CHAPTER 1
INTRODUCTION

1.1 BACKGROUND STUDY

In this report, the term ‘jet sintering’ will be used frequently. Well, for clarification, jet sintering is a new term introduced by the author. Jet sintering is basically used to describe sintering process induced by high temperature and high velocity impact. This term will be used quite often as the study in this report will be based on this concept and term. If the study shows positive response, then the term ‘jet sintering’ will be introduced globally.

The world has moved into a new era since the Industrial Revolution started in England in the 1750s. Since that time, most of the application in our life nowadays requires steel. Steel is one of the basic materials used in almost all the application throughout the world.

Nowadays, there are so many types of steel and alloy fabricated in the foundry and shipped to desired destination for utilization. With the help of modern manufacturing technology, the steel production is even more competitive and better compared to in the mid 1900s.

One of the basic manufacturing methods is sawing. Sawing comprises of four types of saws which are hacksaws, circular saws, band saws and abrasive saws. But here, the author is going to concentrate on abrasive saws only. It is also known as cold saws when cutting metal. This type of sawing method is used of high production rate.

As the sawing operation begins, the saw will remove some of the materials at the area of cutting. Due to friction between the saw and material, the material will chipped out with a very hot temperature and a blazing jet of material come out from the cutting tool. If we let the material to stick on the floor, it will slowly make a hill of deposited material. And usually, the worker will then scrapped this material from the floor and collect it for recycling purpose.

1.2 PROBLEM STATEMENT

So far, there are no further researches being done on this area as this material seems to be useless and ugly. But, if we look deeper into the structure of this material, we can see how beautiful it is formed. Basically, this area of study falls under powder metallurgy as the chipped material which is almost like powder is sintered once it reaches the floor.

As it gets higher due to high deposition concentrated on one place, we can see the crystal structure changed as the height of the hill increased. So, every part in this small hill promises good qualities and attributes to be studied further.

1.3 OBJECTIVES

The main objectives for this project are:

- To establish the mechanism of sintering involved in the jet speed deposited chipped material / debris from abrasive saw cutting process
- To determine the microstructure and grain sizes of sample obtained from jet sintering process
- To determine physical and mechanical properties from deposited debris in this process

1.4 SCOPE OF STUDY

The scope of study will be based on the study of metallographic of sample produced from abrasive sawing cutting process. This sample had shown physically different characteristics for every part of the sample. Once we get the result from different methods of crystal investigation, we will be able to deduce whether this method is a new solution to the rapid prototyping process in the world using steel as the media.

In this project, only one type of material will be used in order to investigate the crystal structure formed from jet sintering process.

CHAPTER 2
LITERATURE REVIEW / THEORY

2.1 INTRODUCTION

Carbon steel, also called plain carbon steel, is steel where the main alloying constituent is carbon. The American Iron and Steel Institute (Carbon Steel) defines carbon steel as: "Steel is considered to be carbon steel when no minimum content is specified or required for chromium, cobalt, columbium, molybdenum, nickel, titanium, tungsten, vanadium or zirconium, or any other element to be added to obtain a desired alloying effect; when the specified minimum for copper does not exceed 0.40 percent; or when the maximum content specified for any of the following elements does not exceed the percentages noted: manganese 1.65, silicon 0.60, copper 0.60."

According to Wikipedia (2009), steel with low carbon content has properties similar to iron. As the carbon content rises, the metal becomes harder and stronger but less ductile and more difficult to weld. In general, higher carbon content lowers the melting point and its temperature resistance. Carbon content influences the yield strength of steel because carbon atoms fit into the interstitial crystal lattice sites of the body-centered cubic (BCC) arrangement of the iron atoms. The interstitial carbon reduces the mobility of dislocations, which in turn has a hardening effect on the iron. To get dislocations to move, a high enough stress level must be applied in order for the dislocations to "break away". This is because the interstitial carbon atoms cause some of the iron BCC lattice cells to distort.

Here are some of the steel properties quoted from efunda.com (refer to Table 2.1):

Table 2.1: Steel properties

Properties	Carbon Steels	Alloy Steels	Stainless Steels	Tool Steels
Density (1000 kg/m^3)	7.85	7.85	7.75-8.1	7.72-8.0
Elastic Modulus (GPa)	190-210	190-210	190-210	190-210
Poisson's Ratio	0.27-0.3	0.27-0.3	0.27-0.3	0.27-0.3
Thermal Expansion (10^{-6}/K)	11-16.6	9.0-15	9.0-20.7	9.4-15.1
Melting Point (°C)			1371-1454	
Thermal Conductivity (W/m-K)	24.3-65.2	26-48.6	11.2-36.7	19.9-48.3
Specific Heat (J/kg-K)	450-2081	452-1499	420-500	
Electrical Resistivity (10^{-9}W-m)	130-1250	210-1251	75.7-1020	
Tensile Strength (MPa)	276-1882	758-1882	515-827	640-2000
Yield Strength (MPa)	186-758	366-1793	207-552	380-440
Percent Elongation (%)	10-32	4-31	12-40	5-25
Hardness (Brinell 3000kg)	86-388	149-627	137-595	210-620

(Source: General Properties of Steel)

2.2 SINTERING

According to Wikipedia (2009) sintering is the process where the particles are heated in a controlled-atmosphere furnace to a temperature below the melting point but sufficiently high to allow bonding (fusion) of the individual particles. This bonding is the one the author is looking for in this process. As the particles fuse together, the strength will be increased and all the physical properties will also increased depending on the chemical composition of the particles.

In the real industrial world, there are using continuous-sintering furnaces which consists of three chambers; burn-off, high temperature and cooling chamber. Basically of new technology is coming up in the future, it must have the ability to fuse the technology with the existing equipments in the foundries nowadays. Figure 2.1 shows a sample of sintered material:

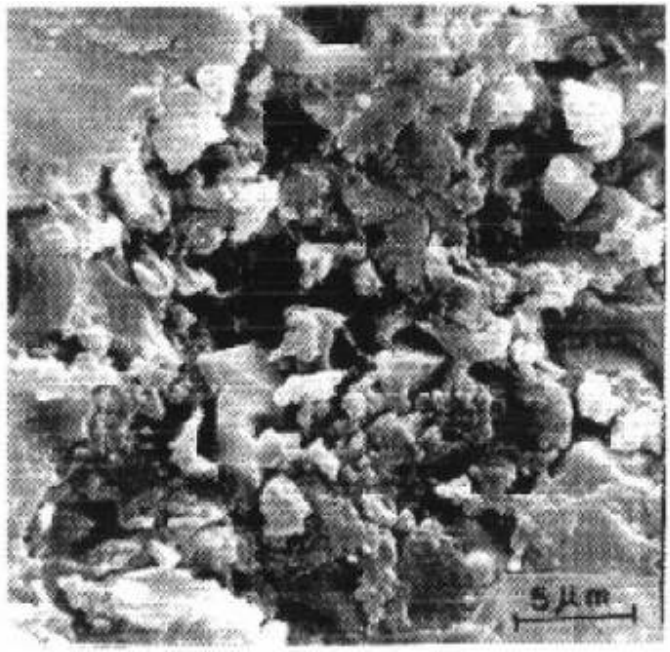

Figure 2.1: Sample of D50 sintered at 1250 degrees for 12 hours
(Source: Science Electronic Library Online)

Sintering process shows great advantages to the industries nowadays. The advantages are:

- possibility of very high purity for the starting materials and their great uniformity
- preservation of purity due to the restricted nature of subsequent fabrication steps
- no requirement for deformation to produce directional elongation of grains
- possibility of creating materials of uniform controlled porosity

Sintering temperature usually occur within 2/3 to 3/4 melting temperature of material. This is the most suitable range of temperature for sintering to occur. But this is only for well compacted samples with certain amount of time required for sintering process. In this study, it will be different because there will be no initial compaction on the material. The sample relies on the impact of the jet spray of material to replace the compaction effect. We will see the correlation between jet impact and compression in the Results and Discussions chapter.

2.3 HARDNESS

According to Metals.About.Com, hardness is defined as resistance to penetration. Hardness is usually measured in terms of Mohrs, Brinell, Vickers and Rockwell scale. All these numbers can be compared using practical conversion tables.

In this study, the author will use Vickers hardness testing. It was developed in 1924 by Smith and Sandland at Vickers Ltd as an alternative to the Brinell method. The Vickers test is often easier to use than other hardness tests since the required calculations are independent of the size of the indenter, and the indenter can be used for all materials irrespective of hardness. The basic principle, as with all common measures of hardness, is to observe the questioned material's ability to resist plastic deformation from a standard source.

The Vickers test can be used for all metals and has one of the widest scales among hardness tests. The unit of hardness given by the test is known as the Vickers Pyramid Number (HV) or Diamond Pyramid Hardness (DPH). The hardness number can be converted into units of pascals, but should not be confused with a pressure, which also has units of pascals. The hardness number is determined by the load over the surface area of the indentation and not the area normal to the force, and is therefore not a pressure.

In this study, the Vickers hardness number will not exceed 400 due to its features. So basically this number is almost equivalent to Brinell hardness number. So here, it is assumed that the value of Vickers is the same as Brinell to make things easier.

Here is the formula to compute the tensile strength from hardness value:

$$\text{TS (MPa)} = \begin{cases} 3.55 \cdot HB & (HB \leq 175) \\ 3.38 \cdot HB & (HB > 175) \end{cases}$$

$$\text{TS (psi)} = \begin{cases} 515 \cdot HB & (HB \leq 175) \\ 490 \cdot HB & (HB > 175) \end{cases}$$

(Source: Tensile Strength)

In this study, the tensile strength of the material is important. It is one of the mechanical properties of this material and it will determine whether the material is plausible for further study in the future or not. This value is one of the main concerns of this study. So by obtaining this value, the author will decide whether it is plausible to continue study on this material or not.

CHAPTER 3
METHODOLOGY

3.1 SAMPLE PRODUCTION

The sample is produced by using normal cutting action which is abrasive cutter. This machine is used to cut hard materials with less damage to the cutting wheel. Here is the picture of the Black & Decker abrasive cutter in the market (refer to Figure 3.1):

Figure 3.1: Sample of abrasive cutter
(Source: Abrasive Saw)

In this experiment, the author is using almost the same abrasive cutter model. The specifications of the abrasive wheel are:

- Wheel thickness – 0.4 cm
- Wheel diameter – 7 inches
- Wheel type – silicon carbide (refer to Figure 3.2)

Figure 3.2: Sample of abrasive cutter wheel
(Source: Hardware World)

For the material being cut, the author uses high temperature carbon steel. The specifications are:

- Material type – high temperature carbon steel rod (refer to Appendix III)
- Rod diameter – 1.5 cm

In this machine also, we have the debris collector. Usually, this debris collector is functions to collect the debris so that it will not make our work station dirty. But in this case, this collector is the main key to induce process that will produce the specimen to be studied. The debris collector specifications are:

- Debris collector type – ceramic floor tile
- Debris collector temperature – 27^{o}C

First of all, the steel rod is put on the bed of the abrasive cutter machine. Then it is clamped so that the rod will not move during cutting action is performed. This action also ensures that the steel rod doesn't bounce off the machine when the abrasive wheel touches the surface of the steel.

During cutting action, abrasive cutter will produce a concentrated spray of metal debris. But due to the rubbing action between the steel rod and high speed abrasive wheel, a high temperature of debris is sheared and ejected from the cutting point. This spray of debris will then hit the debris collector.

The cutting action is continued until the rod is cut into half. Then the steps are then repeated until there is no rod to be cut. This total debris accumulated will produce the specimen that the author wants. This is actually the specimen that the author is going to use in this project. The author will investigate further about this specimen. Below is Figure 3.3 which illustrates the sample production:

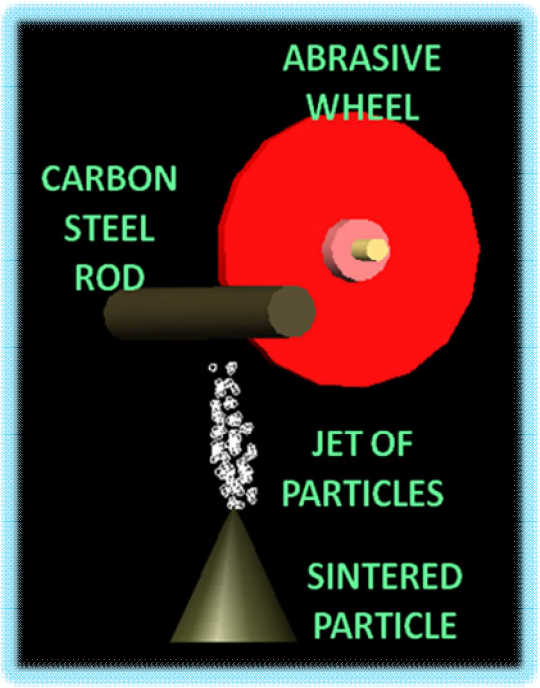

Figure 3.3: Sample production illustration

3.2 SAMPLE TESTING PREPARATION

This is the necessary steps before we can examine the samples. The steps are like below:

3.2.1 Sectioning

In this stage, the sample will be cut to standard square or in small size if not possible. It involves some cutting action that may change the microstructure of the sample on the surface. This is due to heat generated from cutting action and work hardening.

3.2.2 Mounting

Here, the sample will be capsulated in polymer matrix. Usually the polymer is made of thermoset or thermoplastic resin. This is to provide protection to the sample and also to ease material handling later. The mounting resin used will depend on type of the sample we have. Different sample will require different type of mounting resin.

There are also two techniques of mounting used. The first one is compression mounting. Sample will be capsulated in plastic resin under applied heat and pressure. The curing duration and pressure will depend on type of sample.

The second technique is cold/castable mounting. In this technique, the sample will be inserted into the special mold. Melted resin mixed with hardener will be poured and it will be let cured by itself in the room temperature.

In this investigation, the author will use the second technique in order to avoid any damage to the sample.

3.2.3 Grinding

In this step, the author will grind the surface of the sample. This is because the author wants to remove the damage introduced by previous operation. Eventhough this step will also introduce some damage, but we will minimize it using gradual finer grinding step. In the end, we will get a very smooth surface. Before polishing, the author will wash the sample to remove any abrasive and debris.

