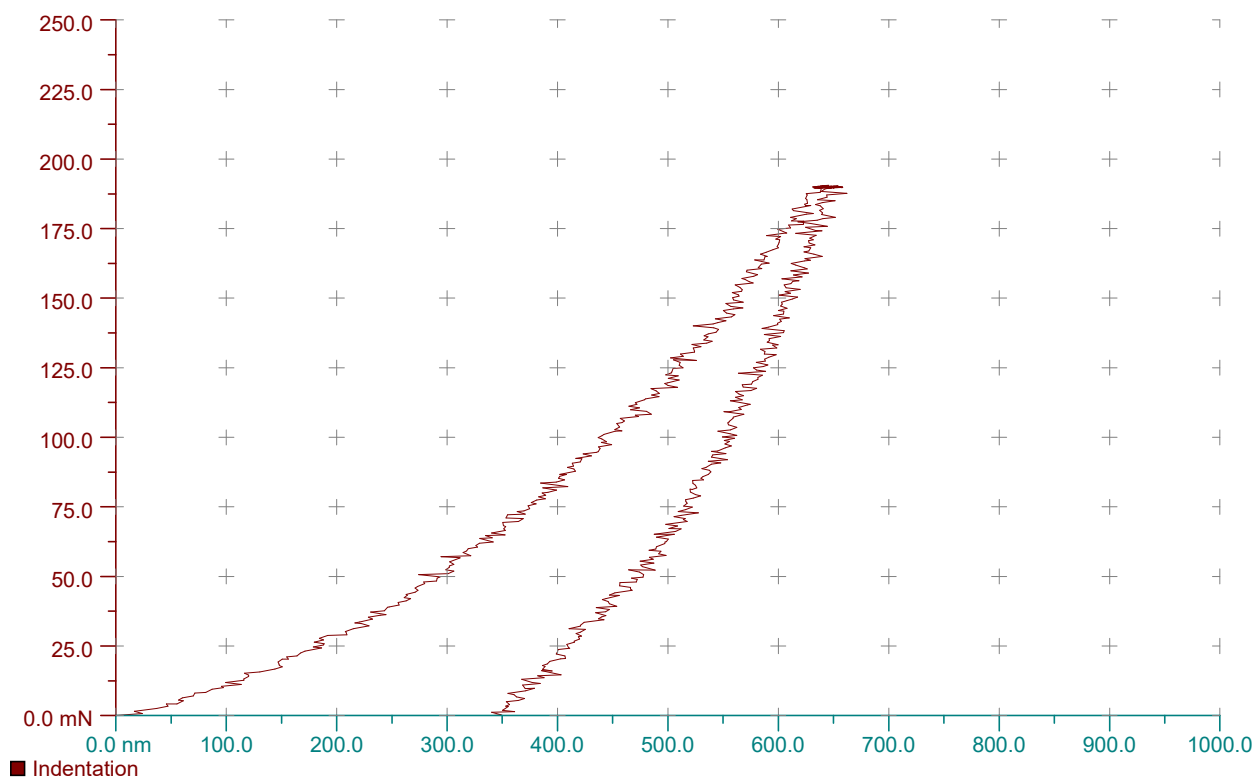
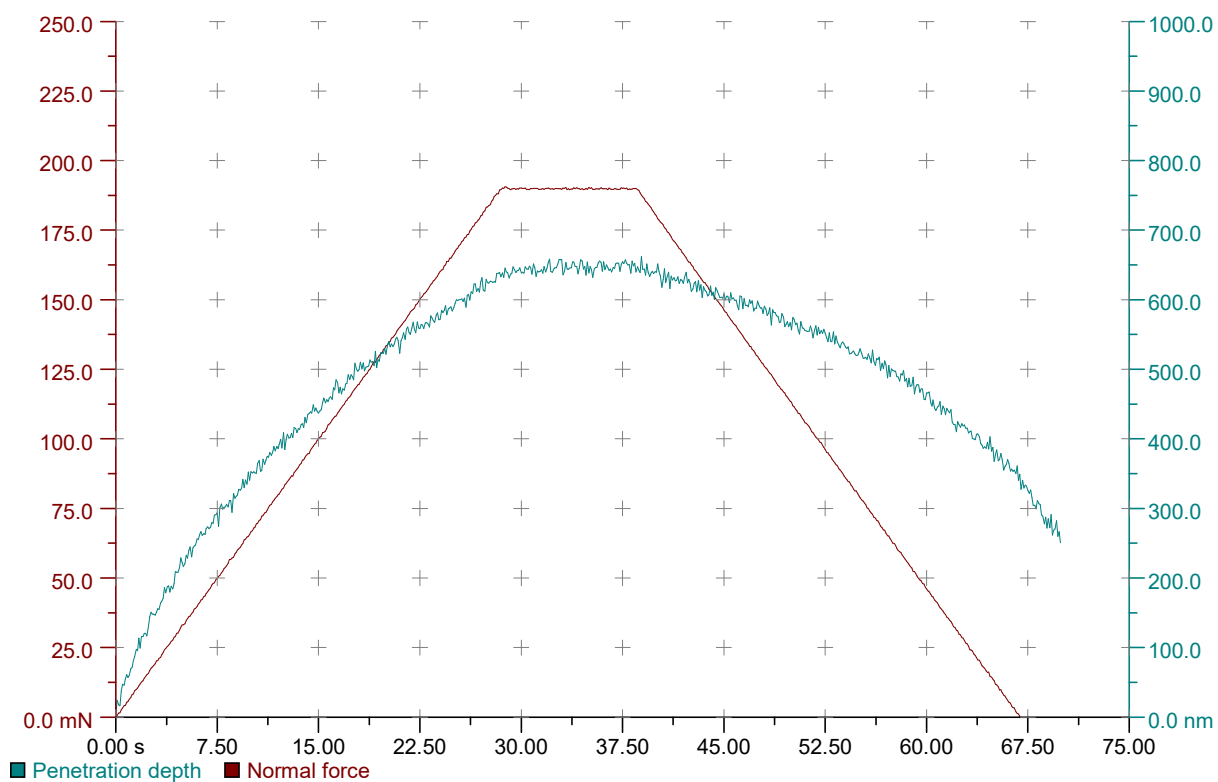
Indenters

Type : Vickers

Serial number : V-H 86

Material : Diamond

Curves



Indentation # 4

Indentation parameters

Standard

Standard

+ Instrument : MHTX S/N: 01-04300

+ Hardware settings

Fn contact : 10 mN

Approach speed : 16600.001 nm/min

Dz sensor in standard range

Load in fine range

X Position :99.72 mm

Y Position :96.90 mm

+ Measurement

Acquisition Rate : 10.0 [Hz]

Linear Loading

Max load : 200.00 mN

Loading rate : 400.00 mN/min

Unloading rate : 400.00 mN/min

Pause : 10.0 s

Date : 24/11/2022

Hour : 17:18:04

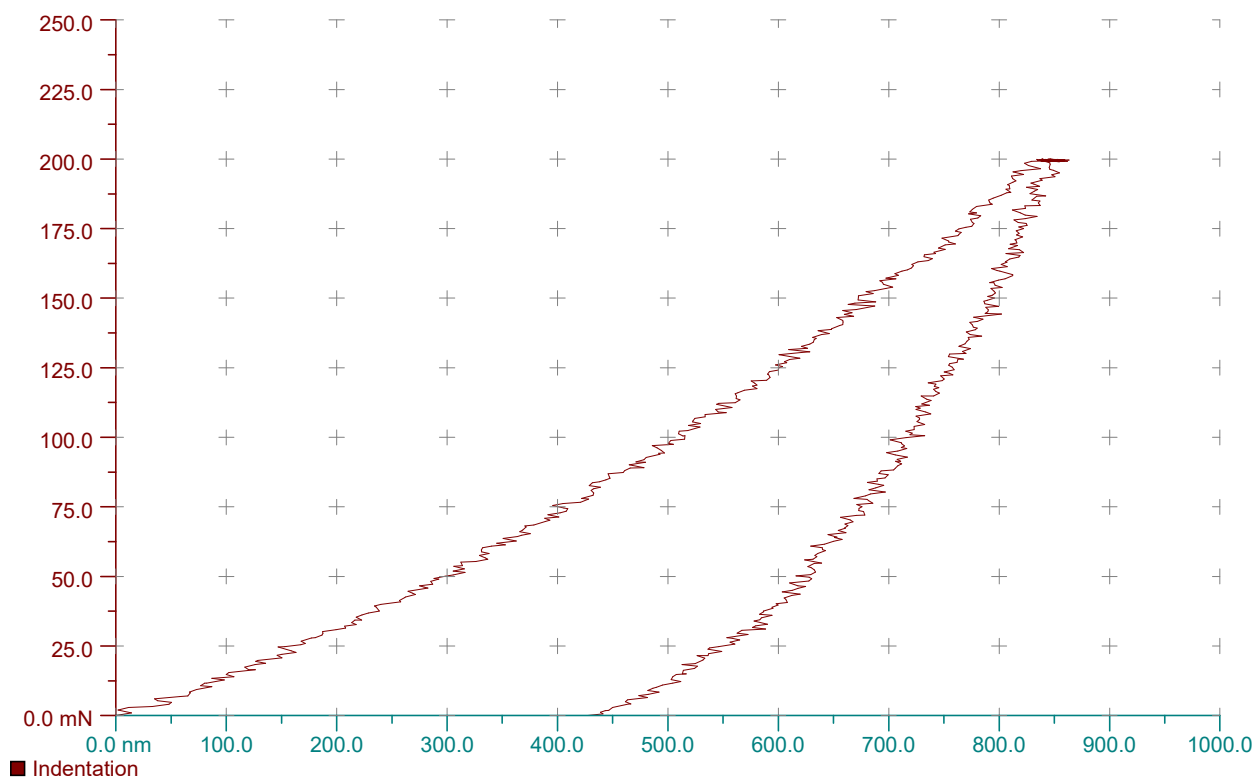
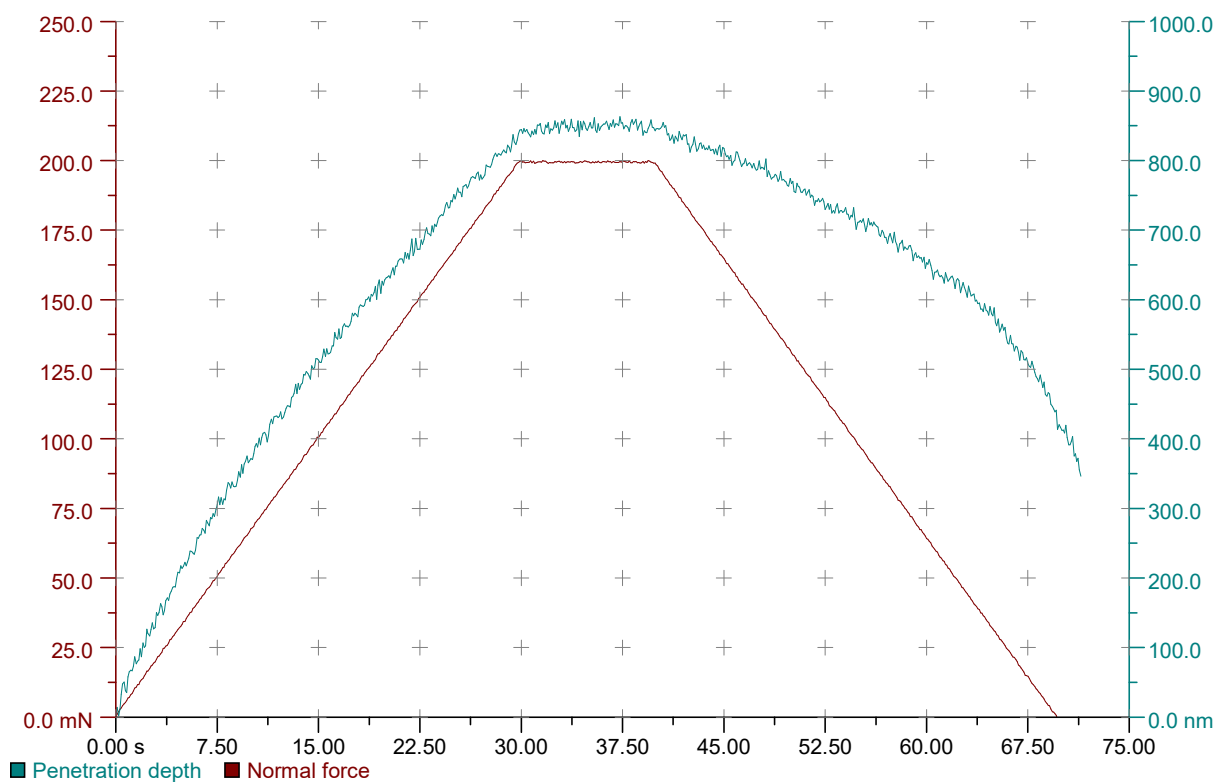
Indenters

Type : Vickers

Serial number : V-H 86

Material : Diamond

Curves



240-200mN

Sample specifications

Reference	:	Client	:
Operator	:		
Poisson's ratio	0.3		
Substrate	:		

Indentation # 1

Indentation parameters

Standard

Standard

+ Instrument : MHTX S/N: 01-04300

+ Hardware settings

Fn contact : 10 mN

Approach speed : 16600.001 nm/min

Dz sensor in standard range

Load in fine range

X Position :98.16 mm

Y Position :96.64 mm

+ Measurement

Acquisition Rate : 10.0 [Hz]