3.2.4 Polishing

This step is essential in order to produce scratch-free surface. It involves two types of polishing which are rough polishing and fine polishing. During polishing, the specimen will be oriented frequently to avoid any marks produced.

3.2.5 Etching

This last step is very important. The author wants to make the microstructure of the sample especially on the surface visible under microscope. It involves some chemical reaction between sample and etching under controlled environment. In the end, we will produce a good surface to be studied further.

3.3 SAMPLE EVALUATION METHODS

Evaluation methods implemented in this project are as per below:

3.3.1 Optical Microscopy

This method is almost similar with scanning electron microscope. This method of testing is useful for us to determine the crystal structure of the sample in different parts of interest. The end result will be used to deduce the appropriate crystal structure of the sintered material.

3.3.2 X-Ray Diffraction (XRD)

This investigation will be conducted in order to study about the crystallography of this sample. From this test, the author is able to identify the crystalline structure of the interest parts inside the sample. Different parts of sample are expected to yield different crystallography which makes the study interesting.

3.3.3 Scanning Electron Microscope (SEM)

This method will be utilized in order to study about the surface of the sample. The surface will be scanned with an electron, decoded by the program and the image of the surface generated will be used to determine the crystal structure, sintering mechanism and textured morphology of the sintered body. This is vital in order for us to determine its availability for further research in the future

3.4 SAMPLE TESTING METHODS

Conducted test method in this project is:

3.4.1 Micro Vickers Hardness Testing

This method is available in UTP and it enables us to investigate about the hardness distribution inside the sample. A few critical spots will be taken and calibrated for this investigation. It will then be recorded into table and converted into tensile strength for references in the future.

3.5 GANTT CHART

Refer to Appendix I & II

CHAPTER 4
RESULTS AND DISCUSSIONS

4.1 SAMPLE PRODUCTION

From the methodology, the author will calculate the speed of the debris of materials during flying in the air and hit the collector. Here, it is assumed that there is no air resistance. So the initial velocity is equal to final velocity of the debris when colliding with debris collector.

Given:

Wheel diameter (d) – 7 inches
- 0.1778m

Wheel speed (ω) - 8000rpm
- 133.33rps

Speed of jet (v) = π d ω
= π (0.1778) (133.33)
= 74.48 m/s
= 268.12 km/h

This is the approximate speed for the jet spray. As we can see, it is fast enough like a F1 car. This means that the jet spray carries with it a great kinetic energy with it. It is originated from the transfer of mechanical energy from the abrasive wheel to the sample.

From the sample production also, the author can see that a very high temperature and concentrated debris is produced. This debris is glowing in red indicating it almost melted during the shearing process. With a high speed and almost melted, it hits the debris collector.

Since the author does this method in the open atmospheric condition, the debris is open to the oxidation during pre-flight from the abrasive wheel to the debris collector. But not all the debris is oxidized. This is because the limited time of contact between the debris and the atmosphere. Only some portion is involved in this case.

When the debris hit the surface of the collector, it hits with a high velocity. And using the momentum theory, the total kinetic energy will be converted into the other forms of energy. The debris will collide among each other in a combination of high temperature and velocity. Since all the debris is collected in one confined area, the heat cannot really being released to the surroundings due to the convection resistance. So the sintering may happened in this case. As a proof, we will see it in the next section.

4.2 SAMPLE TESTING PREPARATION

The first phase is sectioning. Here, the sample is cut into a few small pieces according to the interesting region to be studied. And here, the sample picked from the sample production is cut into four different pieces. From these pieces, the author will study further about its physical characteristics and jet sintering mechanism that occurred inside the sample.

The author has cut the sample into four different sections. These sections are captured by Figure 4.1 and 4.2:

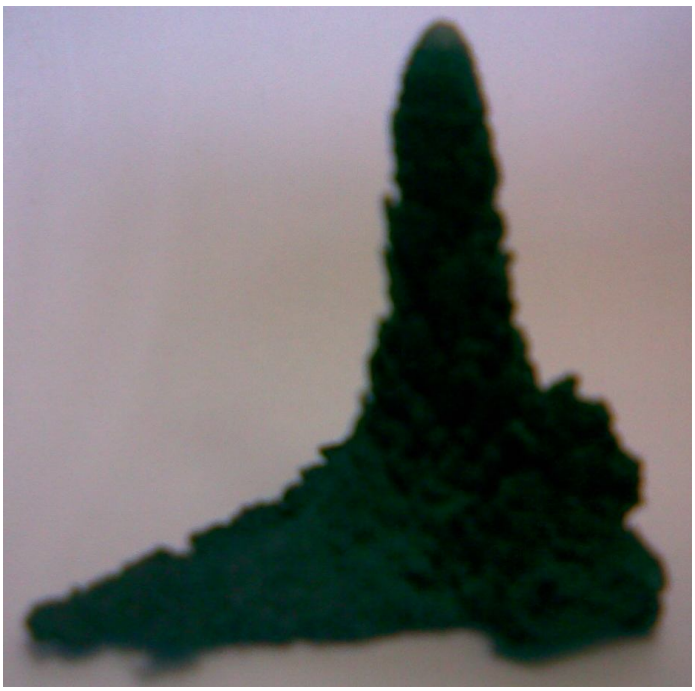

Figure 4.1: Sample picture before cutting

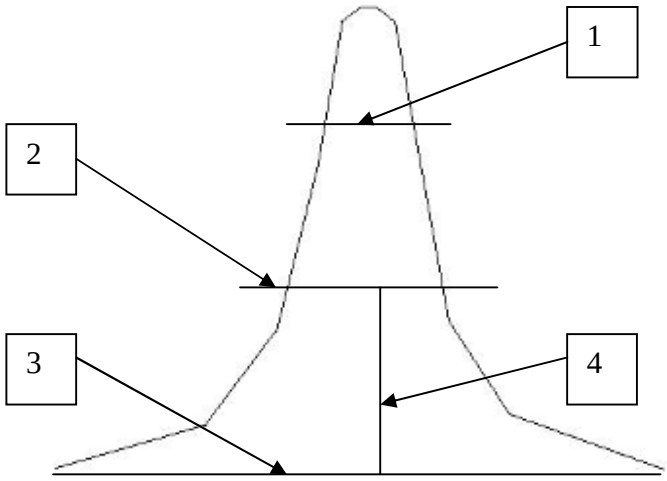

Figure 4.2: Schematic diagram of sample cutting sections

After the sectioning of the sample, the author has captured some of the observations (refer to Figure 4.3):

Figure 4.3: Cross section of 1 after sectioning

At the middle of the sample, the author can see that the surface is very smooth. It indicates that the molecules of the material are very close to each other. There is the possibility of sintering to occur at this region. But as we go to the edge of the sample, the author can almost see some small lines. Here the author will investigate further about the grain boundaries in the microscopy inspection.

Figure 4.4: Cross section of 2 after sectioning

The same phenomena happened in this section as per Figure 4.4. At the core, it appears to be solid. But towards the edge, there are voids. The voids are getting bigger and bigger towards the edge of the sample. The consistency of the new interesting things can be seen here and all these will be studied further.

For section 3, the surface appeared to be grey in colour. No shiny surface like the other sample. Later, the sample will be polished so that it will be easier to investigate under the optical microscope.

For section 4, the observation is even more attractive. This is the result (refer to Figure 4.5):

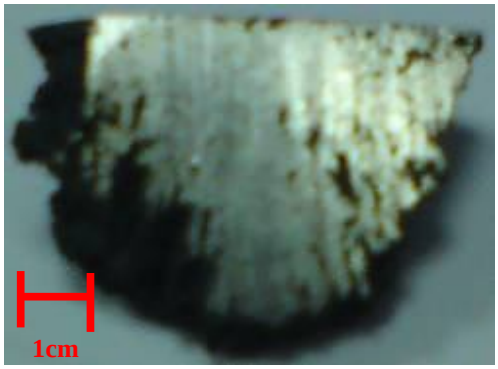

Figure 4.5: Cross section of 4 after sectioning

Then the author proceeds with the second phase which is mounting. This is to ensure that the sample cut earlier is preserved and intact. It will facilitate us in holding the sample better. It will also prevent the sample from crack due to external force.

Here, the author is using the machine provided by UTP in the Material Lab. Here are the picture of the equipment and the end product of it (refer to Figure 4.6 and 4.7):

Figure 4.6: Equipment used for mounting

Figure 4.7: Sample after mounting

It is numbered and kept in a case so that the sample will not lose from sight.

Next, the author moves to the third and fourth phase which are grinding and polishing. The objectives of grinding process are:

- To remove damages introduced by previous operations on the surface of the sample.
- To remove saw marks and levels which may exist on the surface of the specimen
- To produce a plane surface with minimal damage on it

The samples are grinded gradually from coarse to fine size by using silicon carbide abrasive paper. This paper is mounted on the motor driven wheel in order to ease the grinding process. Compared to conventional grinding, this method will speed up the process and also improve the quality of the surface produced. The grinding process is done in wet medium with water as a lubricant. The grinding sequence follows a series of descending grain size. In this experiment, the author chooses the sizing of 60, 240, 400, 600 and 1200 grit.

Between each grinding step, the specimens are washed under running water and it is wiped dry for examination. This step is crucial because it will cool down the specimens. Washing is also to wash away loose abrasive and debris, prevent contamination to the subsequent steps and prevent embedment on the specimen surface.

The fourth step in this sample preparation is polishing. The objective of this step is to produce scratch free surface with mirror like finish. In this case, the author skipped the step because we have already used a finer abrasive paper of 2400 and 4000 grid to replace the real polishing step. During polishing, the specimen orientation is changed continuously to avoid comet trailing. In the end of this process, the author have successfully produced mirror finished of the specimen.

Before the author move to the next phase, the specimen is washed again by stream of water and followed by stream of alcohol/ethanol. Then it is dried under hot air blower. This is to make sure that the surface is water-free and prevent corrosion to the surface of the specimen due to water left on the surface.

The last step of the sample testing preparation is etching. It is to make visible the microstructure surface under the microscope inspection. It involves the chemical reaction between sample and etching step under controlled condition. In this step, since the material is low carbon steel, the author use nital solution. The surface of the specimen is immersed into a small beaker filled with nital solution. When the bright surface disappears, the author quickly rinsed the specimen with running water. Then, the author also washed it under running alcohol/ethanol to remove the excess water from the surface and it is blown by the hot air blower.

But the author made some mistakes in this step. The etching is performed too long. As a result, the surface is corroded due to chemical attack. However, the specimen is still inspected under microscope to record the observations.

4.3 MICROSCOPY INSPECTION 1

In this phase, the author has chosen 21 different points in the specimen which appears to be interesting to be observed and recorded. Even though the specimen is corroded due to too much etching, the observation must still be recorded for future reference. Plus, the author may find something very interesting inside the corroded surface which may not be found elsewhere.

These points are captured by DinoCapture, a new device in the material lab for the optical microscopy inspection (Figure 4.9) and the picture of the sample is taken for examinations. Here are the areas as per Figure 4.8:

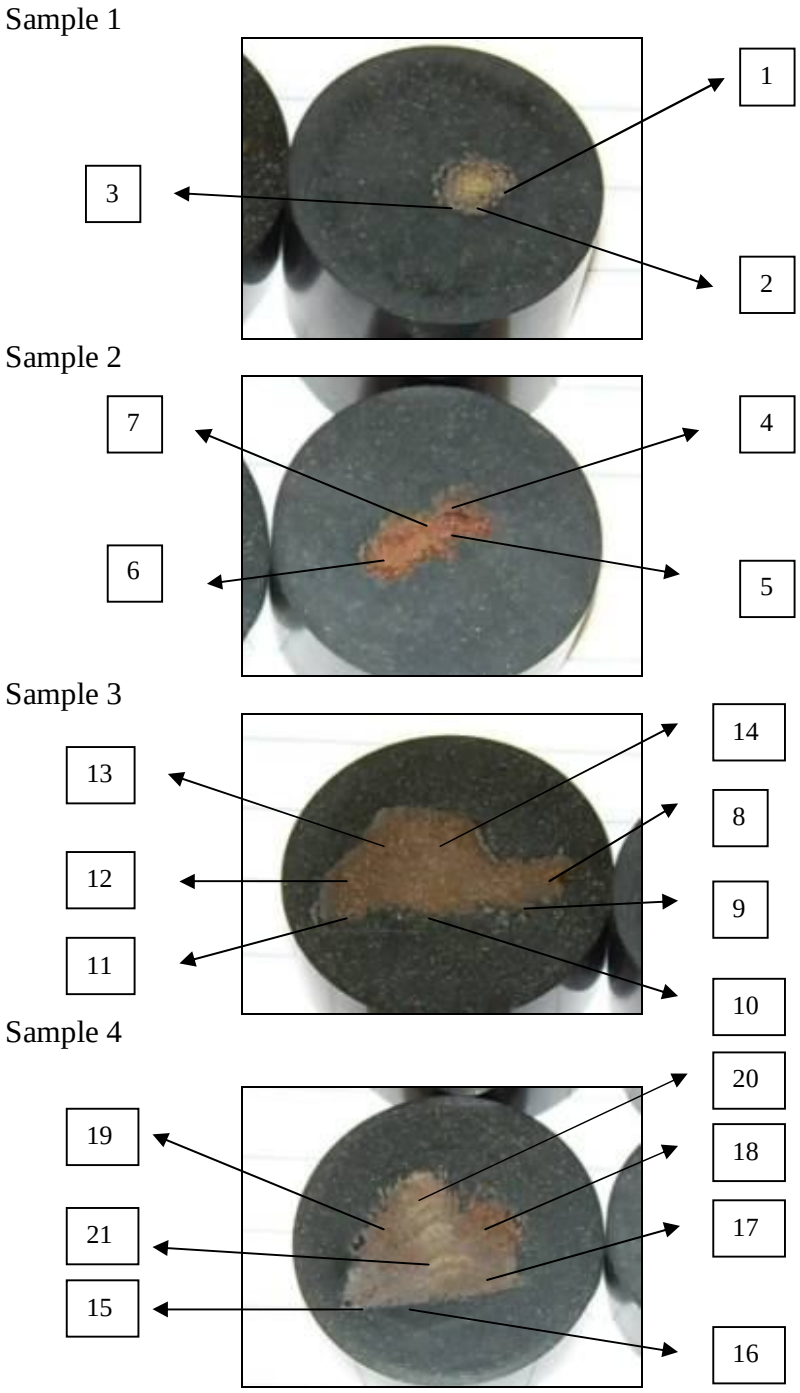

Figure 4.8: Areas of interest in the optical microscopy inspection

Figure 4.9: Example of microscope used in this experiment

Before examining the samples under the microscope, the author need to make sure that the surface is levelled perfectly. In order to do that, the author use one extra mounting section made up specifically for this purpose. This will be the bottom side of the assembly. The top is the sample. Between these two mounting, the author put small portion of plasticin or dough mixture to be sandwiched between them. Special equipment will be used to press all the assembly down. This press action will make sure that the surface of the specimen is levelled accordingly. Here is the picture of the equipment (refer to Figure 4.10):