Linear Loading

Max load : 200.00 mN

Loading rate : 400.00 mN/min

Unloading rate : 400.00 mN/min

Pause : 10.0 s

Date : 24/11/2022

Hour : 17:32:05

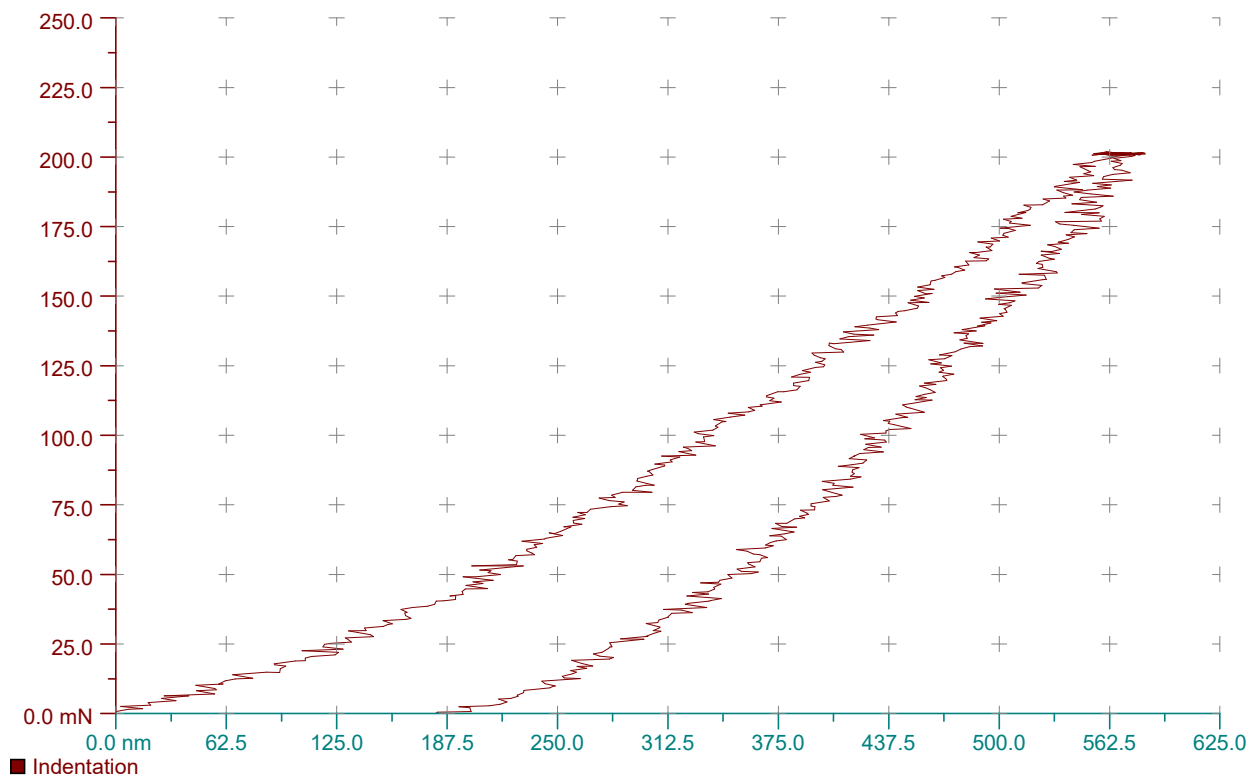
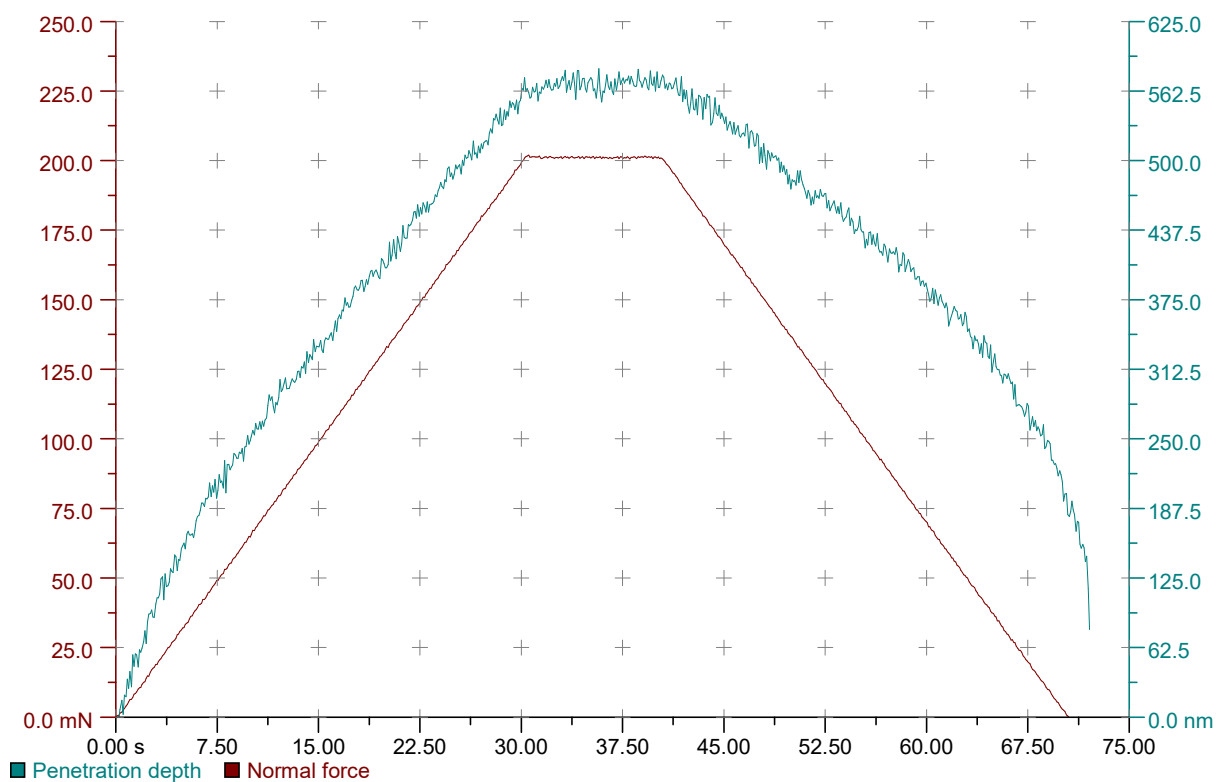
Indenters

Type : Vickers

Serial number : V-H 86

Material : Diamond

Curves



Indentation # 2

Indentation parameters

Standard

Standard

+ Instrument : MHTX S/N: 01-04300

+ Hardware settings

Fn contact : 10 mN

Approach speed : 16600.001 nm/min

Dz sensor in standard range

Load in fine range

X Position :98.66 mm

Y Position :96.64 mm

+ Measurement

Acquisition Rate : 10.0 [Hz]

Linear Loading

Max load : 200.00 mN

Loading rate : 400.00 mN/min

Unloading rate : 400.00 mN/min

Pause : 10.0 s

Date : 24/11/2022

Hour : 17:34:53

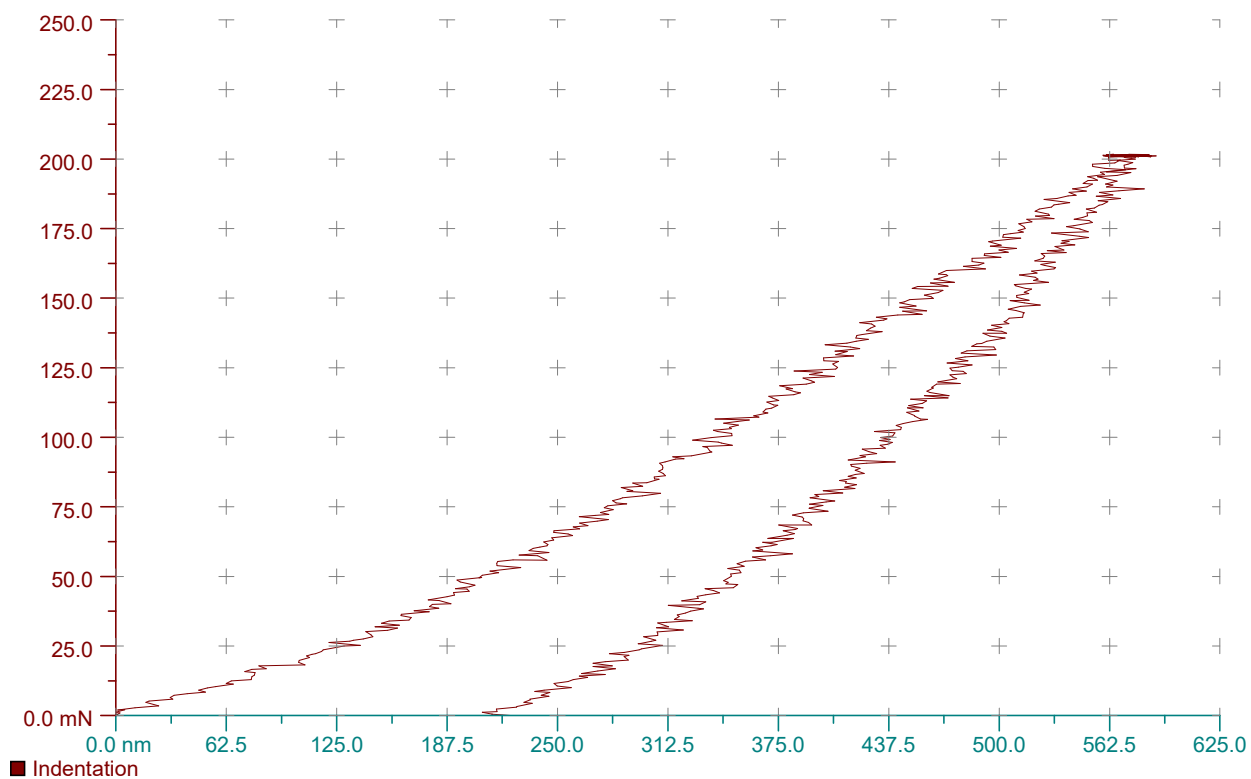
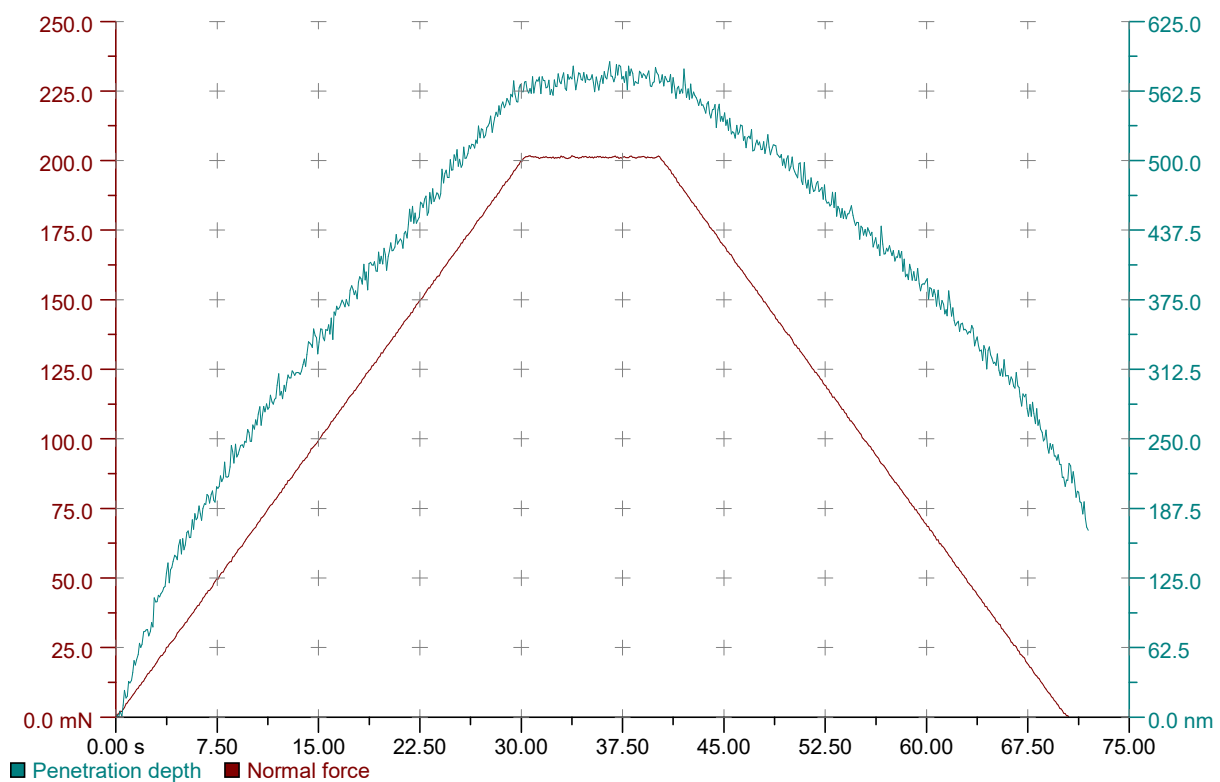
Indenters

Type : Vickers

Serial number : V-H 86

Material : Diamond

Curves



Indentation # 3

Indentation parameters

Standard

Standard

+ Instrument : MHTX S/N: 01-04300

+ Hardware settings

Fn contact : 10 mN

Approach speed : 16600.001 nm/min

Dz sensor in standard range

Load in fine range

X Position :99.16 mm

Y Position :96.64 mm

+ Measurement

Acquisition Rate : 10.0 [Hz]

Linear Loading

Max load : 200.00 mN

Loading rate : 400.00 mN/min

Unloading rate : 400.00 mN/min

Pause : 10.0 s

Date : 24/11/2022

Hour : 17:37:41

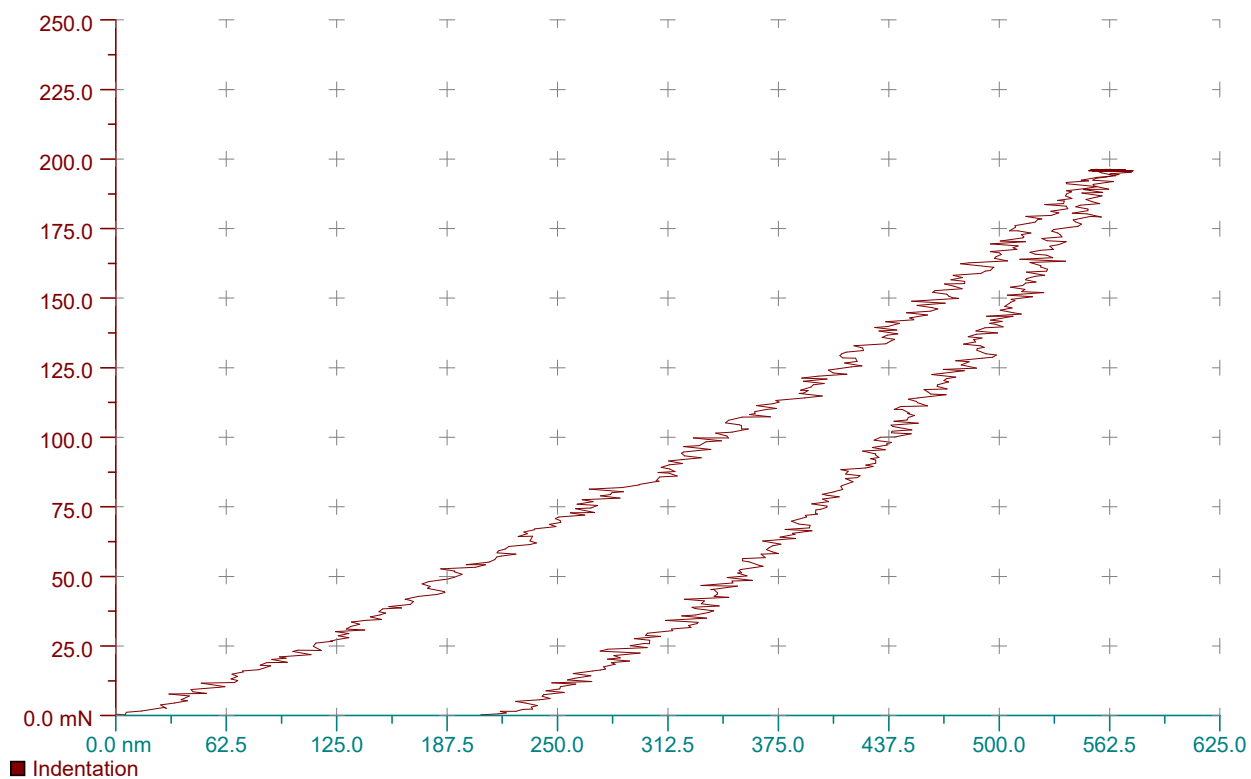
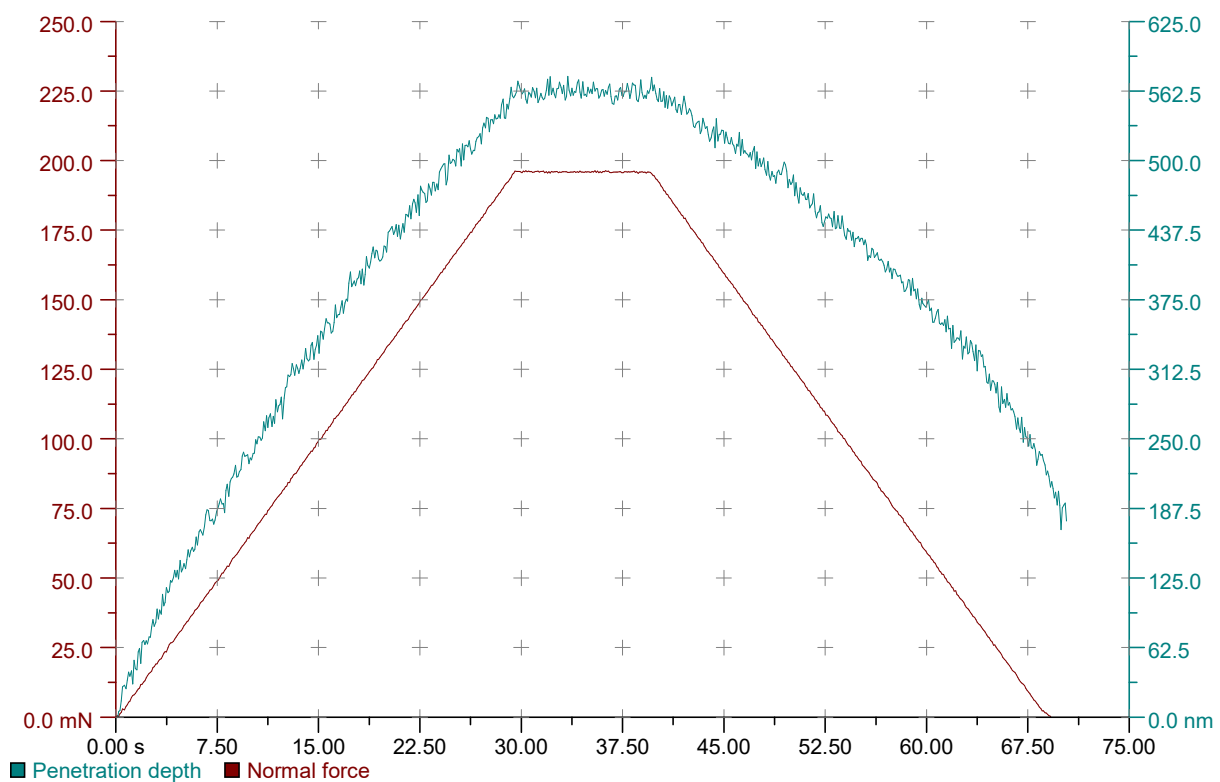
Indenters