Figure 4.10: Specimen level equipment

And here are some of the interesting pictures which the author would like to discuss in this topic:

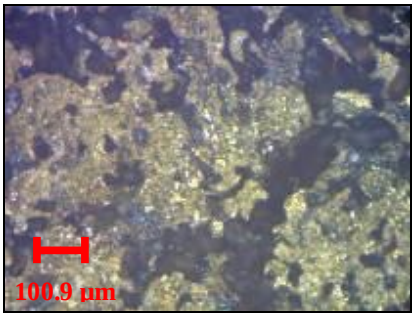

Figure 4.11: Caption from point 3 at 720x real magnification

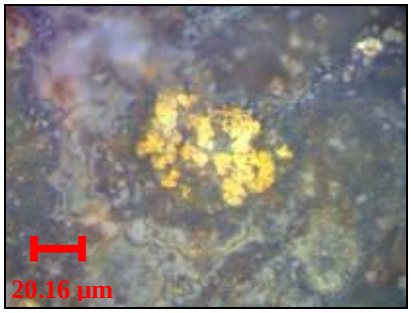

Figure 4.12: Caption from point 4 at 3600x real magnification

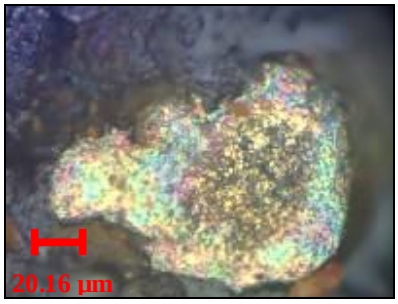

Figure 4.13: Caption from point 9 at 3600x real magnification

Figure 4.14: Caption from point 14 at 720x real magnification

From Figure 4.11, what the author can see is basically the sample is not solid. The microstructure is not visible to the observation due to too much of etching and this appears in all points. The void seems to vary from one sample to another. This make the project later will concentrate on the void fraction in each point so that the author can tabulate the data first-handed.

Figure 4.12 shows us some interesting features. This yellowish area seems to corrode only a little bit compared to the surrounding area. The interaction between the fine particles can be seen through tiny cracks in the sample which may indicate some sintering has occurred but only at a few points only.

The same phenomenon is also observed in Figure 4.13. This time, the area is not corroded at all and it appears to be just fine compared to the other particles surrounding it. The colour distributions indicate some overburn particles due to heat. This thing can only happened if very high heat is involved in the process.

The author has also observed some alien thing inside the specimen. In Figure 4.14, there is something like fibre inside the specimen. This thing may exist during sample preparation or maybe some contaminants during cleaning of the specimen.

All these will be taken into consideration and discussed further in the next microscopic inspection 2. The sample also will be re-polished and observed at the same point to make a comparison between corroded surface and mirror like surface.

4.4 MICROSCOPIC INSPECTION 2

This investigation is performed after failure of microscopy inspection 1. The inspection in each different section is a must in order to study the mechanism of jet sintering. Section 1 studies will be based on how the mechanism of sintering takes place in the early stage of particle accumulation. Section 2 studies will be based on the intermediate stage of sintering where hot particles already started to cool down a little bit after the accumulation.

Section 3 is our main target basically. This section's study will be based on how the interaction between the collector surface and hot particles affect the sintering mechanism in that area. Last but not least, section 4. The author will study the different level of particles after sintering at different height. This section will actually tell us more about how the mechanism of particles during pre-flight in the atmosphere.

Now, let us examine the result from the microscopy inspection. For sample 1, we have only three points of interest. The picture is as per Figure 4.15:

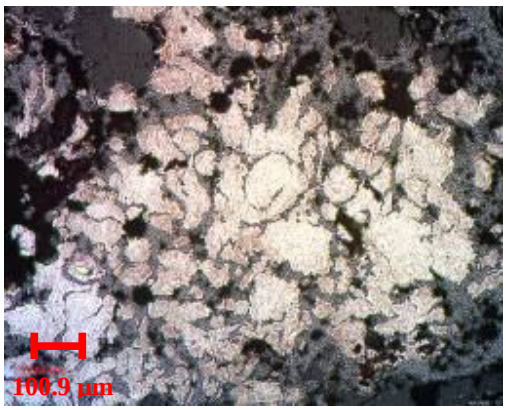

Figure 4.15: Point 1 at 720x real magnification

The author is going to discuss about point 1 in this case. As we can see, the particles are packed closely to each other. There are basically two main regions in this sample which is white and grey in colour. The black region is basically just a mounting material so the author is not going to discuss about it in this case. Since this is a cross section, what we are seeing now is a top view from the specimen. Between particles, the author can see clearly that sintering has occurred in this region.

To see it clearly, the author zoomed in deeper into this picture (refer to Figure 4.16):

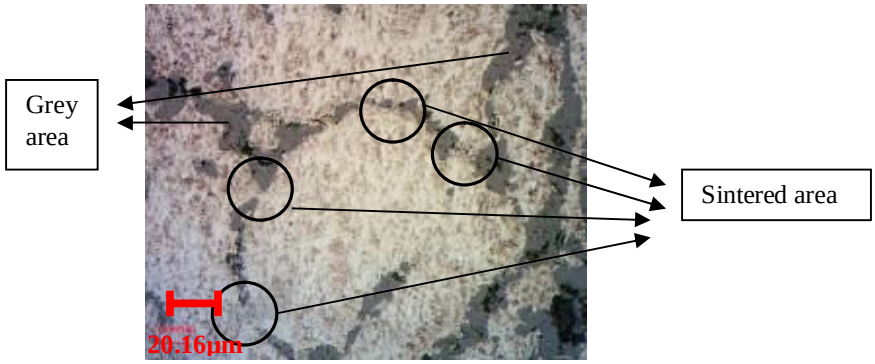

Figure 4.16: Point 1 at 3600x real magnification

From this picture, it is clear that the particles have already sintered during the process. But they only sintered at some areas. The estimation of sintered area between particles is just 10-15% from the real existing area. The other part is just packed closely but not sintered. The gap between the particles is filled with grey area. This is the interesting part because the size of grey area varies quite dramatically. In this picture, it varies around 0.1- 10 micrometer. This area is mysterious to us because up till now, the author is still not capable of determining the composition of the grey area. It might just another oxidation layer or something else. This will be studied further in the next phase using EDX function in SEM to determine the composition of that grey area.

Next, the author moves on to the sample no 2. This sample will examine the middle section of the sintered particles. There are 4 points of interest in this sample. The chosen point in this case is point 7. In this picture, the author can see that the same phenomenon occurred in sample no 2. There are basically three types of region in this point which is black, grey and white. Only at this area, the black represent the void in this material and not the mounting material. The picture is as per Figure 4.17:

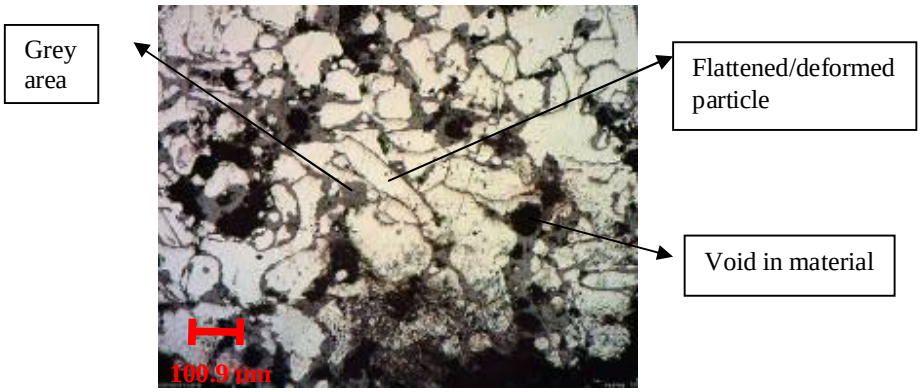

Figure 4.17: Point 7 at 720x real magnification

Here, the author can see that the particle size is quite random. The distribution of the particle size is from small to big. Since this is also the top view of the middle section, the author cannot deduce how the particles stick to each other. But from here, the author can say that during impact, the material seems to flatten. This is evidence that particle state is actually in molten or semi-molten state during pre-flight. The temperature produced from abrasive cutter is high enough to melt the particles. That's why it exhibits the behaviour like above. The author zooms in closer to see the other interesting part in this point (refer to Figure 4.18).

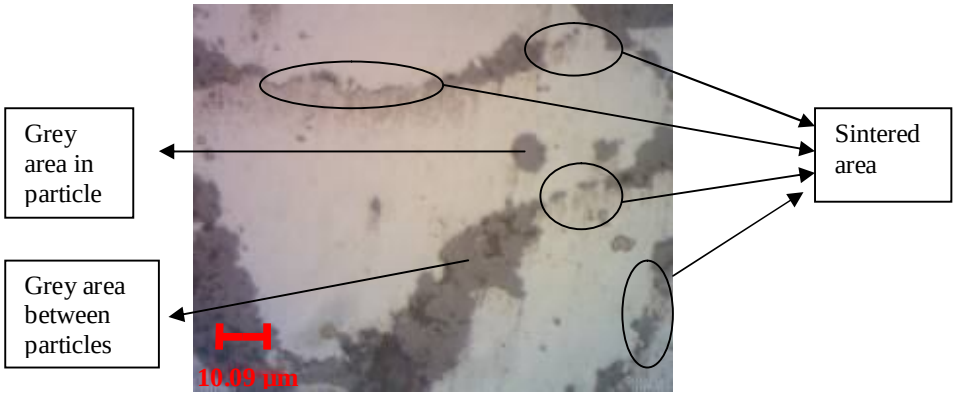

Figure 4.18: Point 7 at 7200x real magnification

In this sample, the author can clearly see that the particles sintered among each other. The surface area of sintered particles is also roughly the same as before which is 10-15% of total particle area. This is maybe due to cooling that occurred after some time. The temperature inside the specimen is no longer adequate for sintering to occur more intensively. As a result, the area of sintered particles remains the same. It's just something odd can be observed in this picture. Spots of grey area seem to appear inside and between the particles. This phenomenon really adds up the mystery inside the material. Further investigation will be done to examine these areas later.

Then, the author move to sample 3. Here, total points of interest are seven. Sample 3 will briefly tell us the mechanism of sintering at the bottom of the material. This portion is the first portion that touched the collector after pre-flight. The point the author choose to discuss here is point 11. The picture is as per Figure 4.19:

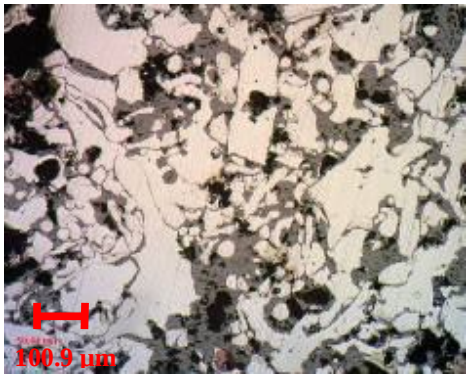

Figure 4.19: Point 11 at 720x real magnification

From this picture, the author can clearly say that three different areas still exist. If we consider the black as the void, then the author can say that in sample 3, there are less void compared to sample two. The material seems to have fewer voids at the bottom and more at the middle. This indicates that the particles in the molten state are squashed during the process.

There are less damping effect in this area because the particles are not loosely packed at the bottom. They travel with a very high speed and smashed onto the collector surface making the particles to really flatten in all directions. Since the jet spray of molten particles is fairly constant in this process, the particles kept smashing each other making it denser than before. That's why the area contains fewer voids than the middle section. The grey area still exists but only in a greater scale than before. To understand more, the author goes deeper into this picture (refer to Figure 4.20).

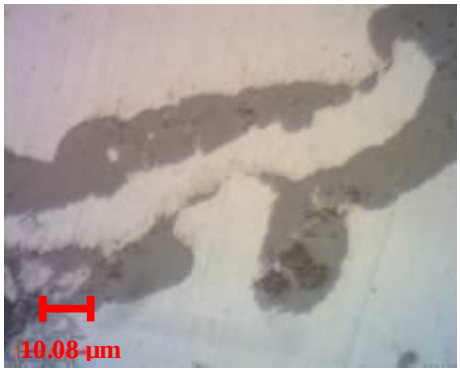

Figure 4.20: Point 11 at 7200x real magnification

This picture exhibits the same thing that happened earlier. The particle seems to sinter at certain portion only but now it's even less. The area of sintered particles reduces to just around 5-10% only. This is because the particles experienced great temperature difference during the occurrence. The collector surface is having low temperature compared to jet particles in the pre-flight. When the particles smashed onto the collector surface, the temperature gradient between the particles and the collector surface is very high. So, heat transfer occurred from particles to collector. As a result, the collector surface is heated by this phenomenon. The downside of this part is, it reduces the temperature of the particles. This reduction prevented the particles to sinter properly. Only high temperature areas survived this phenomenon and sintered. That's why the area of sintering is less in this case.

Last but not least, the author will look to sample no 4. This is a key to our project. This sample basically shows us the material state clearly during pre-flight and after interaction between particles. The point of interest in this case is point 19. The sample picture is as per Figure 4.21:

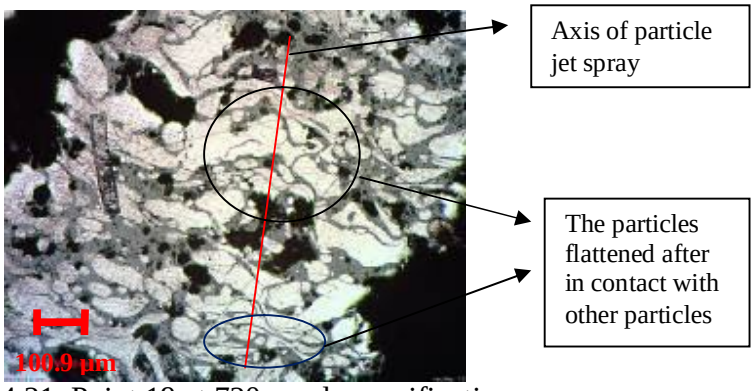

Figure 4.21: Point 19 at 720x real magnification

From this point of interest, the author can see that the direction of particle jet spray is imminent. It is one direction from top to bottom. If the author views all of the points of interest in this sample, the author can see that every single point exhibits the same phenomenon. They showed one direction of particle flow. These particles keep on stacking onto each other in the jet spray process. And the best part is after interaction between particles, they seemed to flatten and flow away from the axis of particle jet spray. This phenomenon proved that the particles are high in temperature during contact. High enough for the particle to melt and it is actually in the molten state during pre-flight. Once it contacted another particle, this molten part will flow to the side of the point of contact just like splash of water. Since it is high in temperature, the sintering can occur in this part.

For some big particles, they are actually in semi molten state. The outer layer of particle is basically melting but, the core is not. When the contact between particles occurred, the molten part will flow and the semi molten part will eventually flattened a bit. That's why the author can see the pattern of the particles inside the specimen as per above. To look further, the author zooms in deeper using microscope (refer to Figure 4.22):

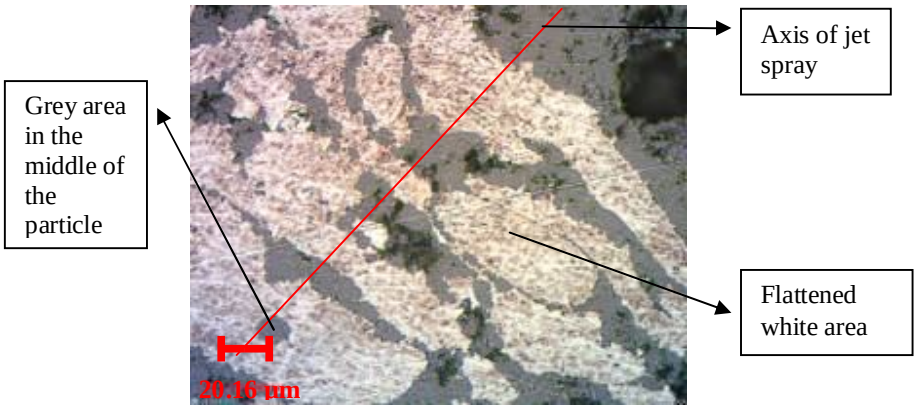

Figure 4.22: Point 19 at 3600x real magnification

Here, the author can clearly see that the particles are packed close to each other. The area of sintering also increased to 10-15% of the total area because the author is looking at the middle section of the sample. But, the main concern here is the grey area seems to have a greater portion. It filled the gap between particles. Here, the issue is still the same, if the grey area is actually oxidation layer, it cannot be too much in this size. It should only appear like small layers and not like this.

Plus, if the grey layer is oxidation later, it cannot appear inside the particle. It should only appear on the boundary of particles only. So basically the status of grey area is still unknown to us. This grey area will be our main priority to be studied later.

In order to see the picture clearly, the author have attached the sample picture in Appendix IV for better review.

The next phase of research will utilize high-end and sophisticated equipments like Scanning Electron Microscope (SEM) and X-Ray Diffraction (XRD). These equipments will be used to statistically determine the chemical composition inside some unknown areas.

4.5 SCANNING ELECTRON MICROSCOPY AND X-RAY DIFFRACTION

In this section, the author should discuss about the result from the analysis and compared with analysis result from spectrometer as per Appendix III. Unfortunately, both equipments are not available due to very long queue of usage in UTP. In total, we have only one SEM for Final Year Students and one XRD for the whole campus. That's why the queue is very long and nothing can be done in order to solve this problem. The evaluation of the material will just end here and will be continued by other students next semester if possible.

However, the sample testing phase will be continued in the next subtopic. This testing is viable throughout the year because there is no need of long queue like evaluation equipments before.

4.6 HARDNESS TESTING

In this phase, it is basically to determine the physical properties of this material. Here is the summary of the results for the hardness testing (refer to Table 4.1). All the details are included in the Appendix V.

Table 4.1: Hardness and tensile strength results

Point of interest	**Average hardness value (HB)**	**Tensile strength (MPa)**
1	94.4	335.0
2	117.0	415.5
3	129.1	458.3
4	235.1	794.5
5	169.0	600.1
6	129.9	461.3
7	162.4	576.5
8	268.7	908.2
9	225.5	762.2
10	196.2	663.3
11	207.7	702.1
12	212.7	718.9
13	257.7	871.0
14	130.2	462.1
15	247.5	836.6
16	162.1	575.5
17	201.2	680.2
18	149.7	531.6
19	202.5	684.6
20	95.3	338.2
21	228.7	772.9

Here, the maximum value of tensile strength is 908.2 MPa and the minimum value is 335.0 MPa. From this result, the author can deduce that this material basically falls within practical steel tensile strength which is 276 – 1882 MPa. This indicates that this material is practically useful in industry based on this value.

But, this material yields a big range of tensile strength. This indicates that the bonding between the particles is not consistent. Sintering process in this sample occurs with a large deviation of properties. Hypothetically, the range of tensile strength is maybe due to the great differences in temperature distribution during jet sintering. So, the sintering is not consistent throughout the sample. That's why the range of tensile strength is big and not consistent.

However, this value is just one out of many features that should be studied regarding this material. Further study will tell us the features of this material.

CHAPTER 5
CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

As a conclusion, all the objectives were achieved. The microscopic inspection has given us a lot of information about the jet sintering mechanism. It also proved that the particles are not solid during pre-flight until the moment of contact. The temperature is high enough to start the sintering process between particles. It is also high enough to allow oxidation to occur on the surface of the particles. Only small portion of material sintered in these samples. The unknowns like grey area will be studied further in the next project due to limited availability of required equipments which disables the capability of us to study further about this area.The microstructure of the material can also be determined by evaluation methods enlisted before. The tensile strength can be determined from this project by Micro Vickers hardness testing.

5.2 RECOMMENDATIONS FOR FURTHER STUDY

To make this study becoming more valuable in the future, a few extra steps must be taken in order to improve the result from the experiment:

- The material of the experiment must be changed with a lower melting temperature material. Example, aluminium. This will increase the possibility of proving this jet sintering mechanism in an intensive and proper condition.

- The material preparation should be done in vacuum or inert gas environment. This will produce less oxidation during material preparation. It will be good to have less oxidation because this will form a layer of protective coating which may prevent the sintering process from happening.
- This technique may be another viable solution for preparing aluminium foam. This end material is used to absorb impact during accident occurred. If the technique is used and proven, it will be a new finding for the industry as one alternative for making the aluminium foam.
- In preparing the material, please use a new abrasive cutting wheel in order to reduce impurities. This impurity is something which is not necessary for this study. It may disturb the result and the end result of the study as well.

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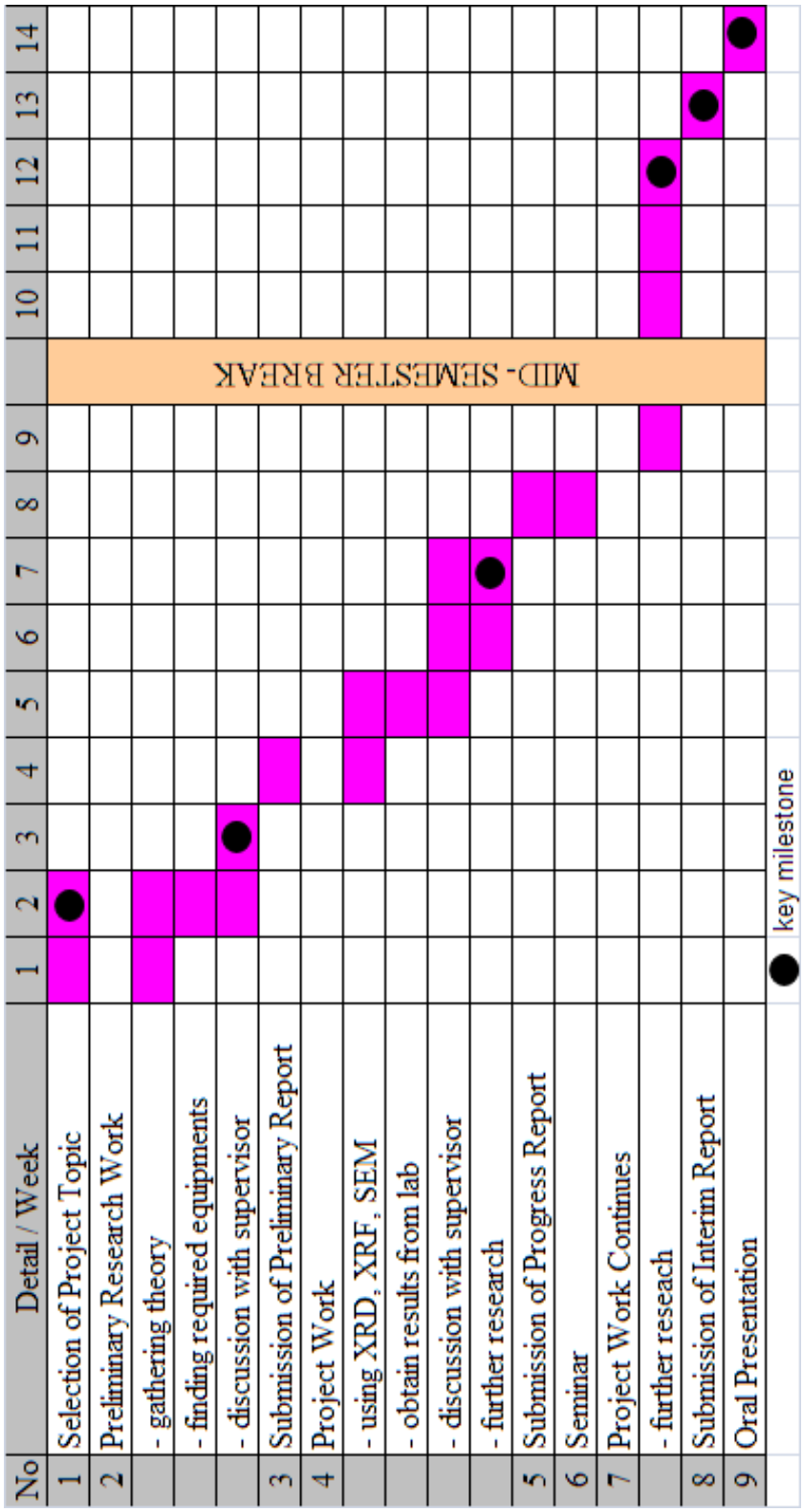
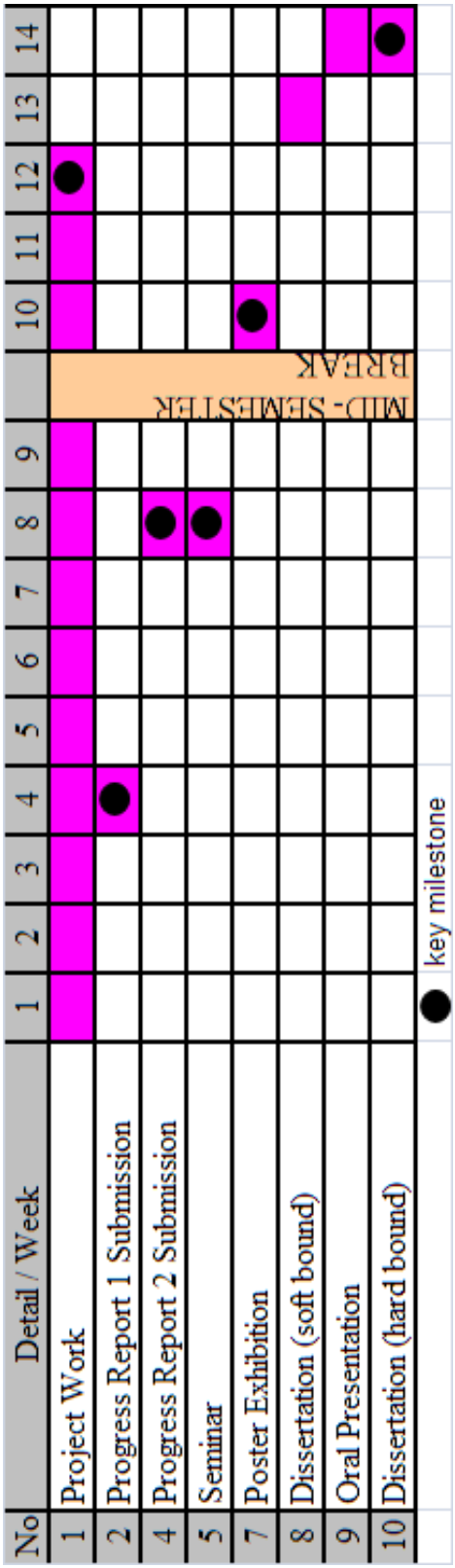
APPENDIX I – GANTT CHART FOR FYP 1