Type : Vickers

Serial number : V-H 86

Material : Diamond

Curves



Indentation # 4

Indentation parameters

Standard

Standard

+ Instrument : MHTX S/N: 01-04300

+ Hardware settings

Fn contact : 10 mN

Approach speed : 16600.001 nm/min

Dz sensor in standard range

Load in fine range

X Position :99.66 mm

Y Position :96.64 mm

+ Measurement

Acquisition Rate : 10.0 [Hz]

Linear Loading

Max load : 200.00 mN

Loading rate : 400.00 mN/min

Unloading rate : 400.00 mN/min

Pause : 10.0 s

Date : 24/11/2022

Hour : 17:40:30

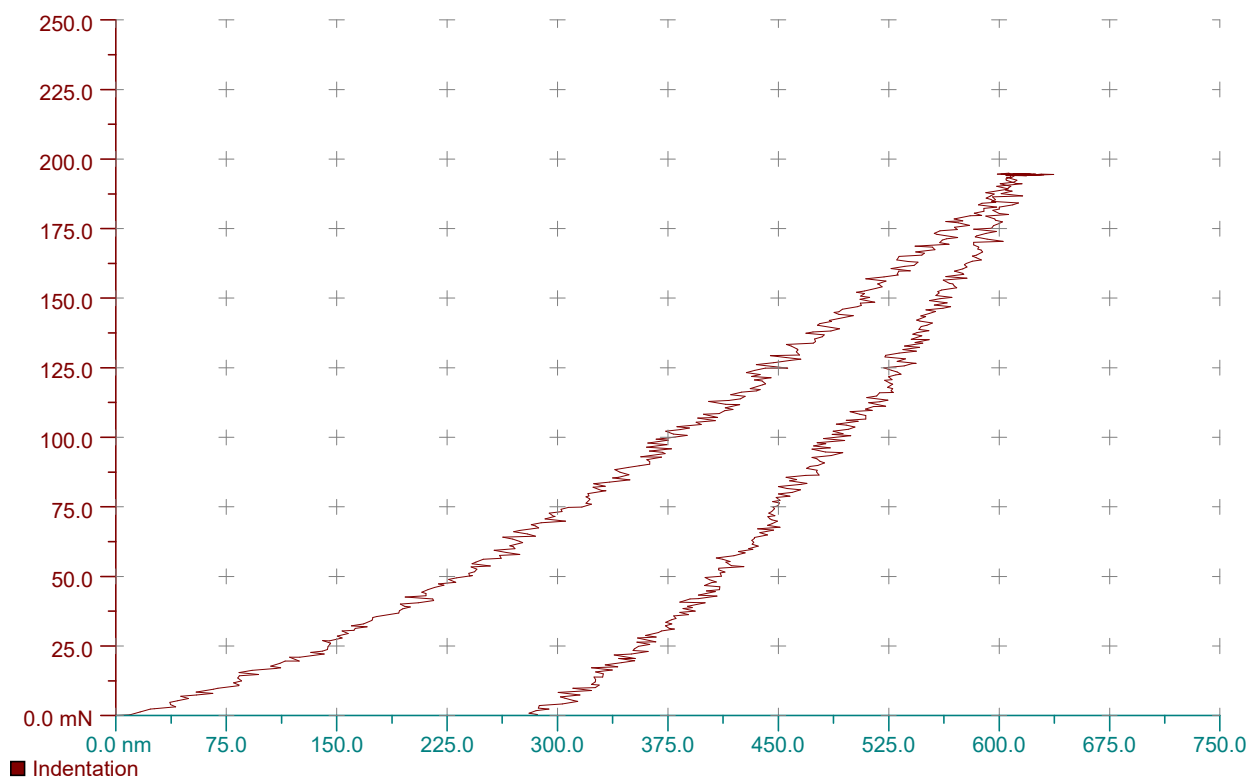
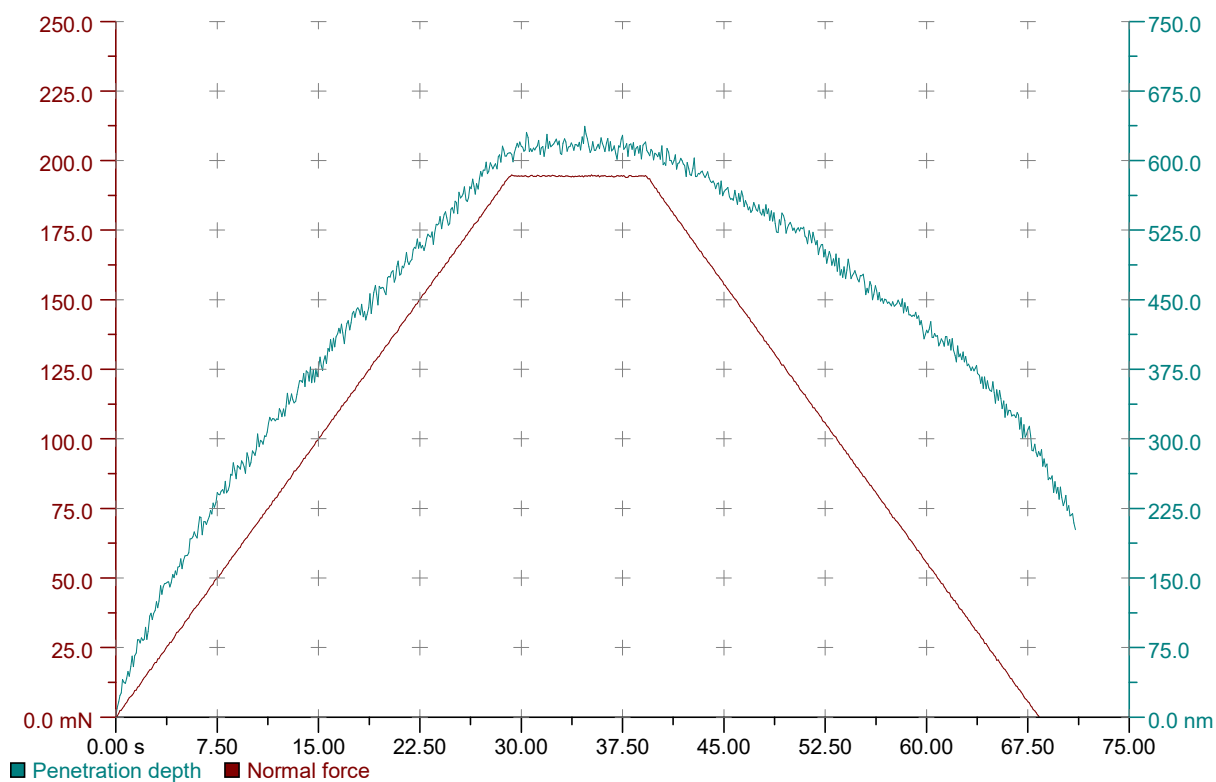
Indenters

Type : Vickers

Serial number : V-H 86

Material : Diamond

Curves



Indentation # 5

Indentation parameters

Standard

Standard

+ Instrument : MHTX S/N: 01-04300

+ Hardware settings

Fn contact : 10 mN

Approach speed : 16600.001 nm/min

Dz sensor in standard range

Load in fine range

X Position : 100.16 mm

Y Position : 96.64 mm

+ Measurement

Acquisition Rate : 10.0 [Hz]

Linear Loading

Max load : 200.00 mN

Loading rate : 400.00 mN/min

Unloading rate : 400.00 mN/min

Pause : 10.0 s

Date : 24/11/2022

Hour : 17:43:24

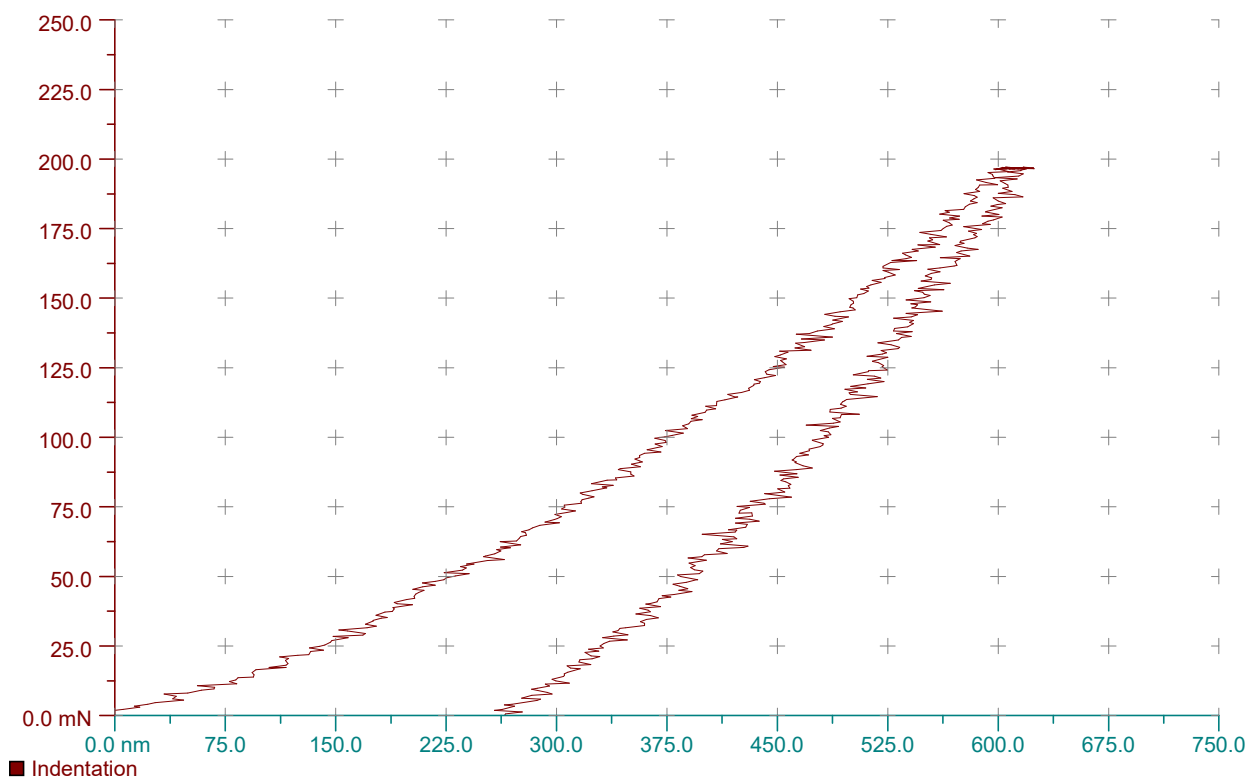
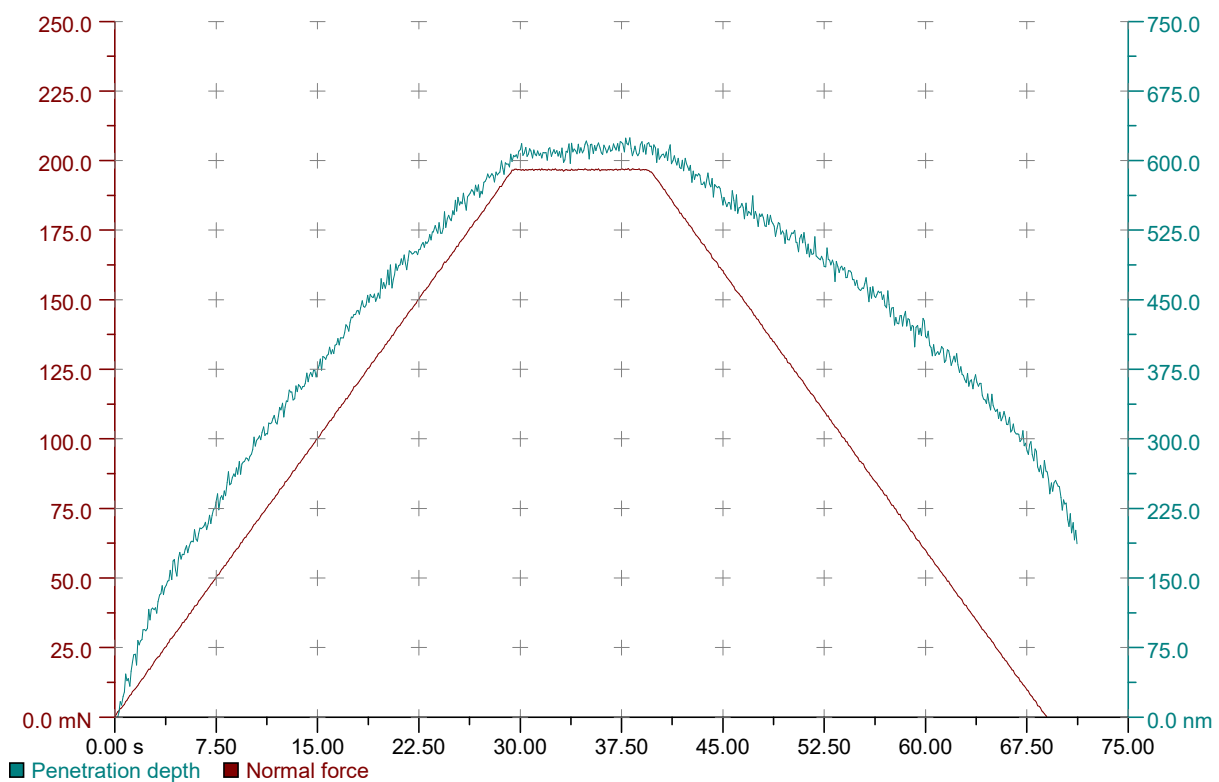
Indenters