APPENDIX II – GANTT CHART FOR FYP 2



APPENDIX III – ANALYSIS RESULT FROM SPECTROMETER

Hasil Pengujian Komposisi Baja API 5L X65

Lab No : 121/sp.lab/Ex.POLMAN/2004

Order No : PF-40330

Kode Sampel : 01*06*04

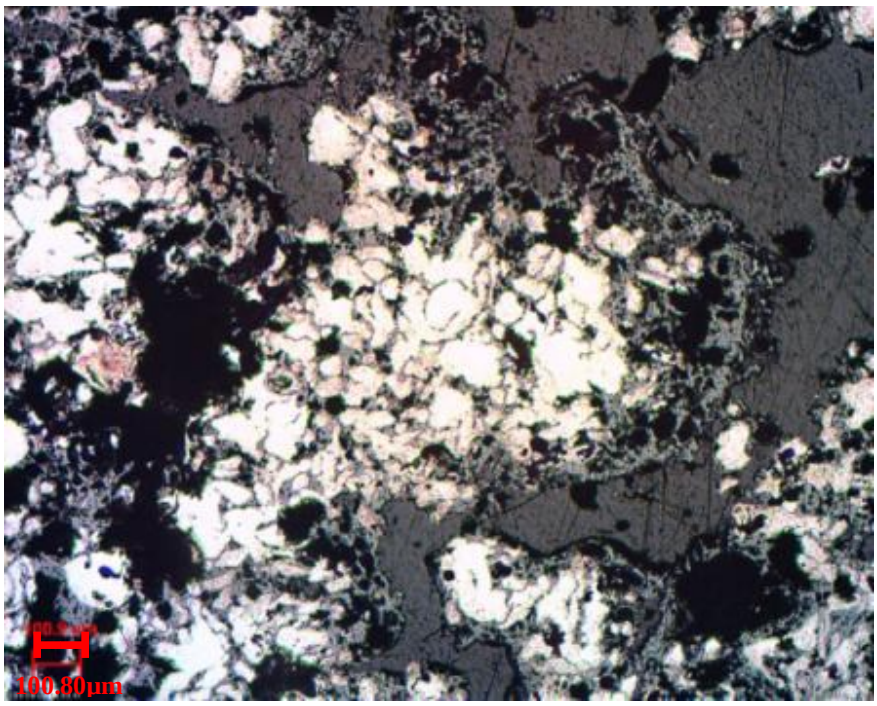
Analisa : Spectrometer

Program : Felast

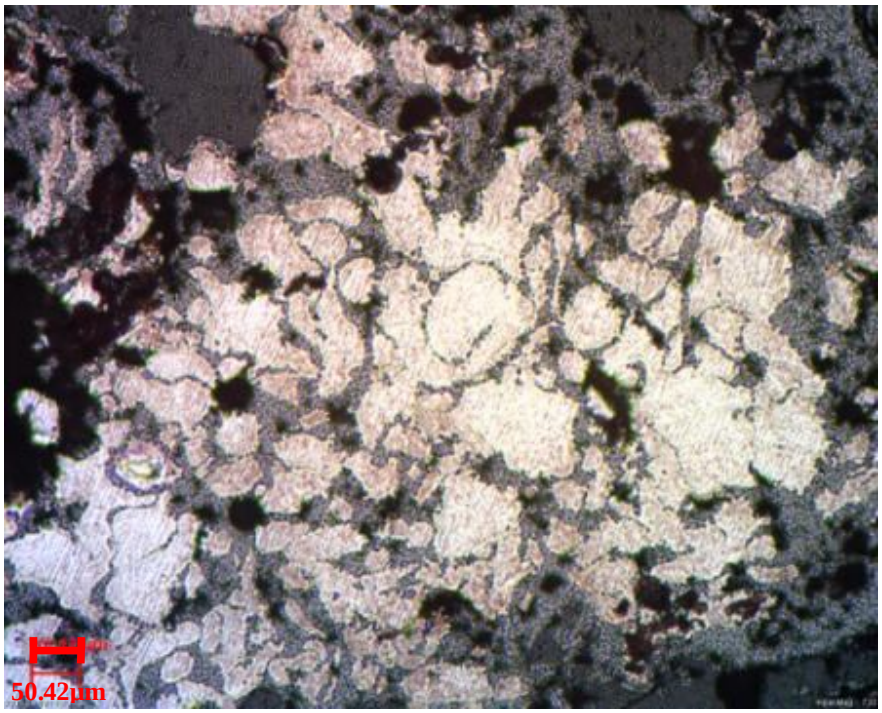
Hasil/Result :

Unsur	(%)
C	0.07367
Si	0.28822
S	0.00675
P	0.01532
Mn	1.5353
Ni	0.01286
Cr	0.02244
Mo	-
V	0.02755
Cu	0.00513
W	0.00298
Ti	0.01691
Sn	0.00047
Al	0.02823
Pb	-
Sb	-
Nb	0.03957
Zr	0.00089
Zn	0.00138
Fe	97.93274