Type : Vickers

Serial number : V-H 86

Material : Diamond

Curves



400-200mN

Sample specifications

Reference	:	Client	:
Operator	:		
Poisson's ratio	0.3		
Substrate	:		

Indentation # 1

Indentation parameters

Standard

Standard

+ Instrument : MHTX S/N: 01-04300

+ Hardware settings

Fn contact : 10 mN

Approach speed : 16600.001 nm/min

Dz sensor in standard range

Load in fine range

X Position :97.66 mm

Y Position :96.02 mm

+ Measurement

Acquisition Rate : 10.0 [Hz]

Linear Loading

Max load : 200.00 mN

Loading rate : 400.00 mN/min

Unloading rate : 400.00 mN/min

Pause : 10.0 s

Date : 24/11/2022

Hour : 17:55:04

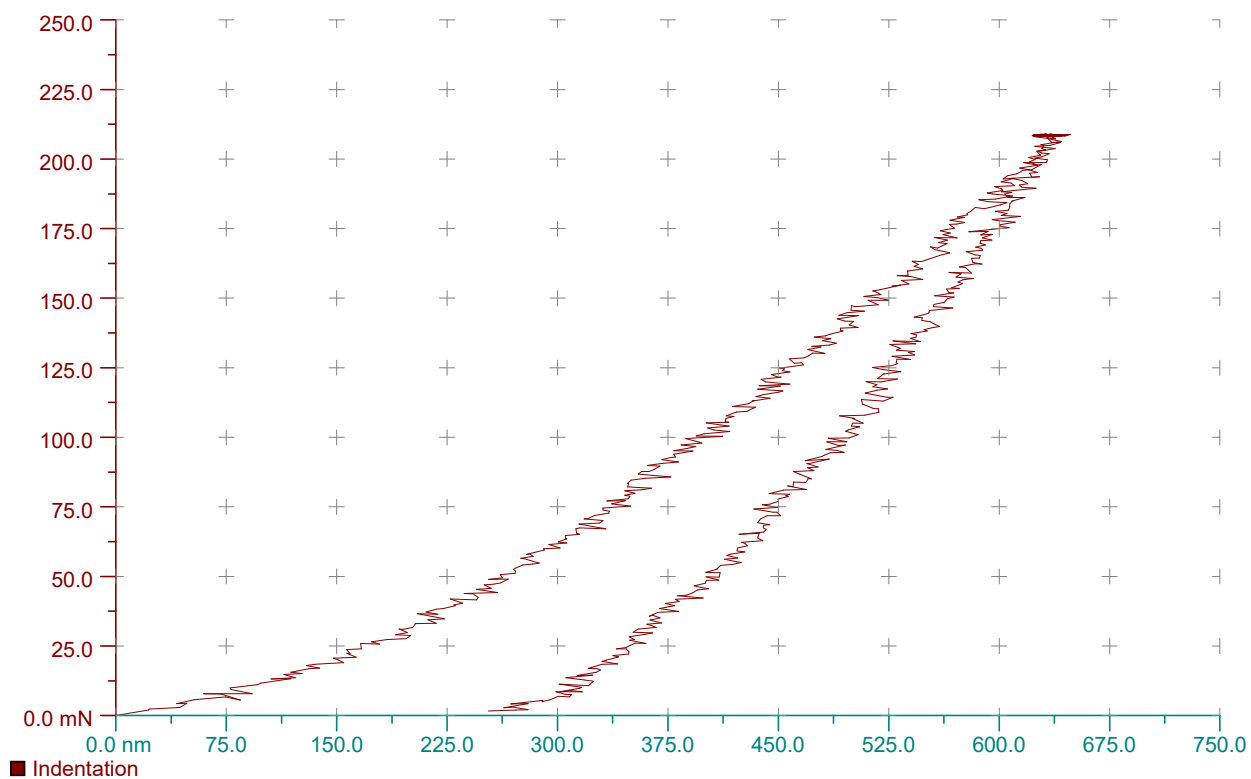
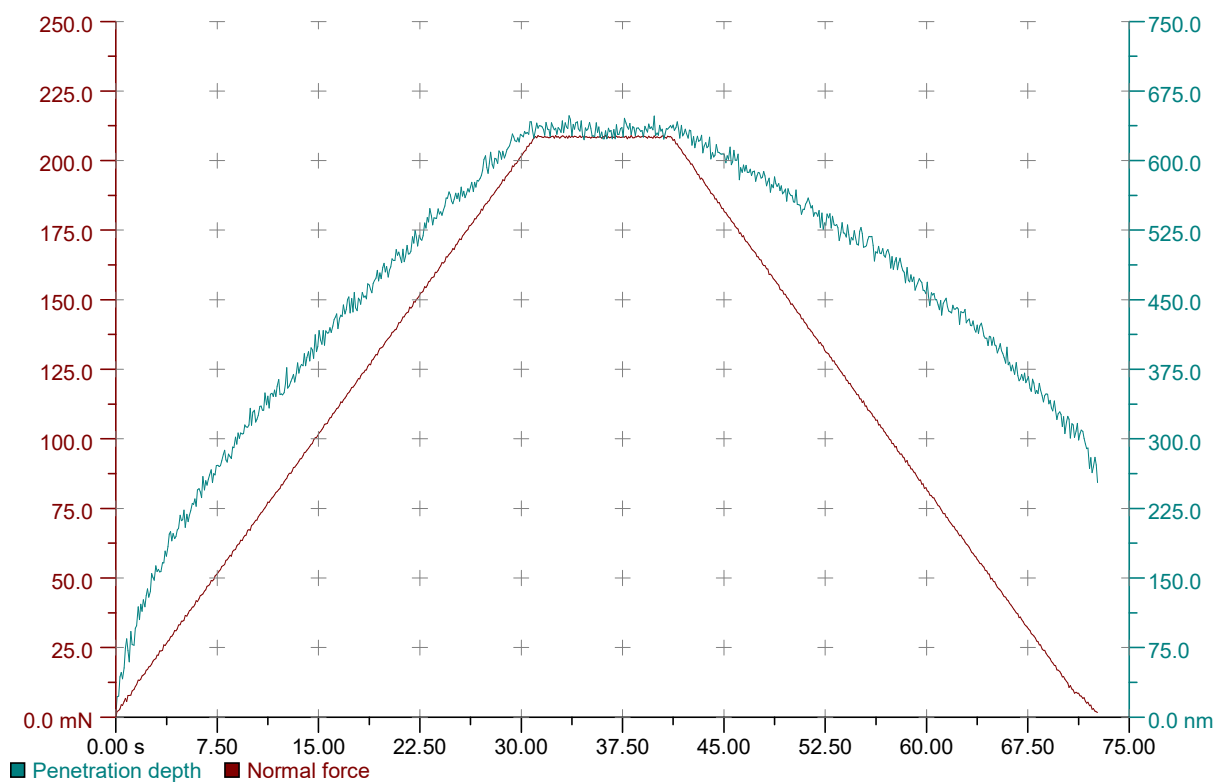
Indenters

Type : Vickers

Serial number : V-H 86

Material : Diamond

Curves



Indentation # 2

Indentation parameters

Standard

Standard

+ Instrument : MHTX S/N: 01-04300

+ Hardware settings

Fn contact : 10 mN

Approach speed : 16600.001 nm/min

Dz sensor in standard range

Load in fine range

X Position :98.16 mm

Y Position :96.02 mm

+ Measurement

Acquisition Rate : 10.0 [Hz]

Linear Loading

Max load : 200.00 mN

Loading rate : 400.00 mN/min

Unloading rate : 400.00 mN/min

Pause : 10.0 s

Date : 24/11/2022

Hour : 17:58:06

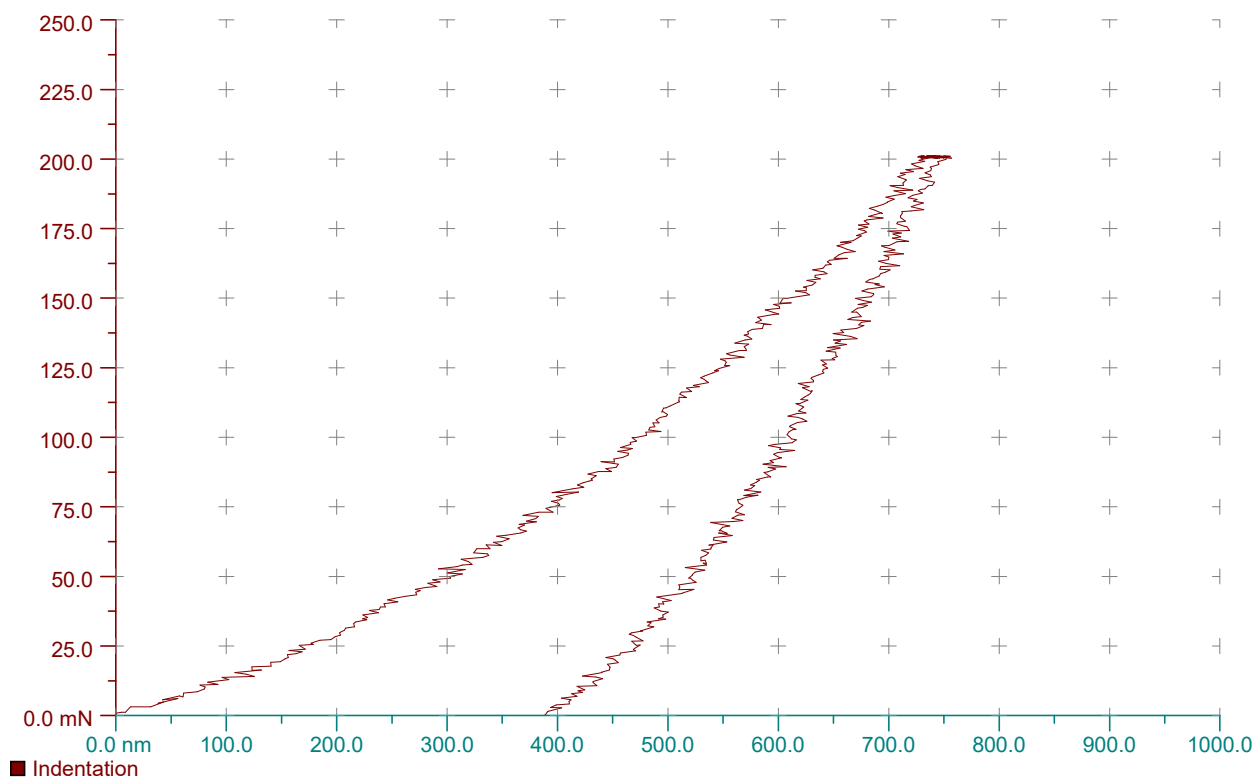
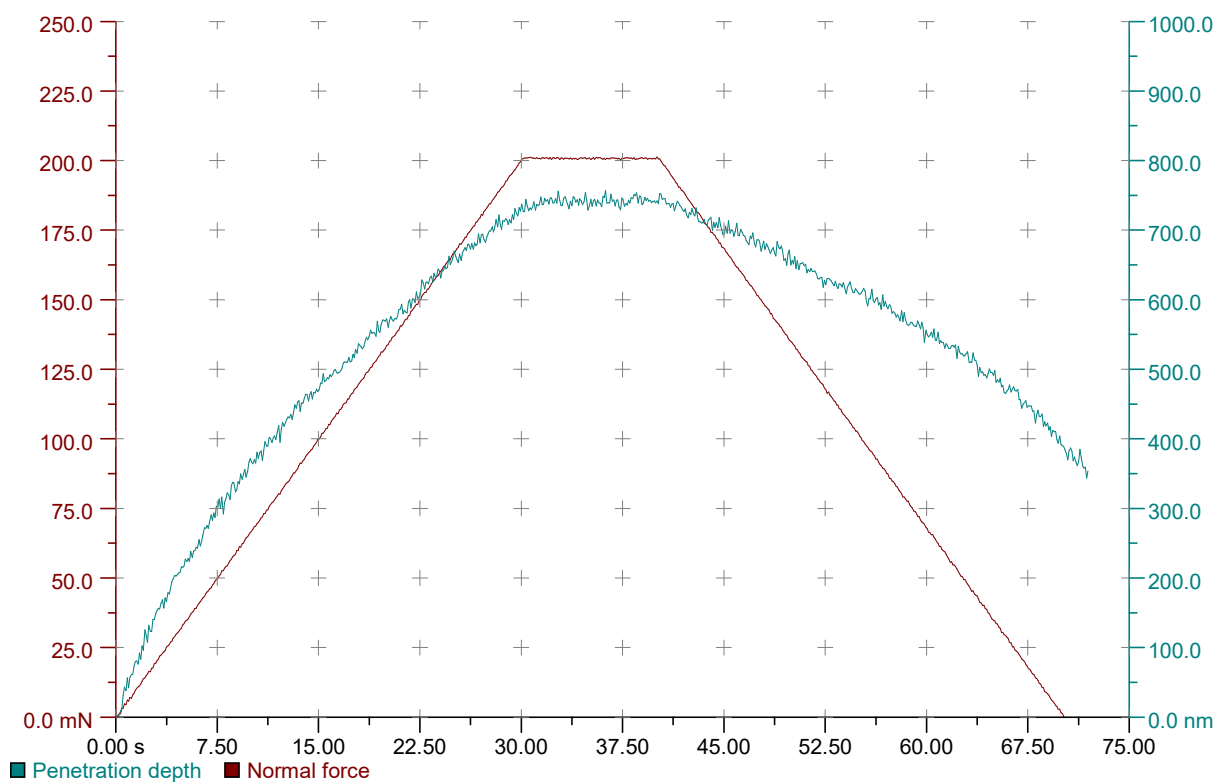
Indenters

Type : Vickers

Serial number : V-H 86

Material : Diamond

Curves



Indentation # 3

Indentation parameters

Standard

Standard

+ Instrument : MHTX S/N: 01-04300

+ Hardware settings

Fn contact : 10 mN

Approach speed : 16600.001 nm/min

Dz sensor in standard range

Load in fine range

X Position :95.35 mm

Y Position :92.89 mm

+ Measurement

Acquisition Rate : 10.0 [Hz]

Linear Loading

Max load : 200.00 mN

Loading rate : 400.00 mN/min

Unloading rate : 400.00 mN/min

Pause : 10.0 s

Date : 24/11/2022

Hour : 18:33:51

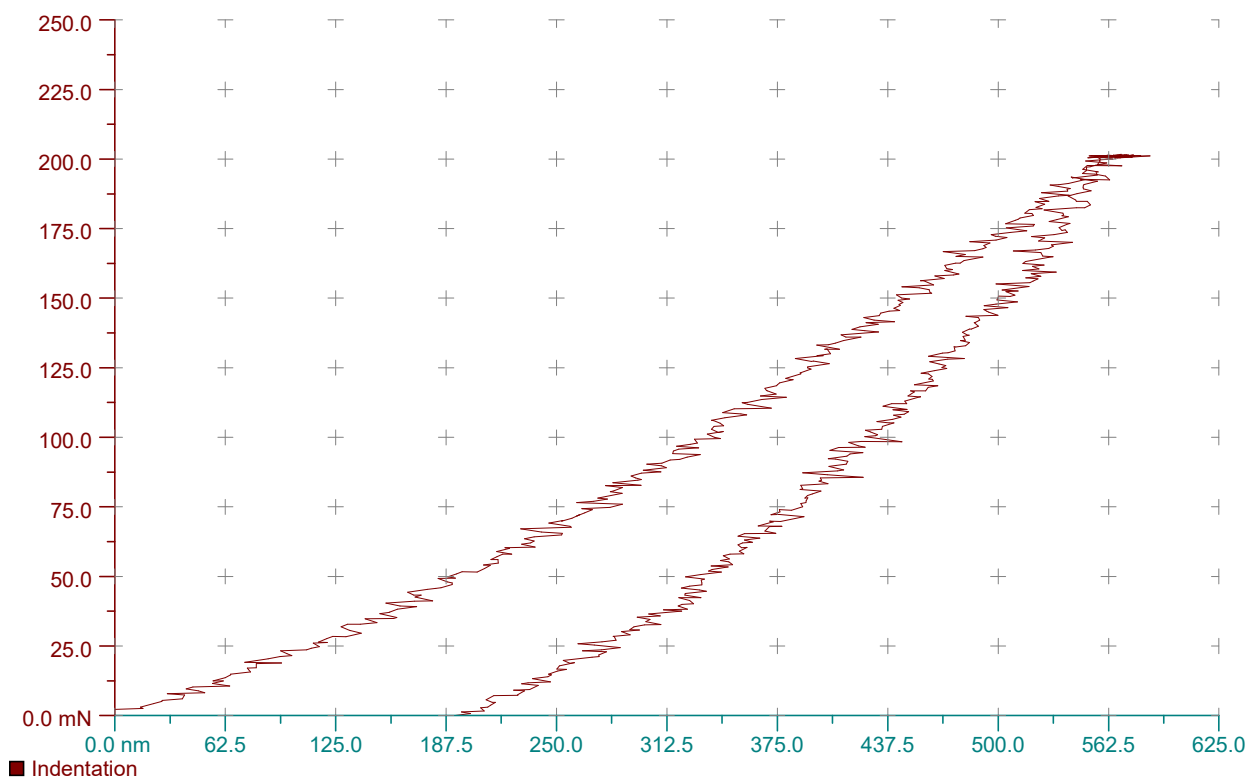
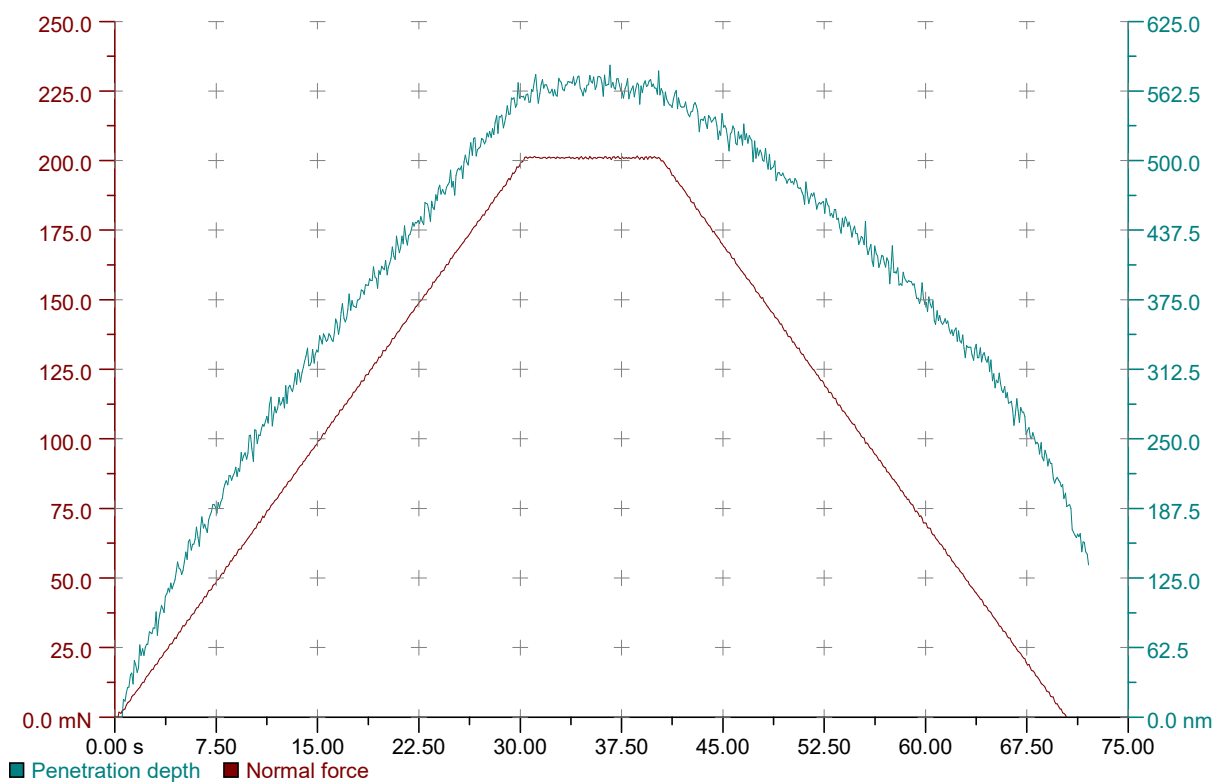
Indenters

Type : Vickers

Serial number : V-H 86

Material : Diamond

Curves



Indentation # 4

Indentation parameters

Standard

Standard

+ Instrument : MHTX S/N: 01-04300

+ Hardware settings

Fn contact : 10 mN

Approach speed : 16600.001 nm/min

Dz sensor in standard range

Load in fine range

X Position :95.85 mm

Y Position :92.89 mm

+ Measurement

Acquisition Rate : 10.0 [Hz]

Linear Loading

Max load : 200.00 mN

Loading rate : 400.00 mN/min

Unloading rate : 400.00 mN/min

Pause : 10.0 s

Date : 24/11/2022

Hour : 18:36:36

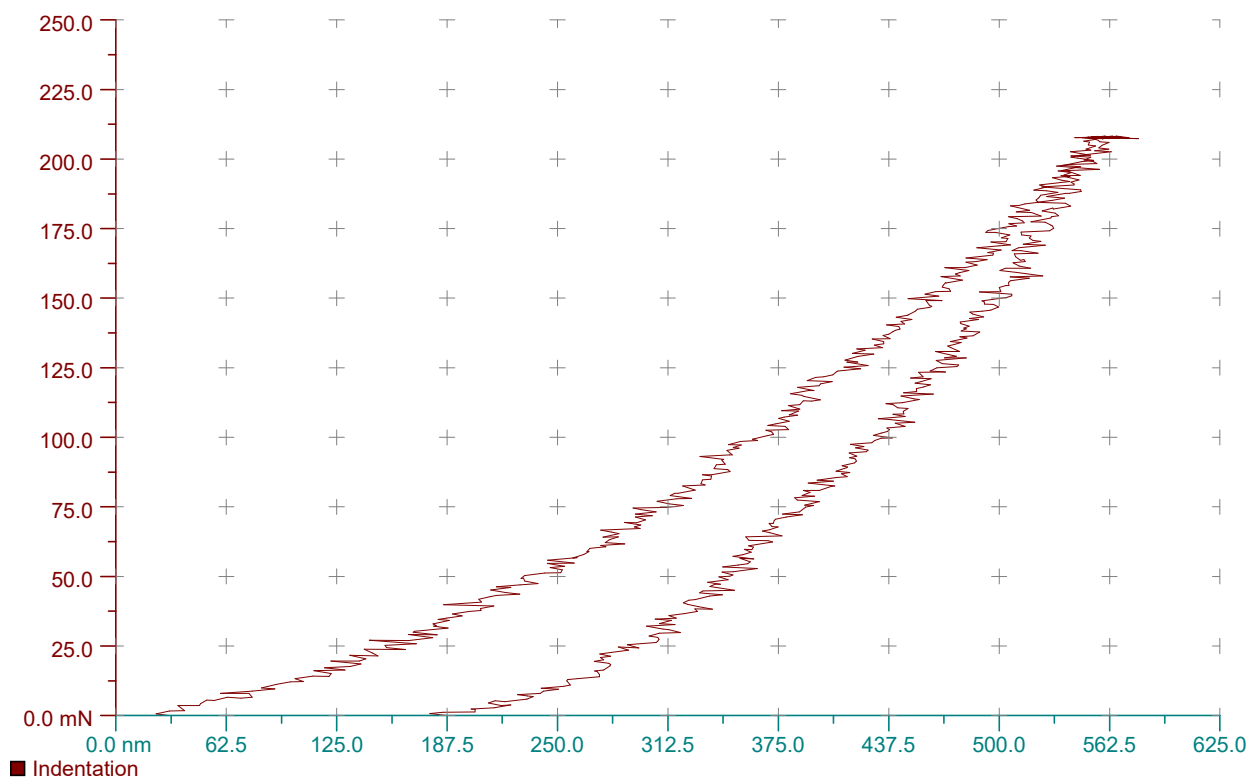
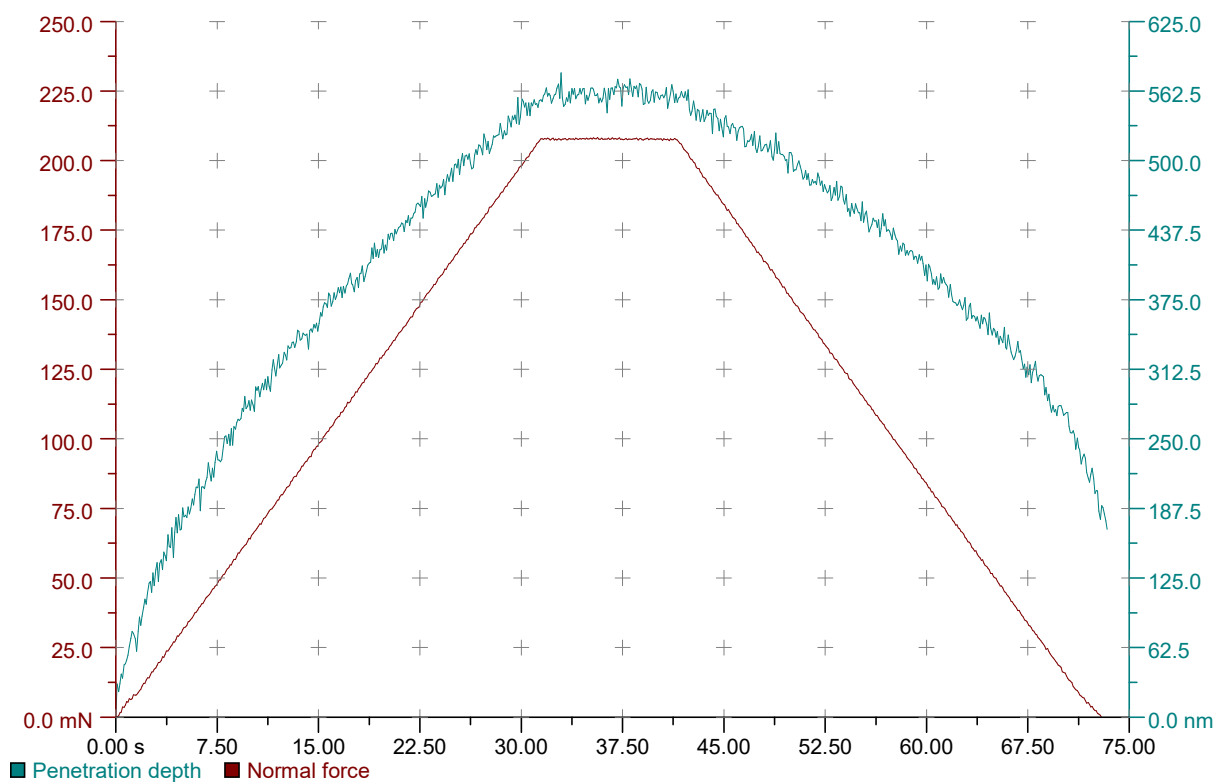
Indenters

Type : Vickers

Serial number : V-H 86

Material : Diamond

Curves



Indentation # 5

Indentation parameters

Standard

Standard

+ Instrument : MHTX S/N: 01-04300

+ Hardware settings

Fn contact : 10 mN

Approach speed : 16600.001 nm/min

Dz sensor in standard range

Load in fine range

X Position :96.35 mm

Y Position :92.89 mm

+ Measurement

Acquisition Rate : 10.0 [Hz]