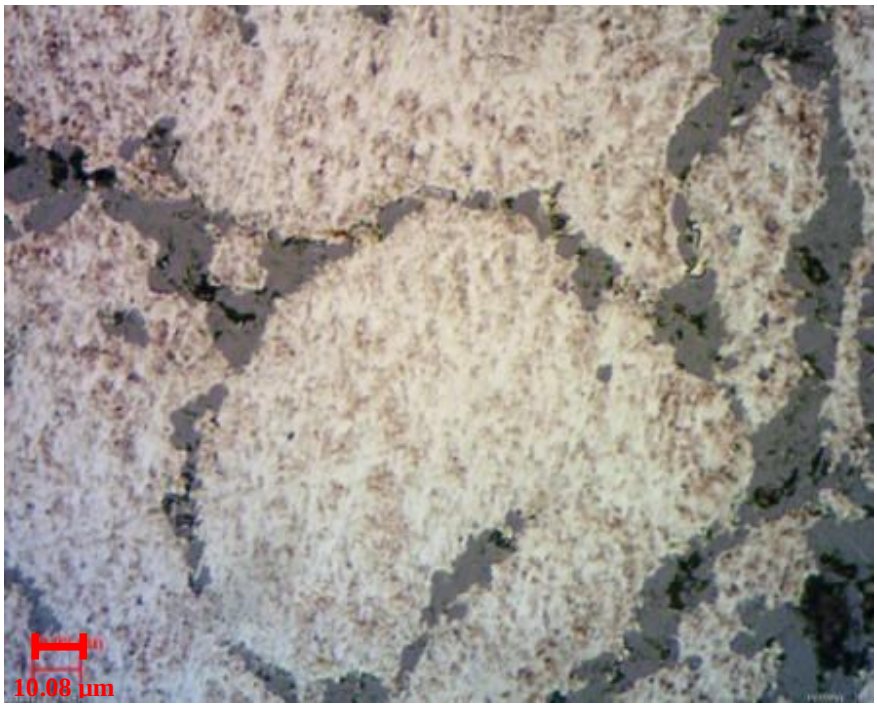
APPENDIX IV – SAMPLE PICTURES TAKEN FROM OPTICAL MICROSCOPIC INSPECTION



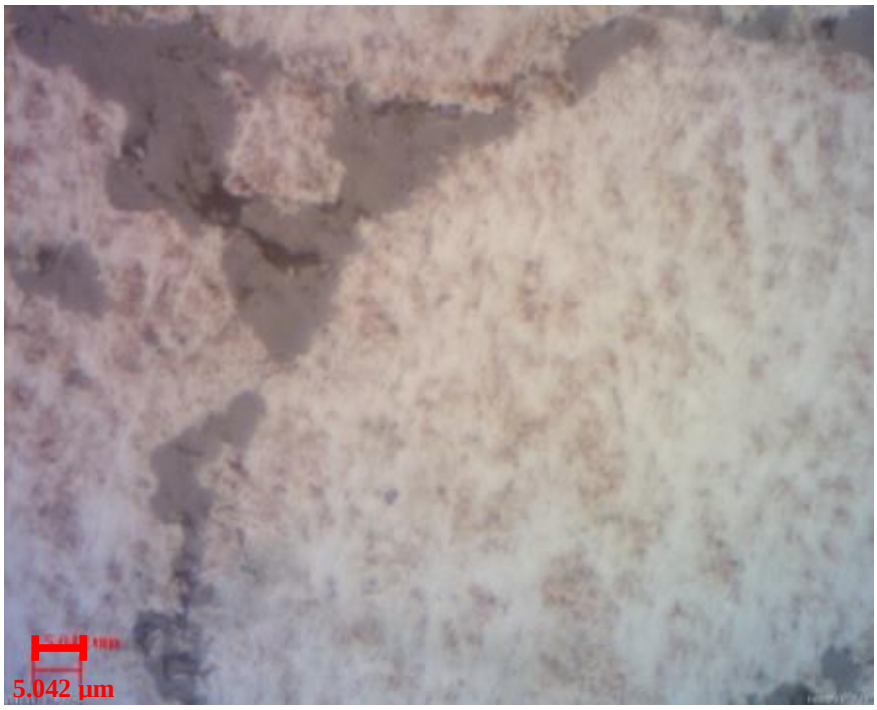
Point 1 at 360x real magnification



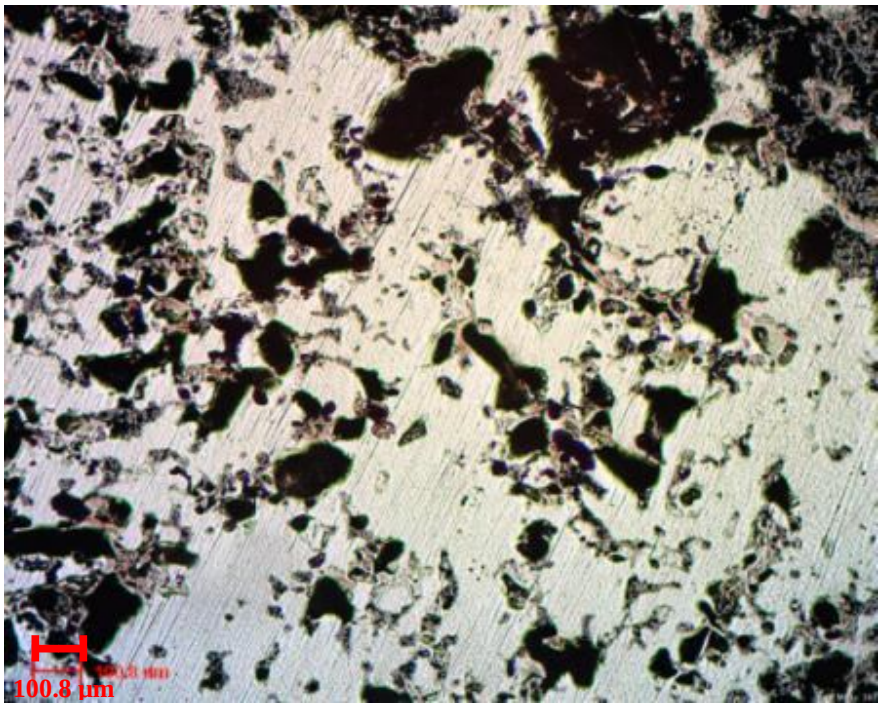
Point 1 at 720x real magnification



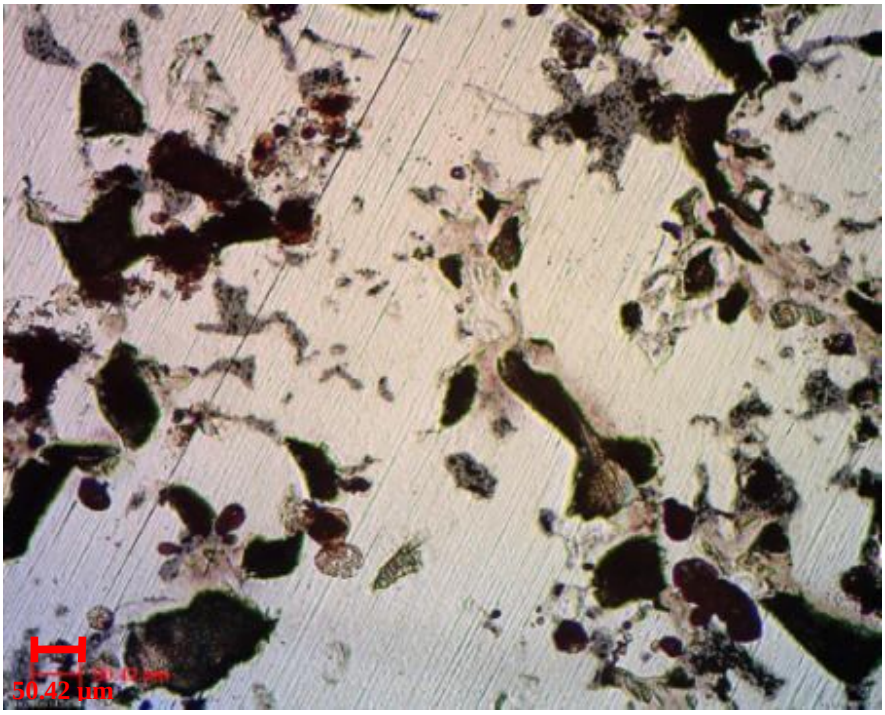
Point 1 at 3600x real magnification



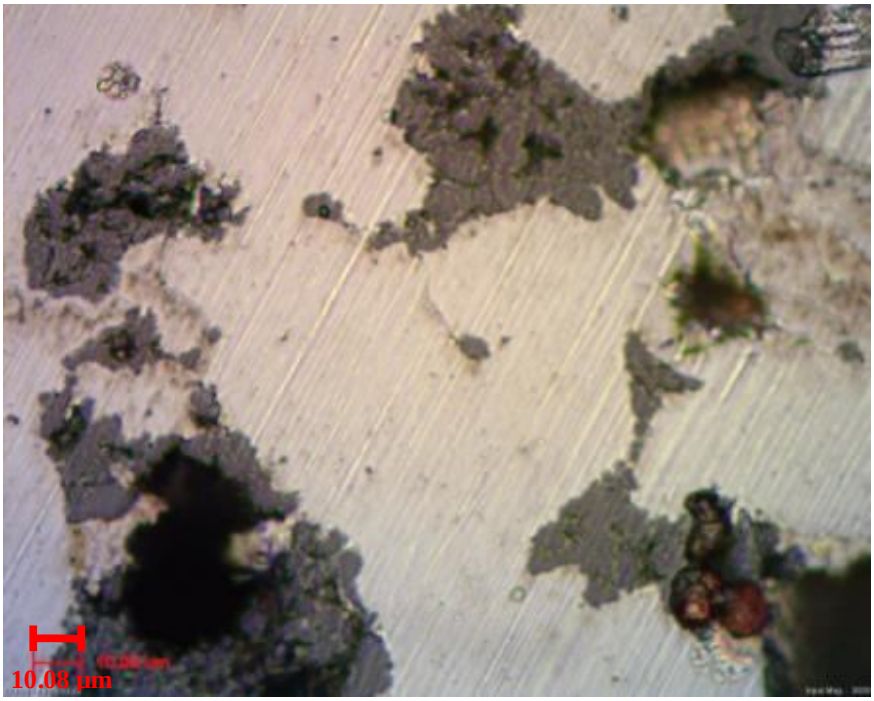
Point 1 at 7200x real magnification



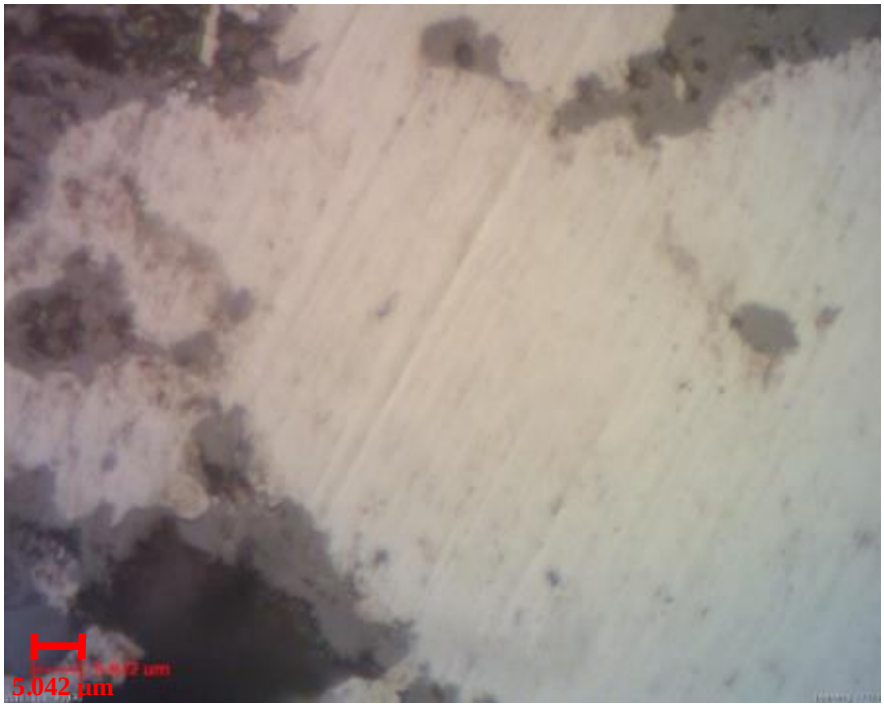
Point 2 at 360x real magnification



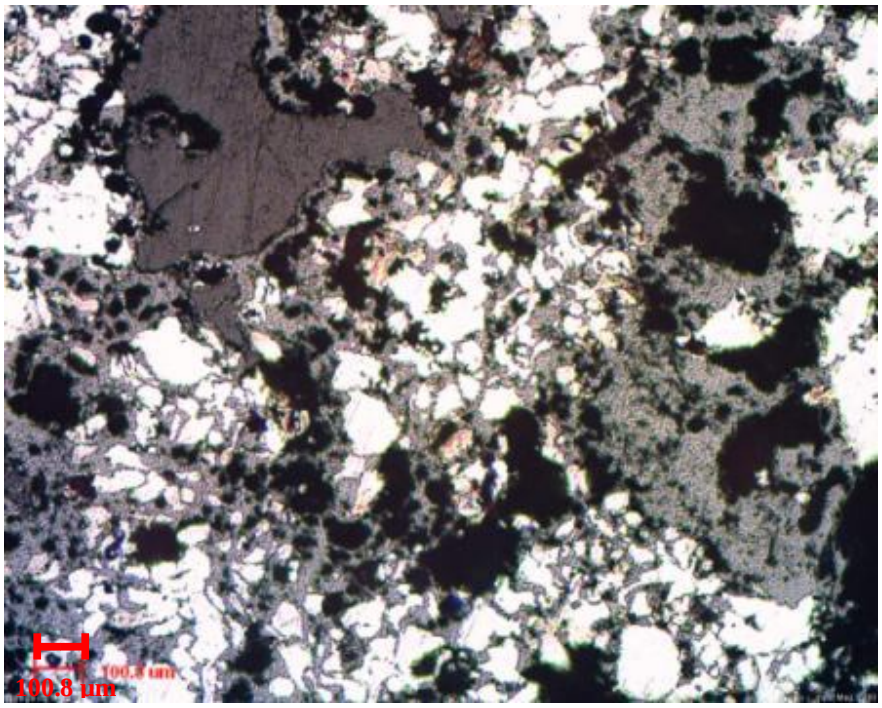
Point 2 at 720x real magnification



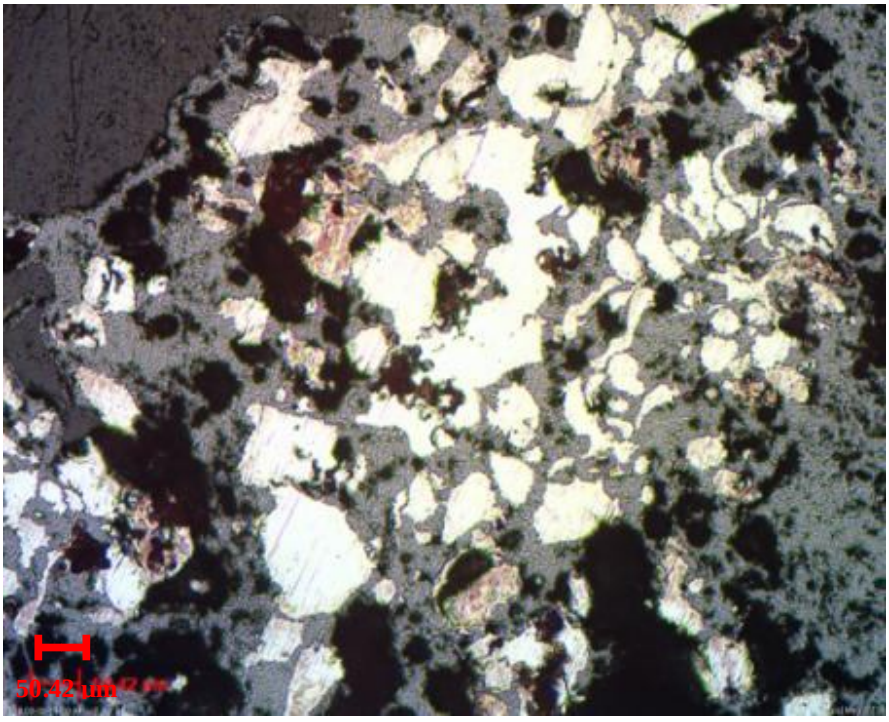
Point 2 at 3600x real magnification



Point 2 at 7200x real magnification



Point 3 at 360x real magnification



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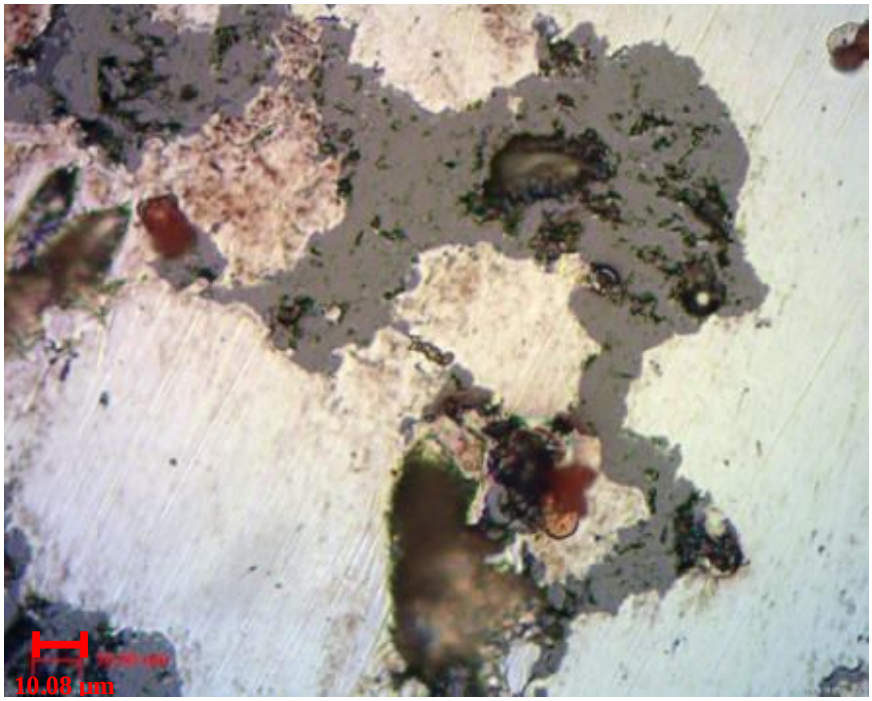
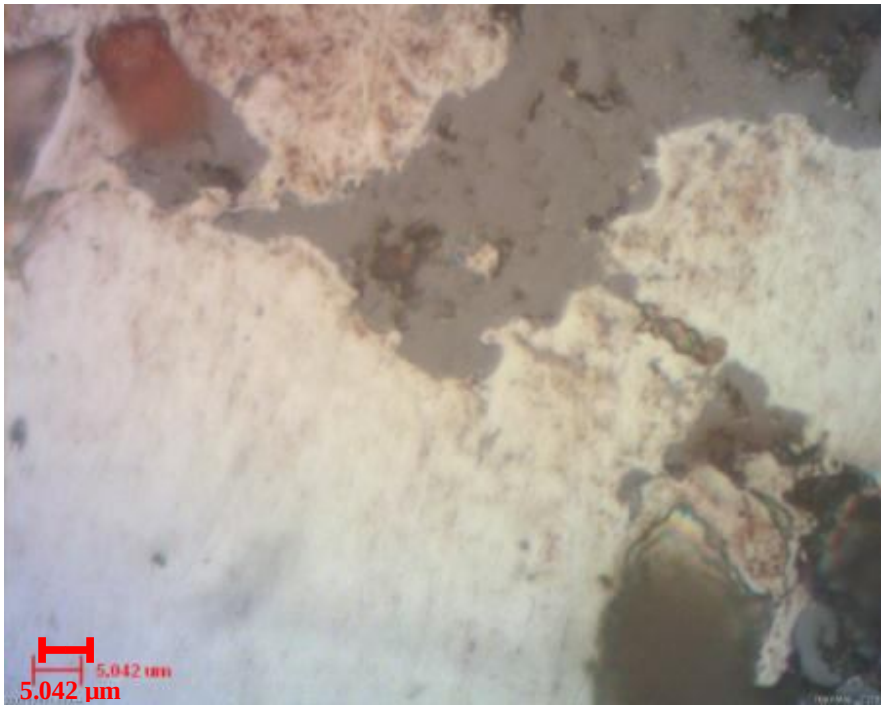
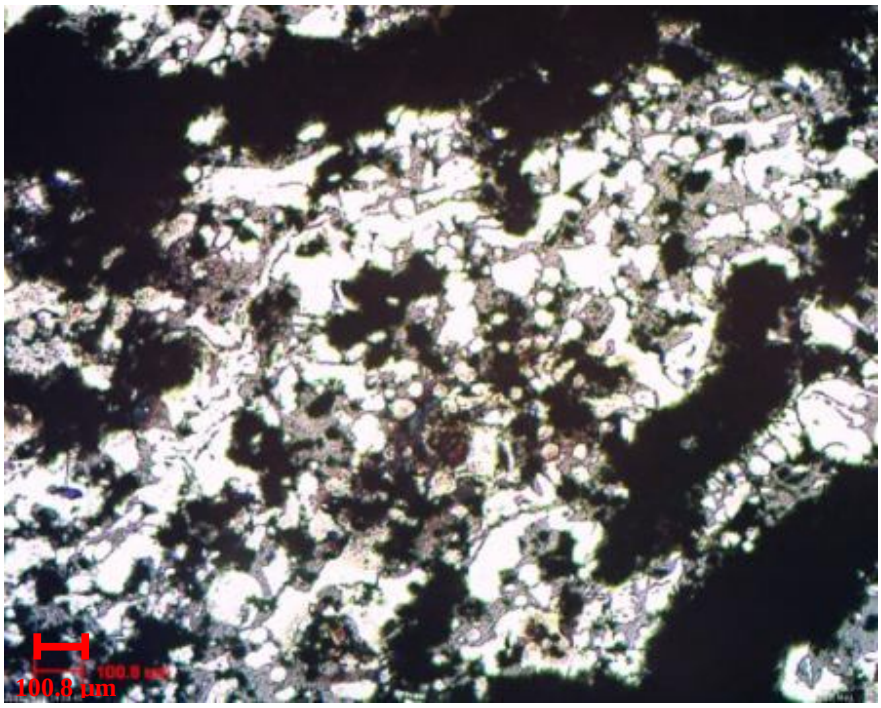