Linear Loading

Max load : 200.00 mN

Loading rate : 400.00 mN/min

Unloading rate : 400.00 mN/min

Pause : 10.0 s

Date : 24/11/2022

Hour : 18:39:02

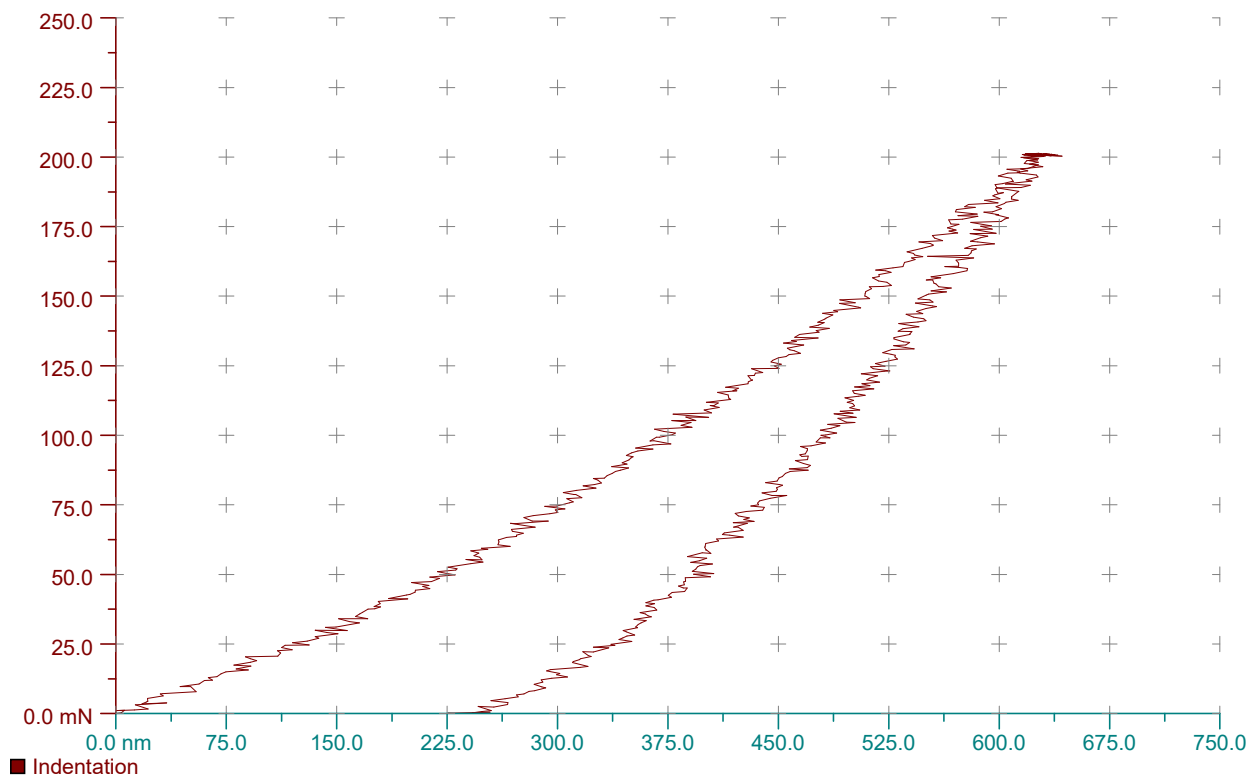
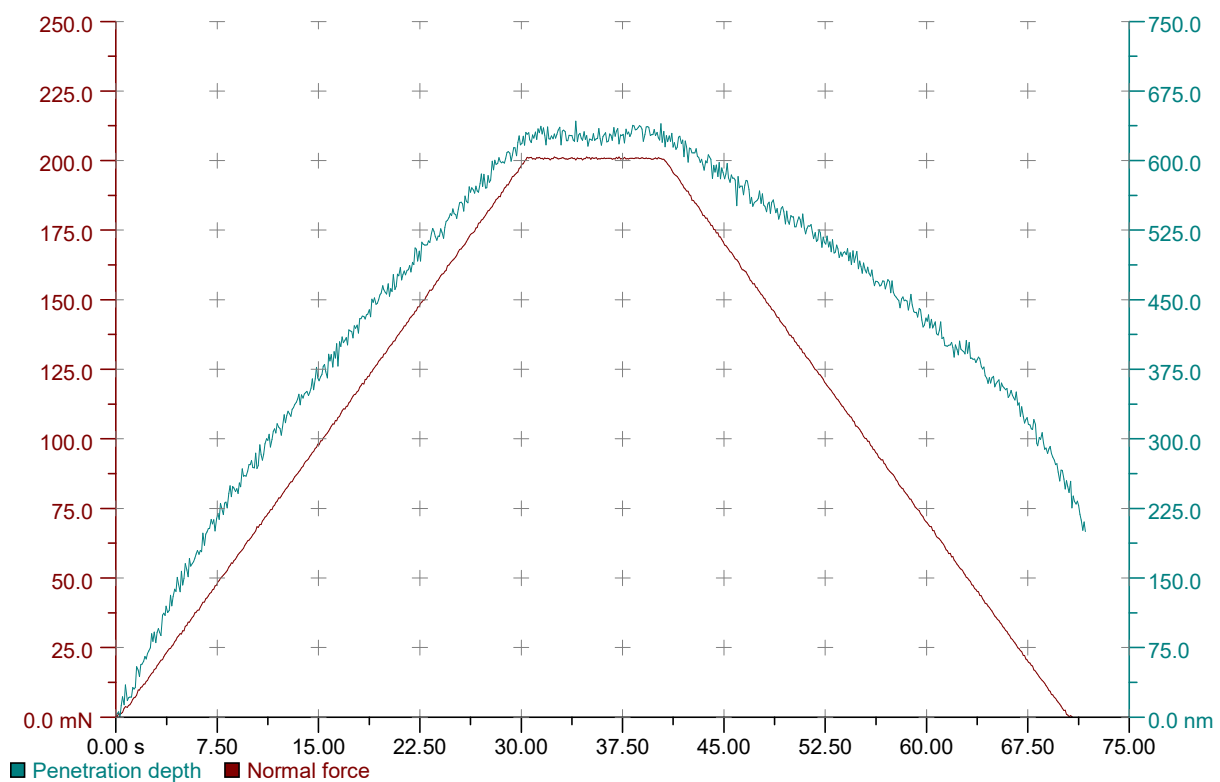
Indenters

Type : Vickers

Serial number : V-H 86

Material : Diamond

Curves



800-200mN

Sample specifications

Reference	:	Client	:
Operator	:		
Poisson's ratio	0.3		
Substrate	:		

Indentation # 1

Indentation parameters

Standard

Standard

+ Instrument : MHTX S/N: 01-04300

+ Hardware settings

Fn contact : 10 mN

Approach speed : 16600.001 nm/min

Dz sensor in standard range

Load in fine range

X Position :97.26 mm

Y Position :92.89 mm

+ Measurement

Acquisition Rate : 10.0 [Hz]

Linear Loading

Max load : 200.00 mN

Loading rate : 400.00 mN/min

Unloading rate : 400.00 mN/min

Pause : 10.0 s

Date : 24/11/2022

Hour : 19:15:26

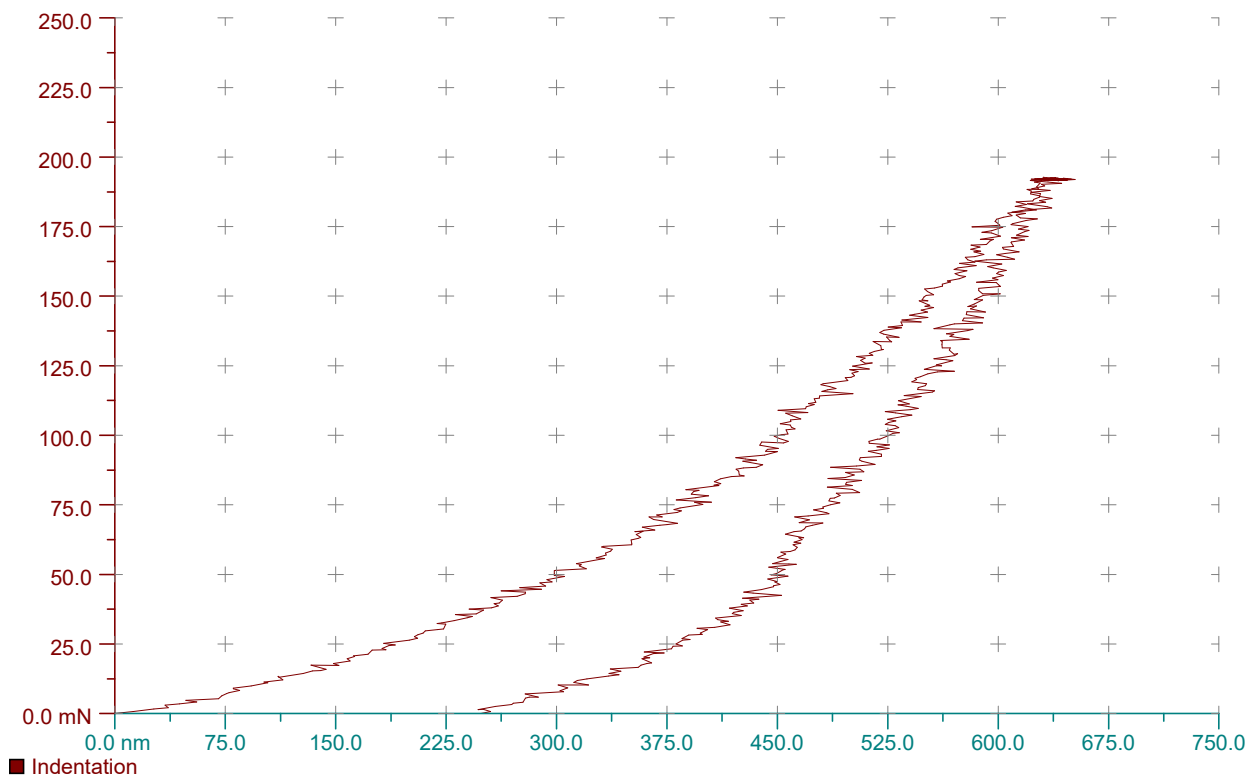
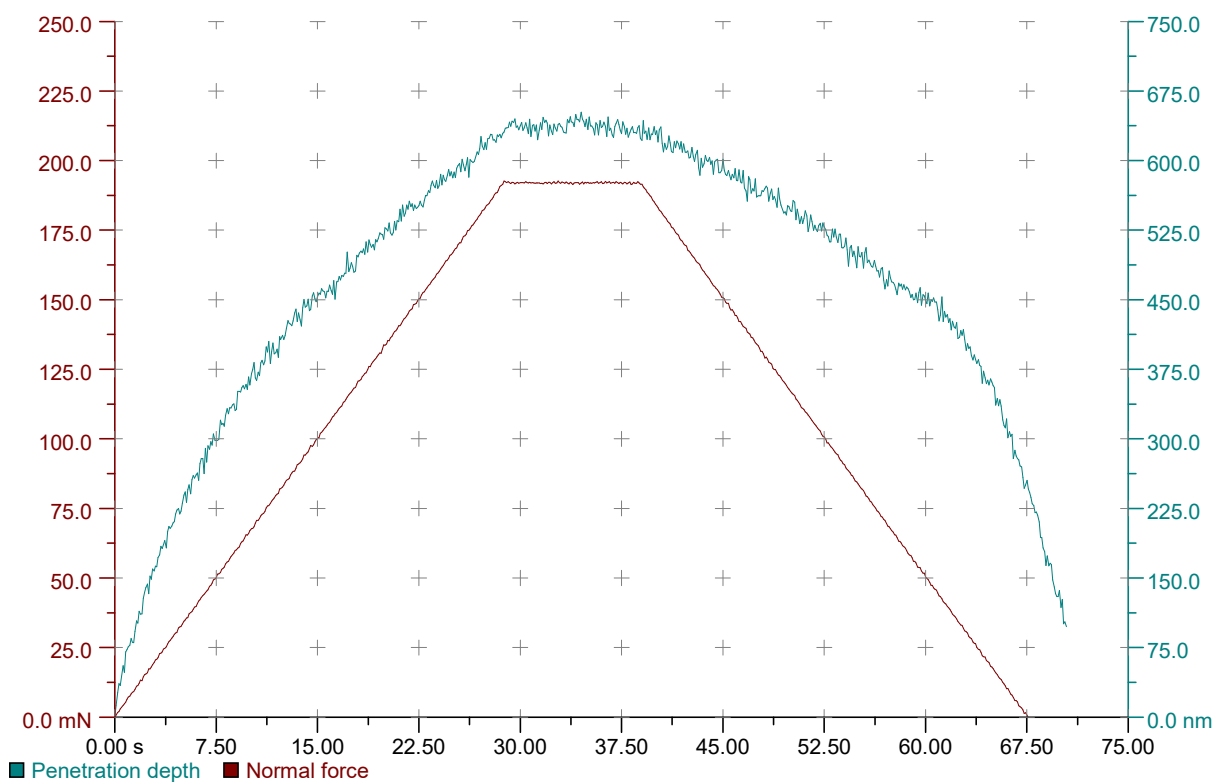
Indenters

Type : Vickers

Serial number : V-H 86

Material : Diamond

Curves



Indentation # 2

Indentation parameters

Standard

Standard

+ Instrument : MHTX S/N: 01-04300

+ Hardware settings

Fn contact : 10 mN

Approach speed : 16600.001 nm/min

Dz sensor in standard range

Load in fine range

X Position :97.76 mm

Y Position :92.89 mm

+ Measurement

Acquisition Rate : 10.0 [Hz]

Linear Loading

Max load : 200.00 mN

Loading rate : 400.00 mN/min

Unloading rate : 400.00 mN/min

Pause : 10.0 s

Date : 24/11/2022

Hour : 19:18:12

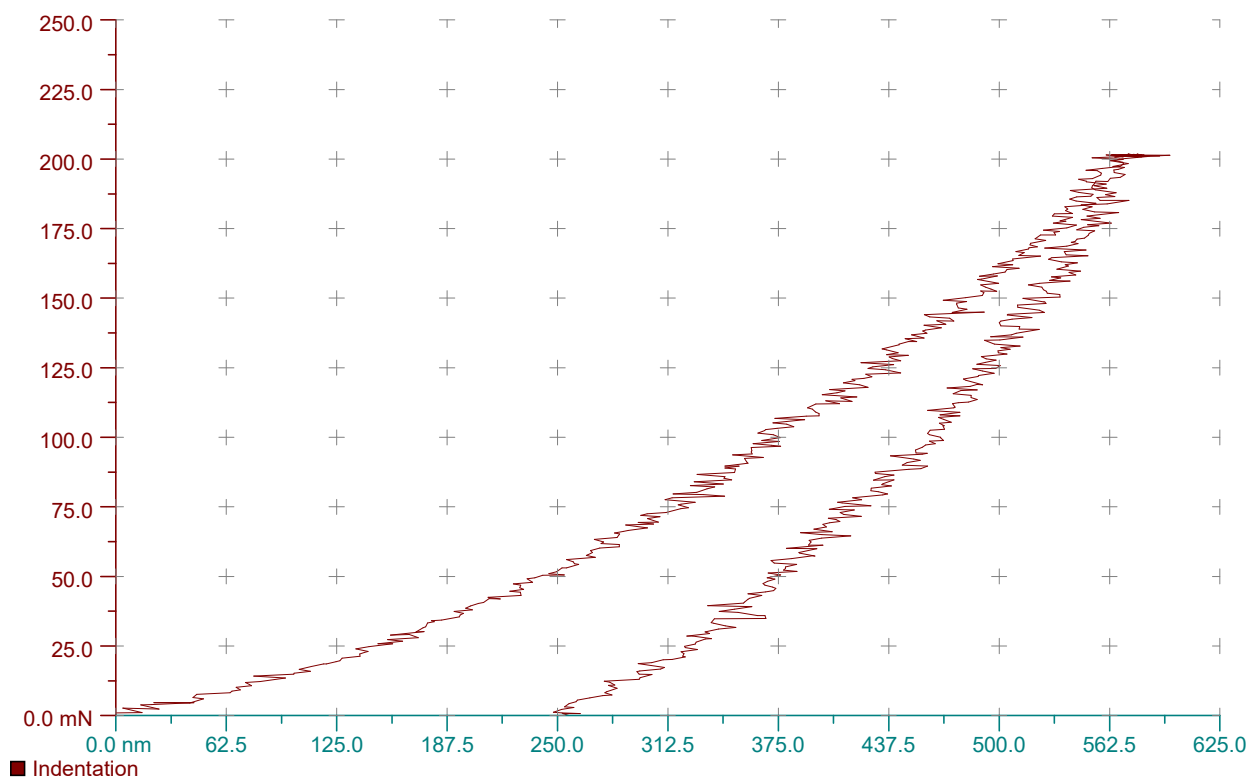
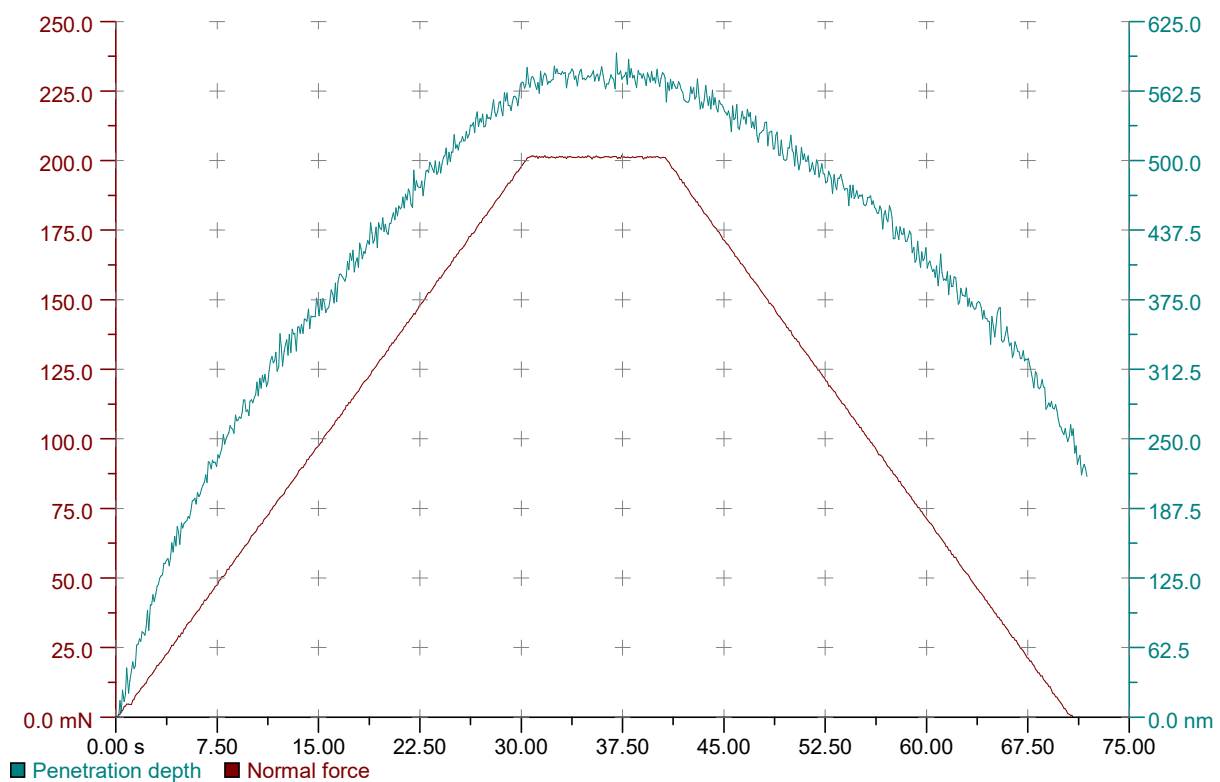
Indenters

Type : Vickers

Serial number : V-H 86

Material : Diamond

Curves



Indentation # 3

Indentation parameters

Standard

Standard

+ Instrument : MHTX S/N: 01-04300

+ Hardware settings

Fn contact : 10 mN

Approach speed : 16600.001 nm/min

Dz sensor in standard range

Load in fine range

X Position :98.26 mm

Y Position :92.89 mm

+ Measurement

Acquisition Rate : 10.0 [Hz]

Linear Loading

Max load : 200.00 mN

Loading rate : 400.00 mN/min

Unloading rate : 400.00 mN/min

Pause : 10.0 s

Date : 24/11/2022

Hour : 19:20:57

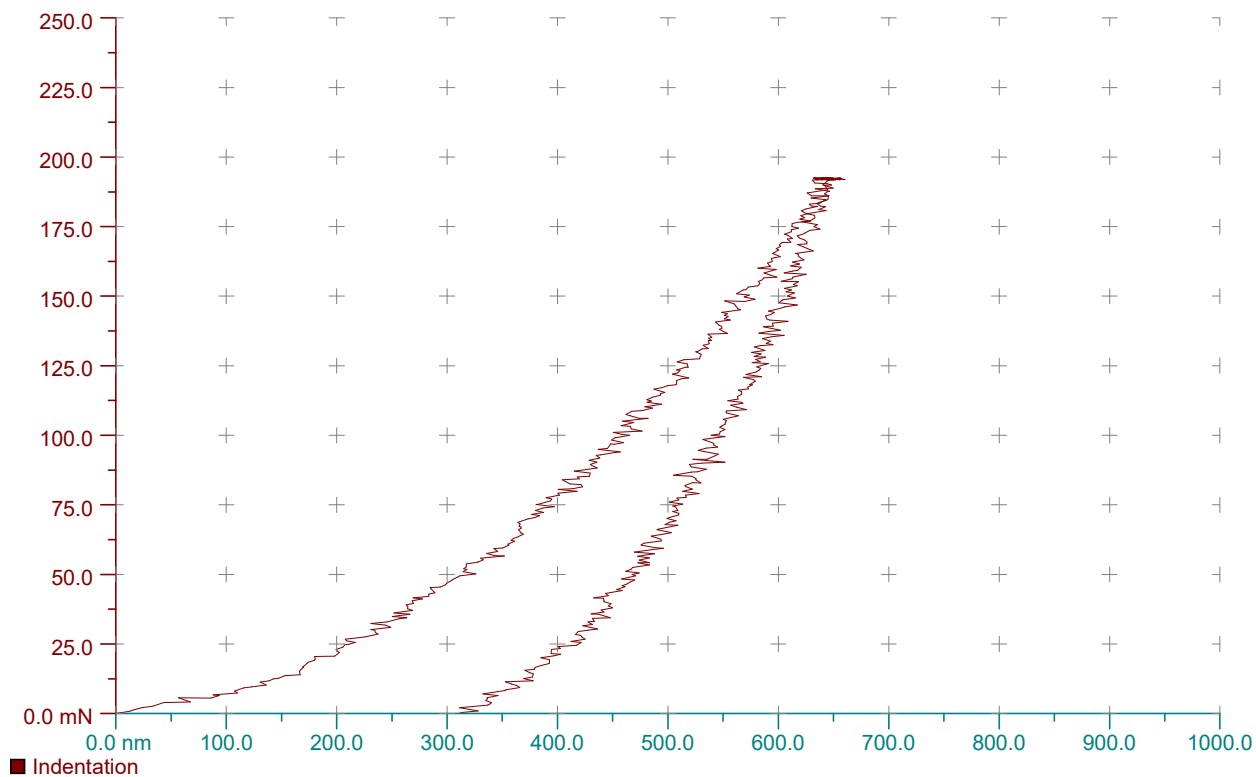
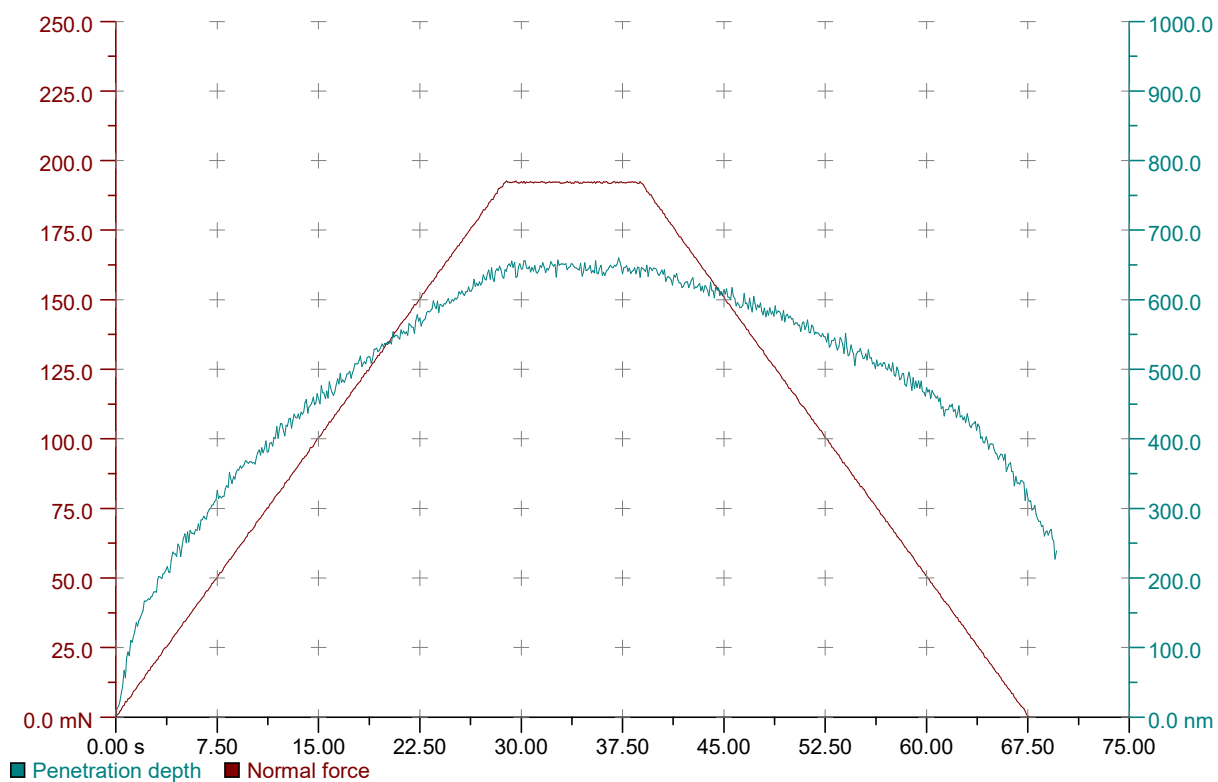
Indenters

Type : Vickers

Serial number : V-H 86

Material : Diamond

Curves



Indentation # 4

Indentation parameters

Standard

Standard

+ Instrument : MHTX S/N: 01-04300

+ Hardware settings

Fn contact : 10 mN

Approach speed : 16600.001 nm/min

Dz sensor in standard range

Load in fine range

X Position :98.76 mm

Y Position :92.89 mm

+ Measurement

Acquisition Rate : 10.0 [Hz]

Linear Loading

Max load : 200.00 mN

Loading rate : 400.00 mN/min

Unloading rate : 400.00 mN/min

Pause : 10.0 s

Date : 24/11/2022

Hour : 19:23:38

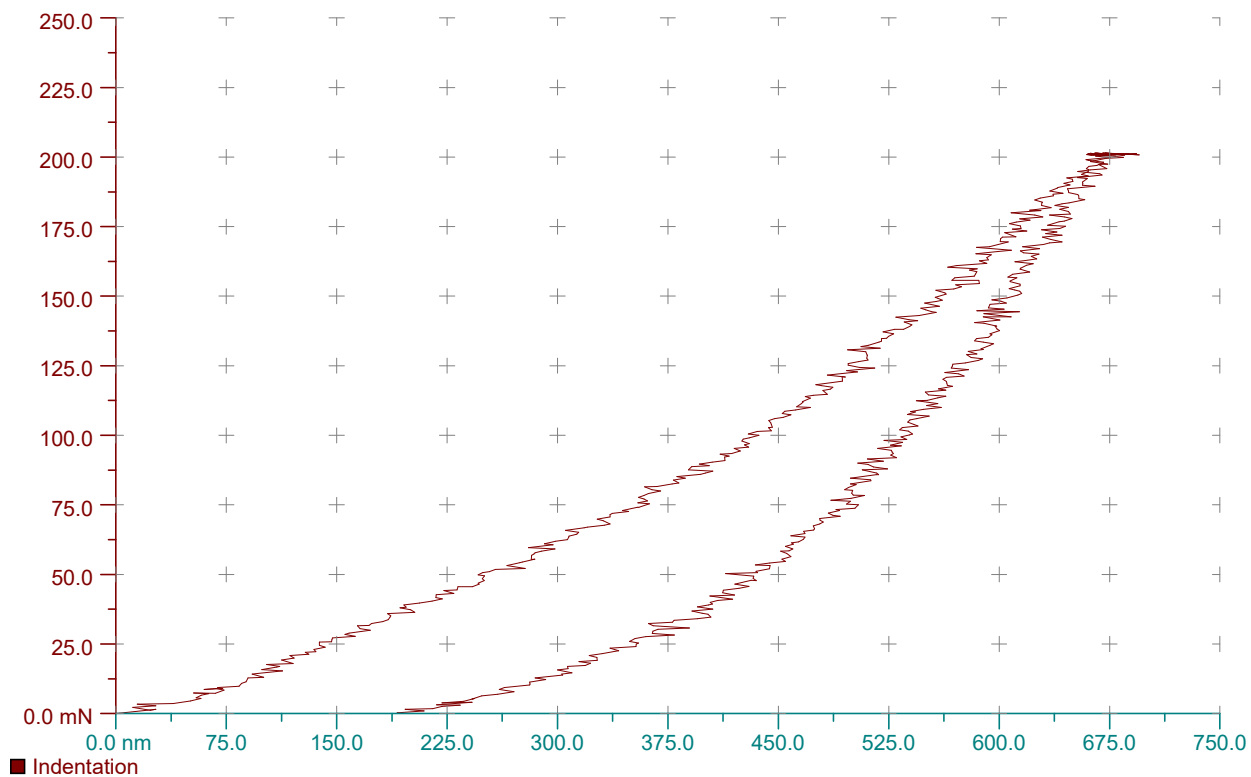
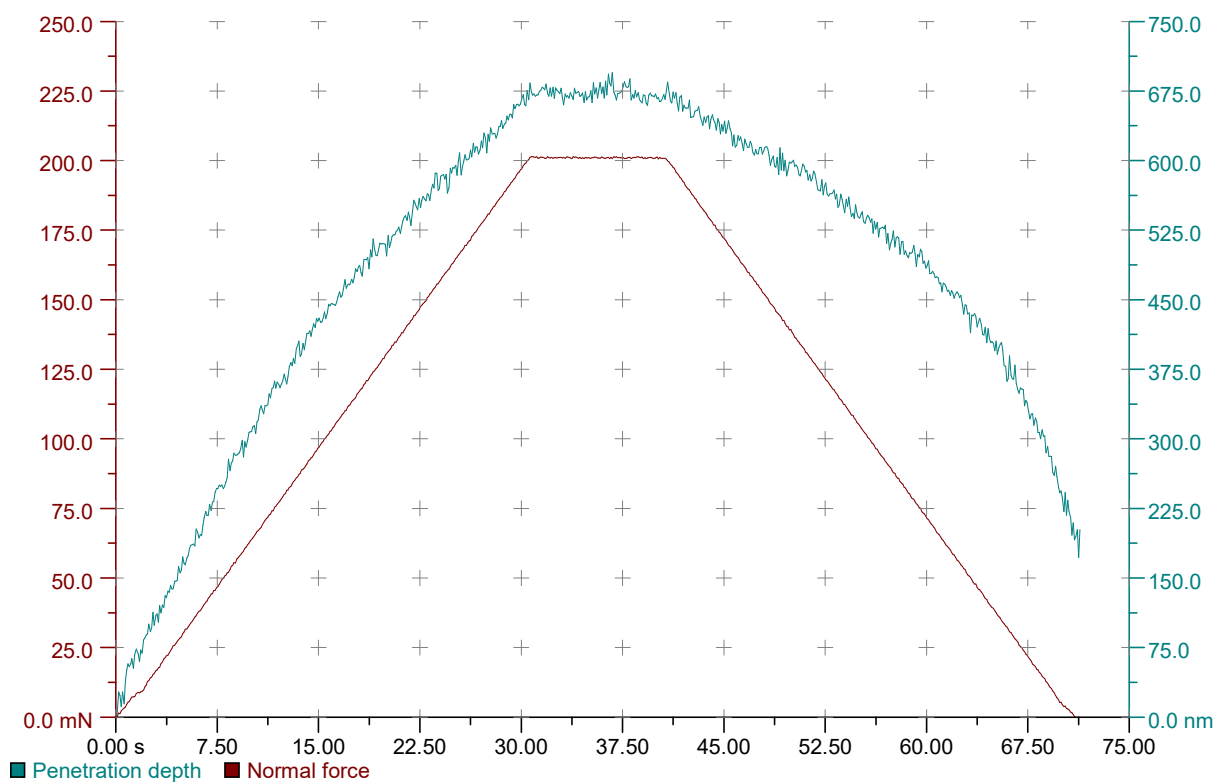
Indenters

Type : Vickers

Serial number : V-H 86

Material : Diamond

Curves



Indentation # 5

Indentation parameters

Standard

Standard

+ Instrument : MHTX S/N: 01-04300

+ Hardware settings

Fn contact : 10 mN

Approach speed : 16600.001 nm/min

Dz sensor in standard range

Load in fine range

X Position :99.26 mm

Y Position :92.89 mm

+ Measurement

Acquisition Rate : 10.0 [Hz]