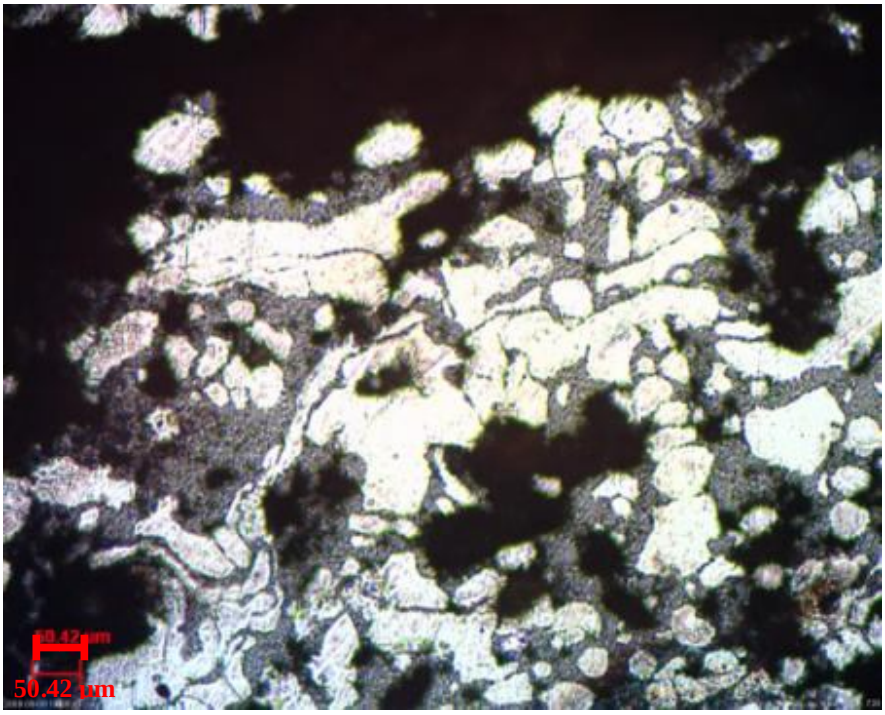
Point 3 at 3600x real magnification



Point 3 at 7200x real magnification



Point 4 at 360x real magnification



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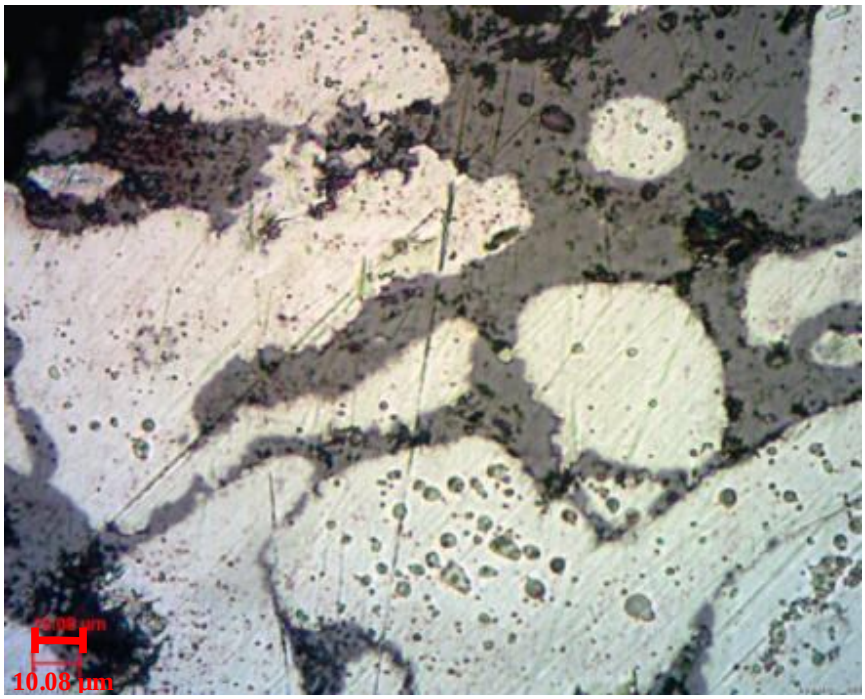
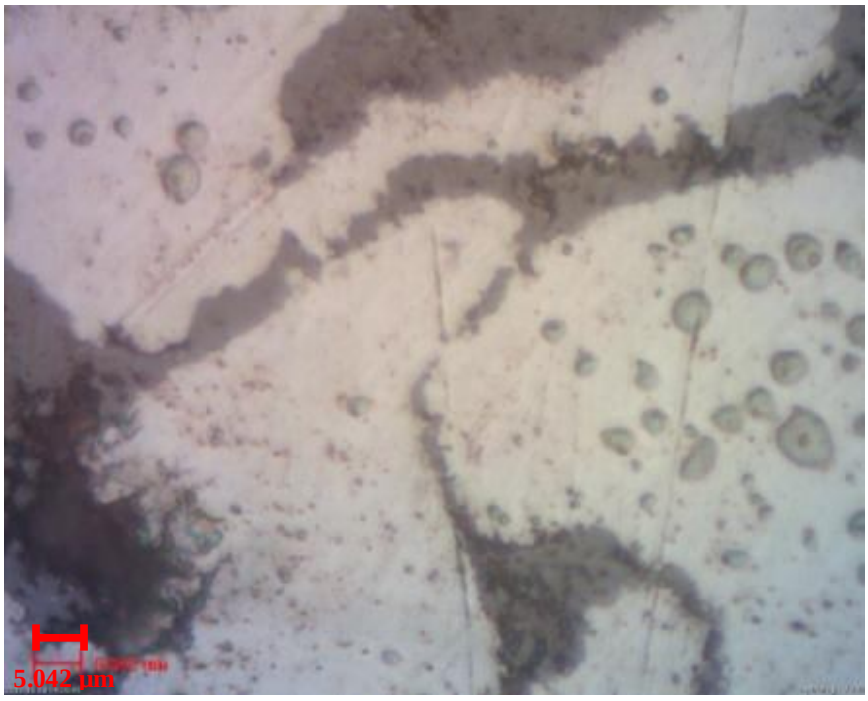
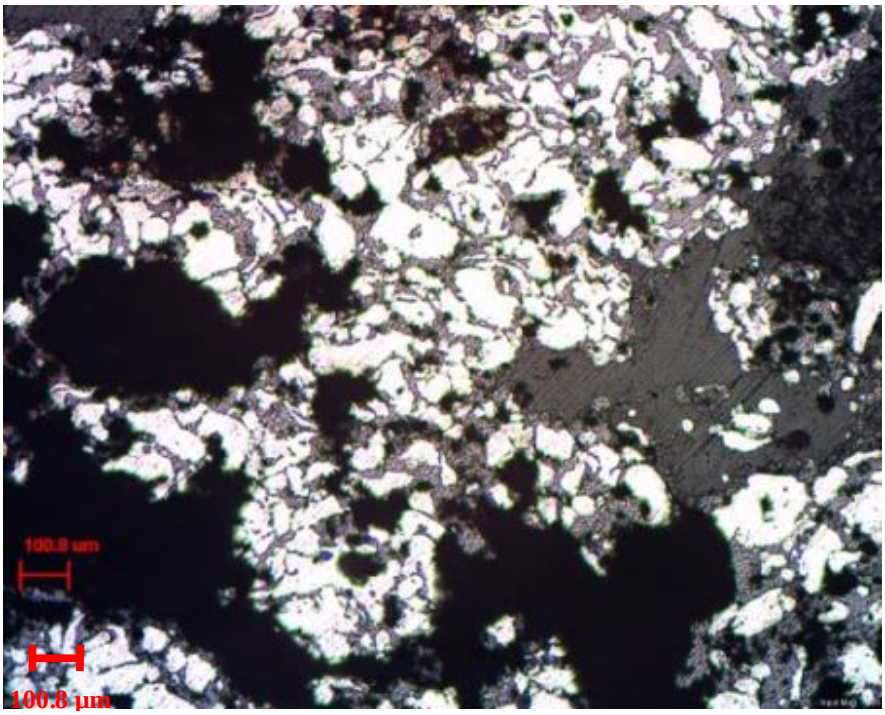


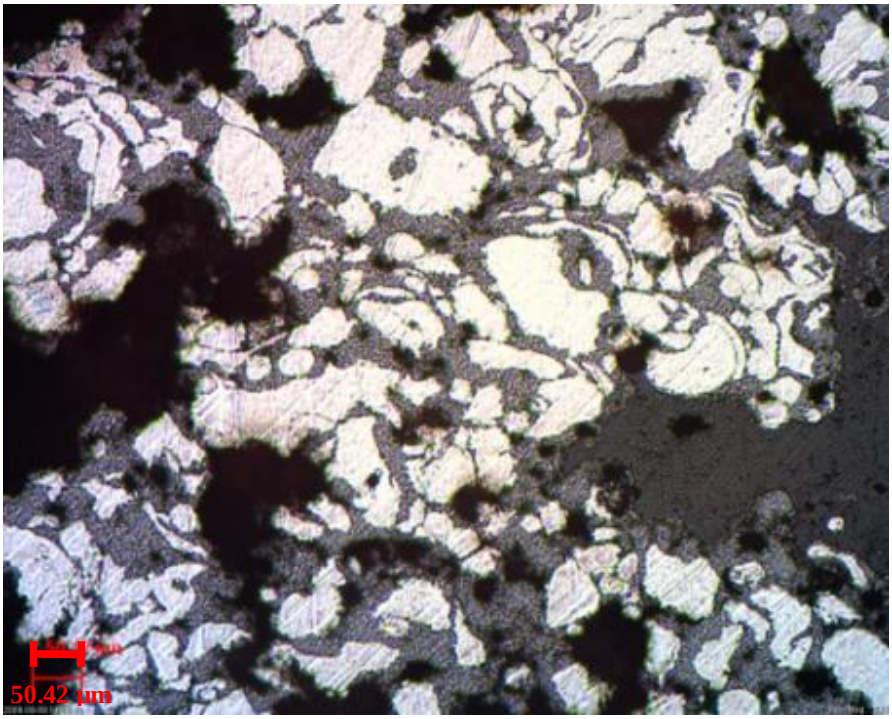
Point 4 at 3600x real magnification



Point 4 at 7200x real magnification



Point 5 at 360x real magnification



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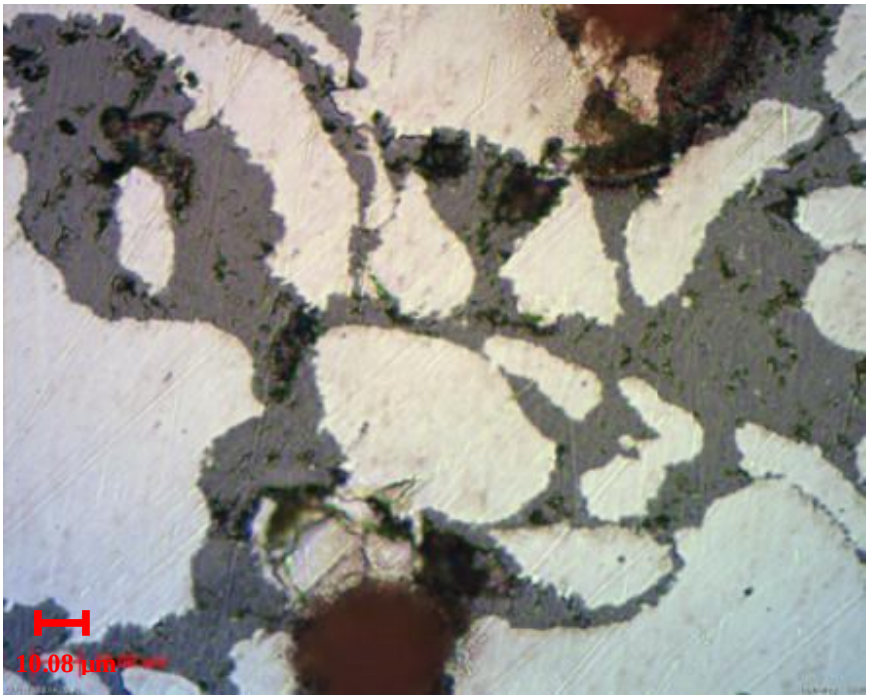