Linear Loading

Max load : 200.00 mN

Loading rate : 400.00 mN/min

Unloading rate : 400.00 mN/min

Pause : 10.0 s

Date : 24/11/2022

Hour : 19:26:18

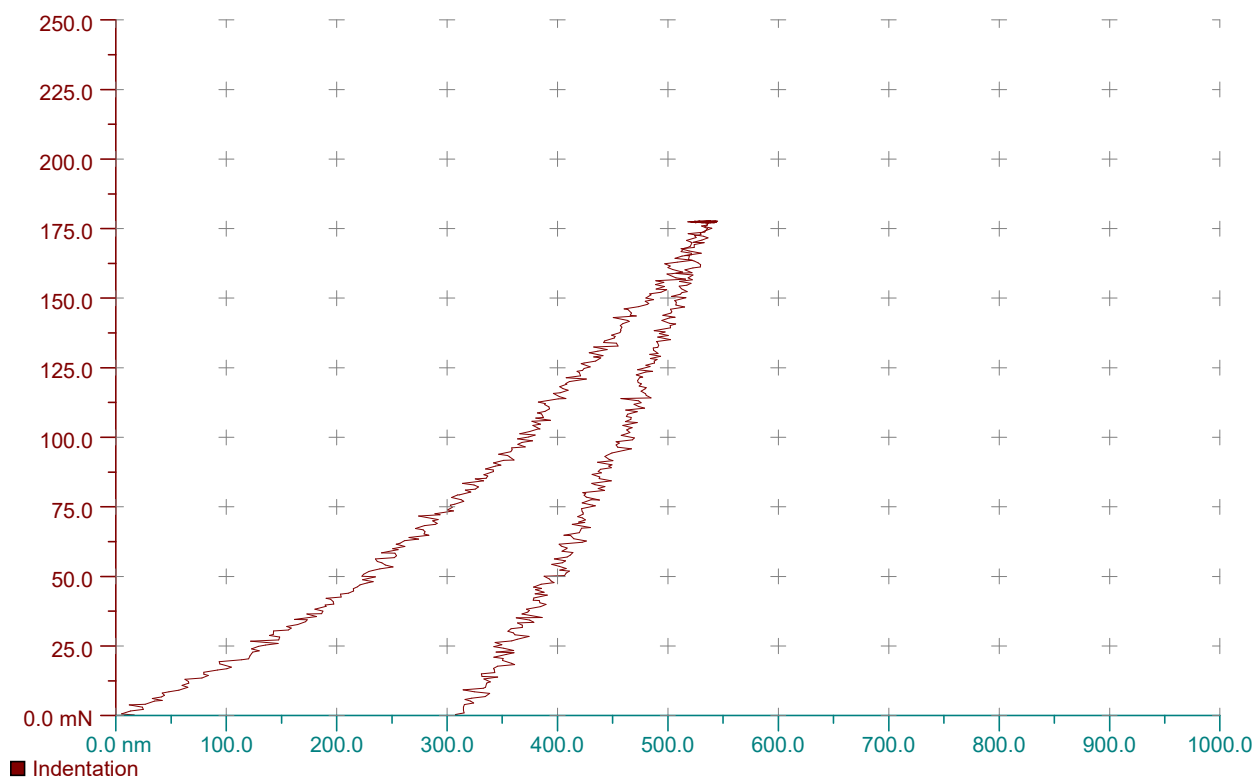
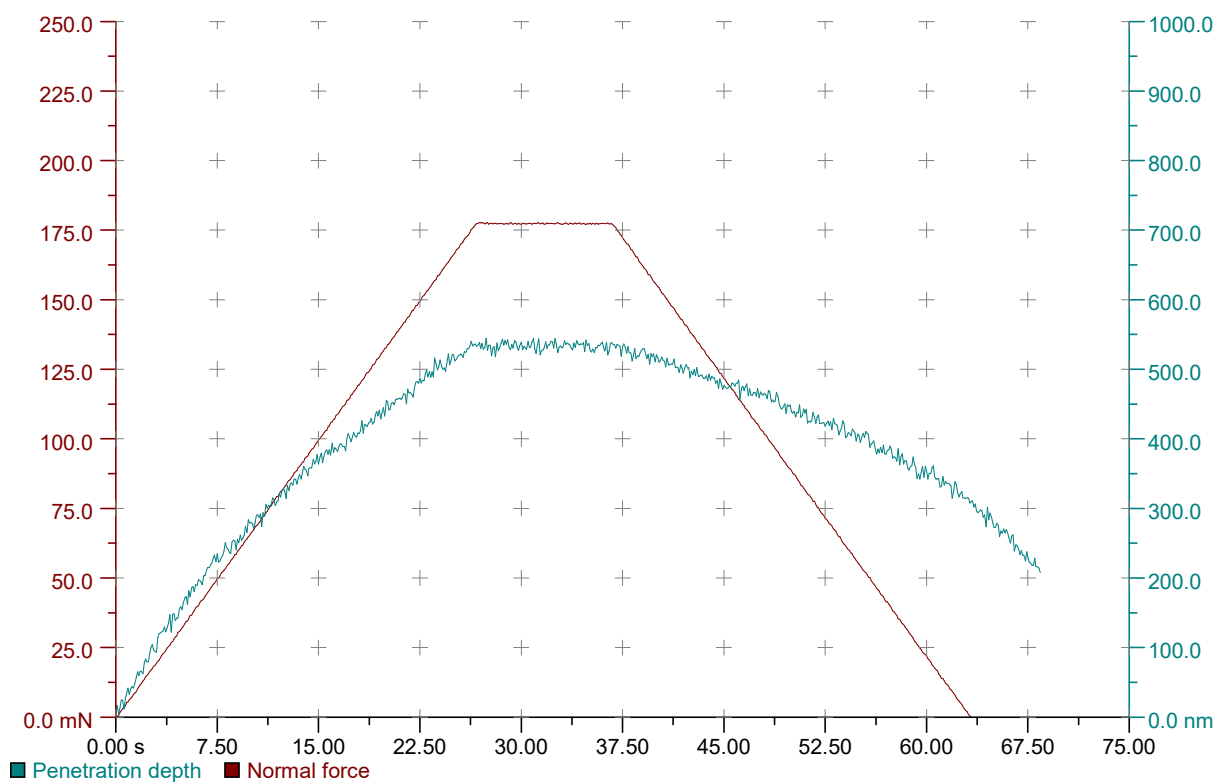
Indenters

Type : Vickers

Serial number : V-H 86

Material : Diamond

Curves



Statistic

New Report

		Polished	60-200mN	240-200mN	400-200mN
HV (O&P)	Data : 1	2868.276	2332.844	3874.486	3100.314
[Vickers]	Data : 2	3195.401	2149.948	3971.481	2094.916
	Data : 3	2715.464	2334.347	3682.873	4203.280
	Data : 4	2972.477		3065.033	3762.581
	Data : 5	2651.863		3072.631	3308.195
	Mean	2880.696	2272.380	3533.301	3293.857
	Std Dev	216.381	106.031	436.541	794.021
EIT (O&P)	Data : 1	304.058	267.733	393.014	344.666
[GPa]	Data : 2	341.157	498.793	393.172	264.962
	Data : 3	337.606	392.014	409.233	400.083
	Data : 4	330.778		338.942	476.173
	Data : 5	299.005		343.198	330.968
	Mean	322.521	386.180	375.512	363.370
	Std Dev	19.601	115.641	32.159	79.304
E* (O&P)	Data : 1	334.130	294.212	431.883	378.754
[GPa]	Data : 2	374.897	548.125	432.058	291.167
	Data : 3	370.995	430.784	449.707	439.652
	Data : 4	363.492		372.464	523.267
	Data : 5	328.577		377.141	363.702
	Mean	354.418	424.373	412.650	399.308
	Std Dev	21.540	127.078	35.340	87.147
Er (O&P)	Data : 1	258.734	234.135	313.719	284.708
[GPa]	Data : 2	282.524	370.847	313.811	232.202
	Data : 3	280.302	313.138	323.018	317.798
	Data : 4	275.998		281.139	359.298
	Data : 5	255.392		283.796	276.118
	Mean	270.590	306.040	303.096	294.025
	Std Dev	12.625	68.632	19.230	47.580

		800-200mN
HV (O&P)	Data : 1	2448.383
[Vickers]	Data : 2	3252.329
	Data : 3	2500.336
	Data : 4	2457.984
	Data : 5	3118.990
	Mean	2755.604
	Std Dev	395.888
EIT (O&P)	Data : 1	370.797
[GPa]	Data : 2	461.794
	Data : 3	382.230
	Data : 4	330.387
	Data : 5	520.706
	Mean	413.183
	Std Dev	76.704
E* (O&P)	Data : 1	407.469
[GPa]	Data : 2	507.466
	Data : 3	420.033
	Data : 4	363.062
	Data : 5	572.205
	Mean	454.047
	Std Dev	84.291
Er (O&P)	Data : 1	300.634
[GPa]	Data : 2	351.778
	Data : 3	307.418
	Data : 4	275.750
	Data : 5	381.715
	Mean	323.459
	Std Dev	42.574

Appendix B

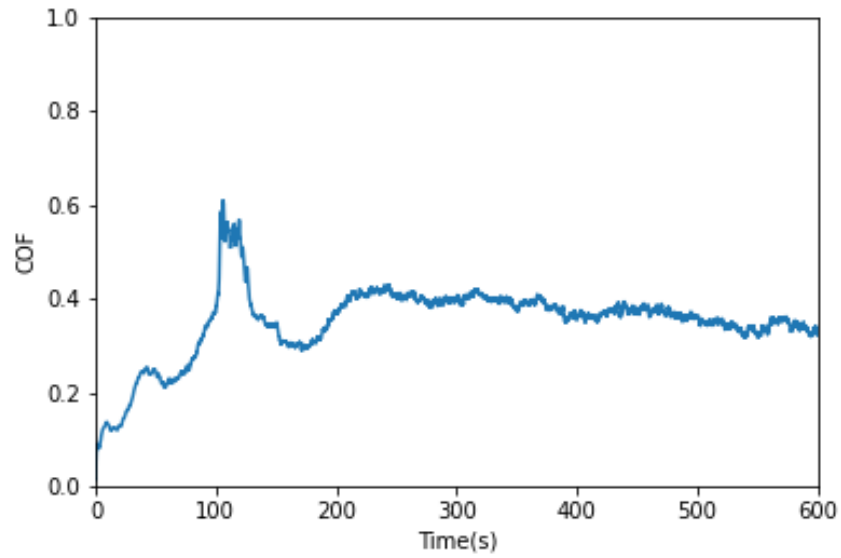


Figure 1: COF vs Time for the substrate

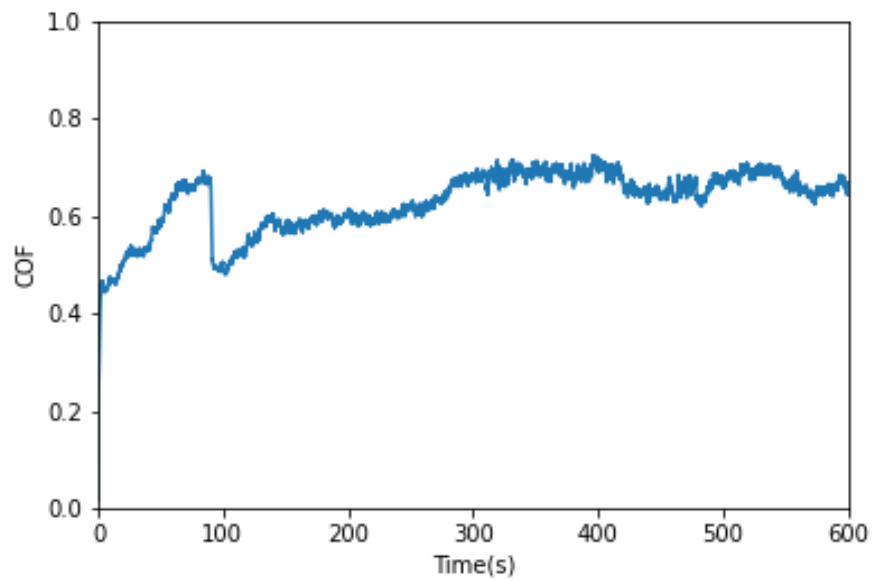


Figure 2: COF vs Time for the sample that treated with 60 grit-size sandpaper

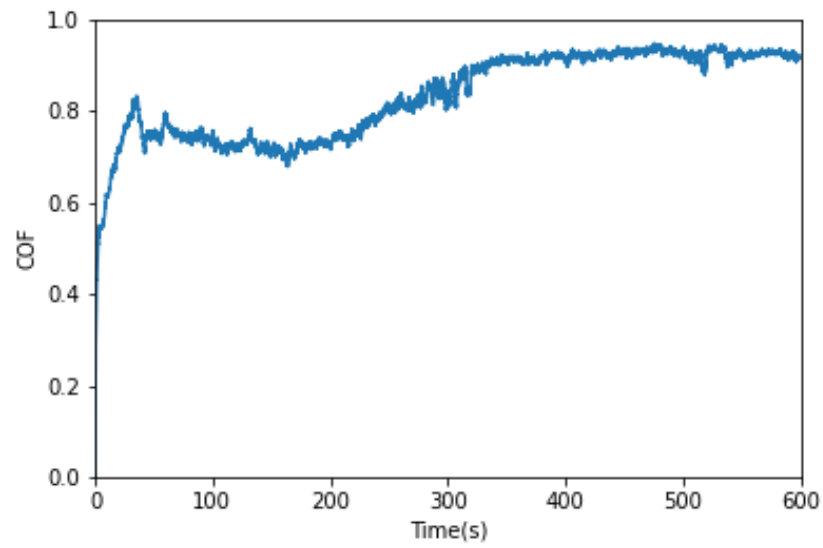


Figure 3: COF vs Time for the sample that treated with 400 grit-size sandpaper

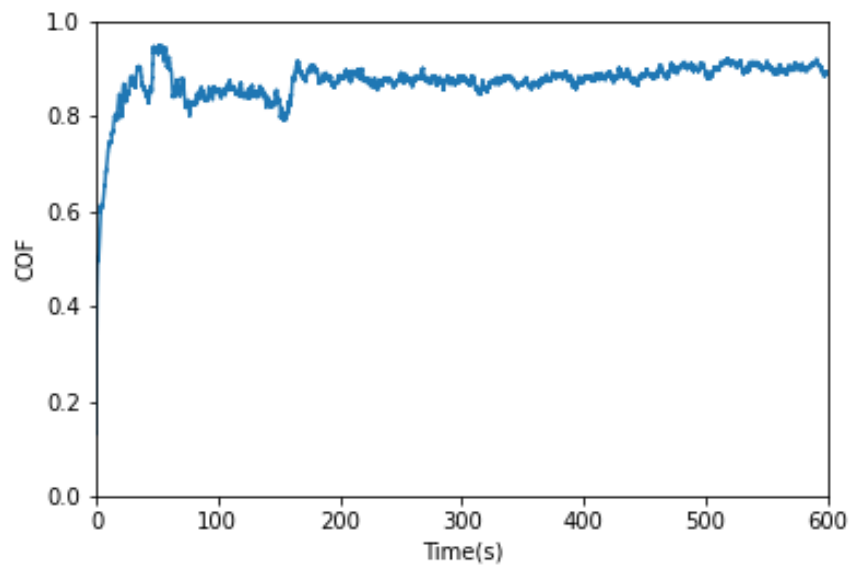


Figure 4: COF vs Time for the sample that treated with 800 grit-size sandpaper

Vitae

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Title of qualification awarded: BSc Mechanical Engineering

Year: September 2014-January 2020

Publication

Develop hard CA-PVD coating of CrNiAlSiN for higher wear resistant coating in internal combustion engine, in progress. |