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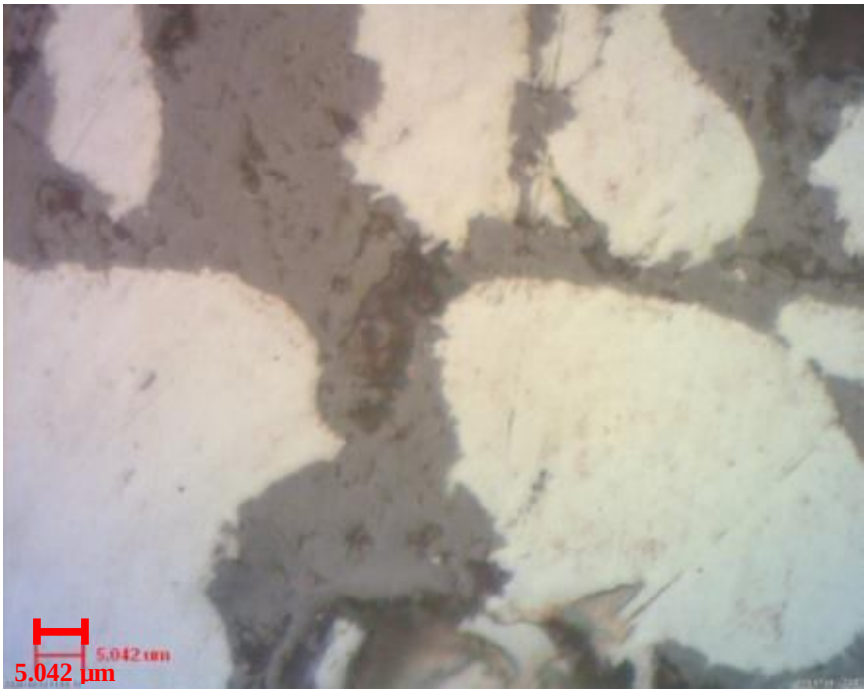
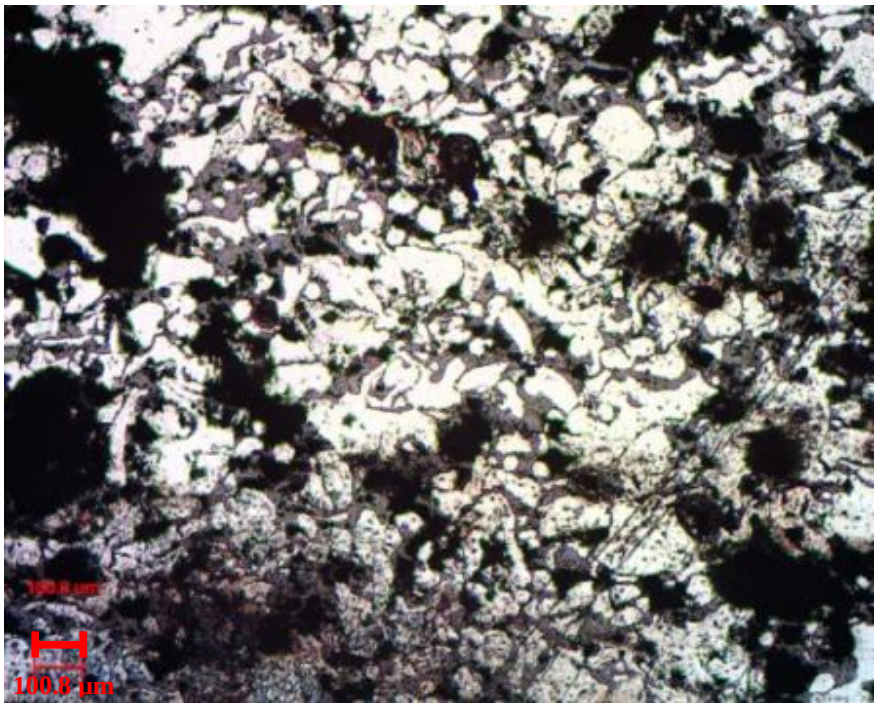
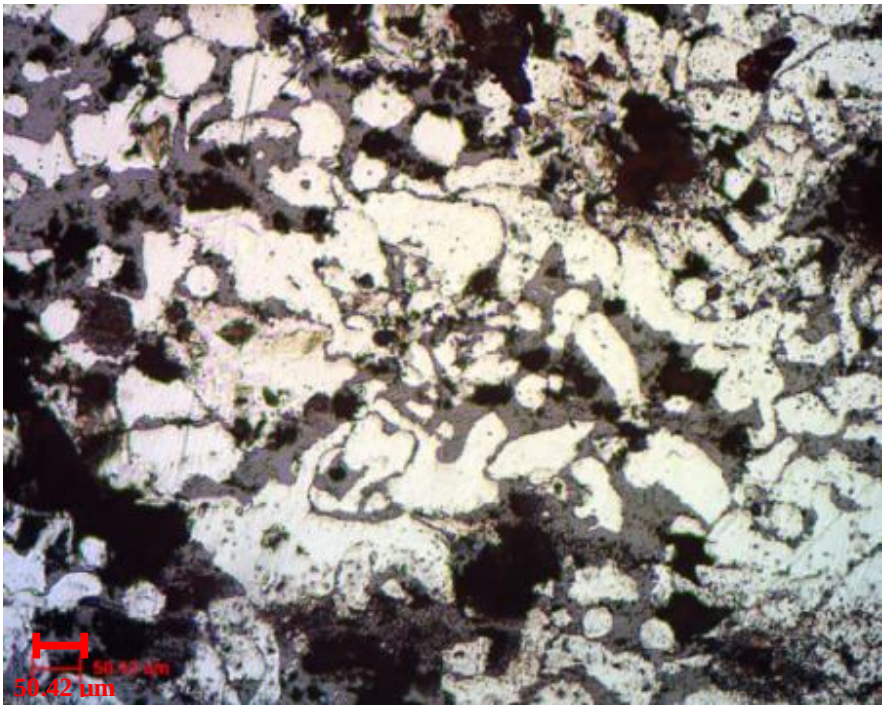


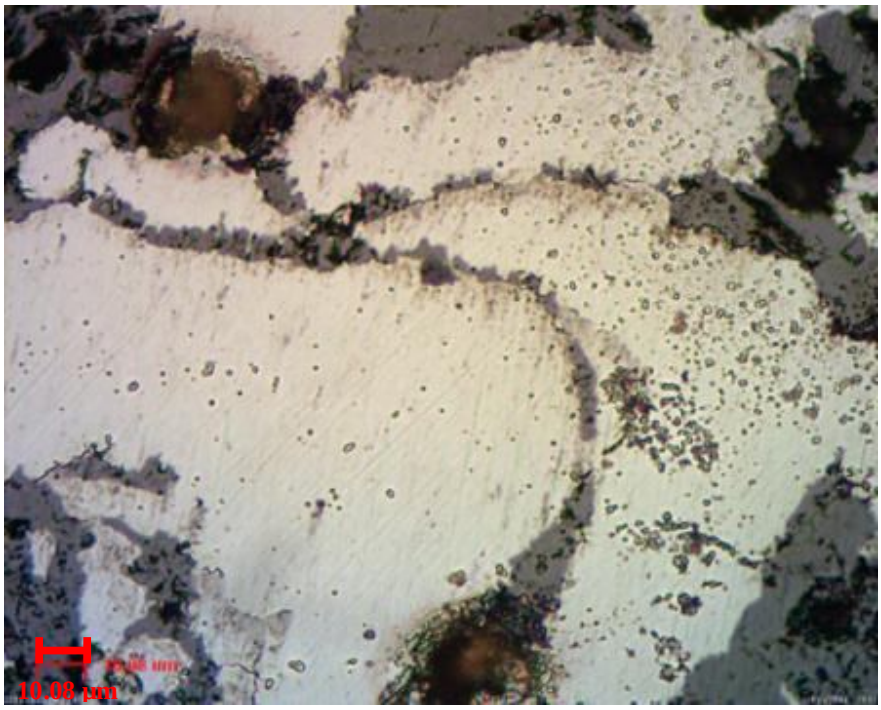
Point 5 at 7200x real magnification



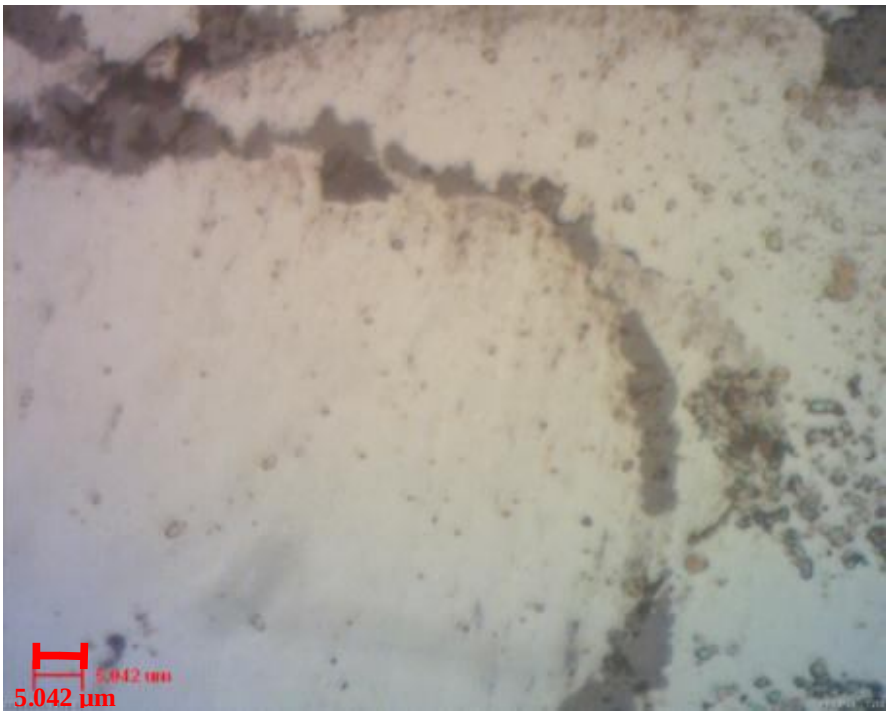
Point 6 at 360x real magnification



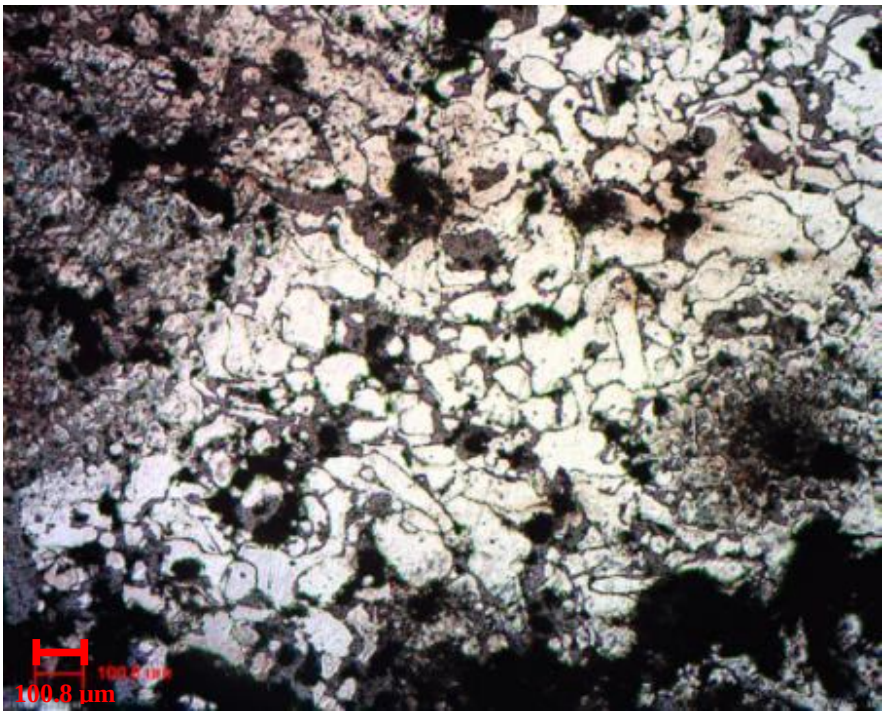
Point 6 at 720x real magnification



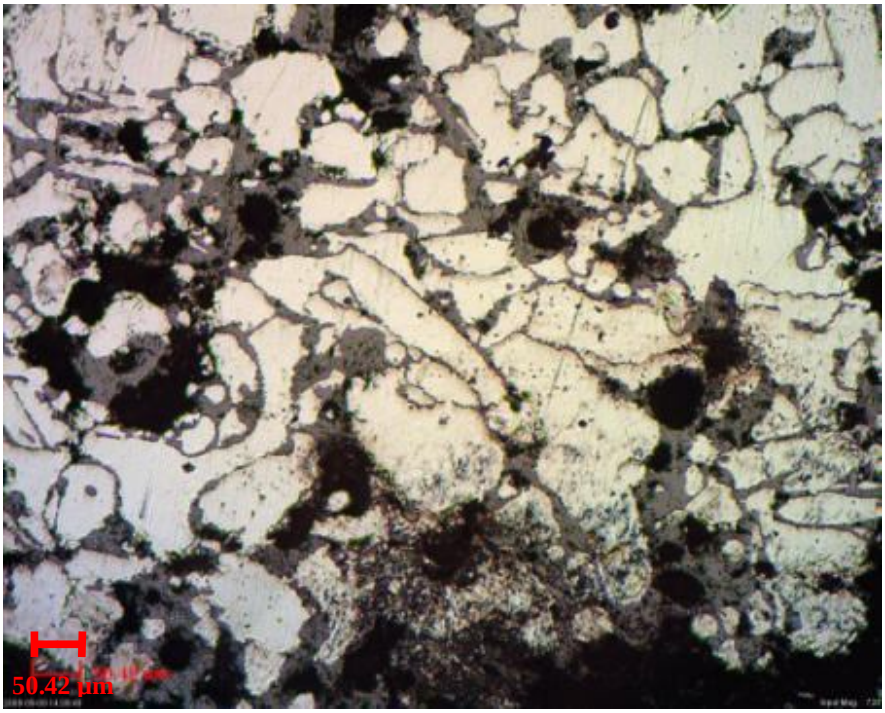
Point 6 at 3600x real magnification



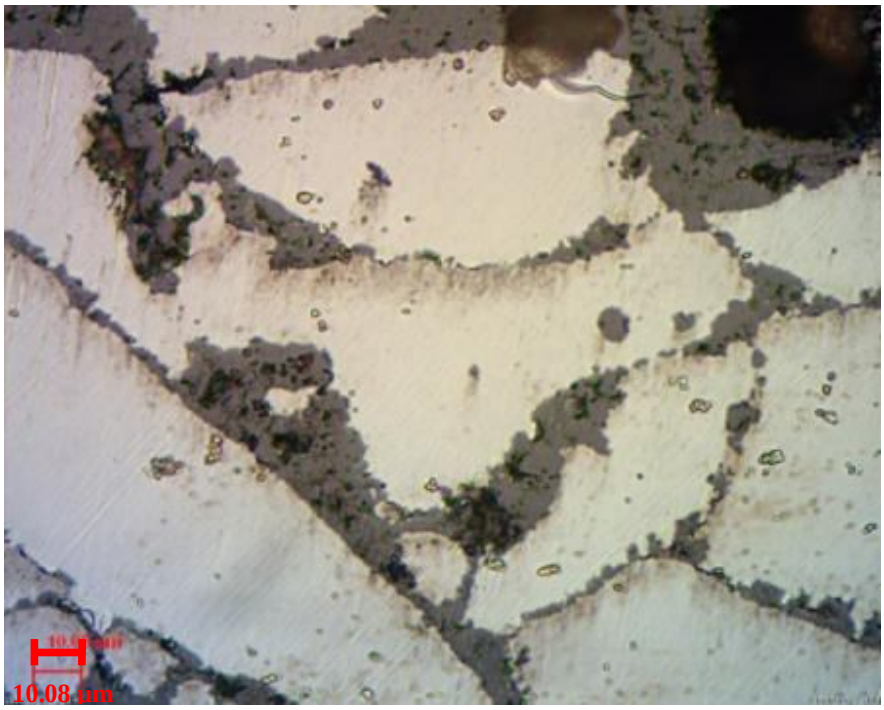
Point 6 at 7200x real magnification



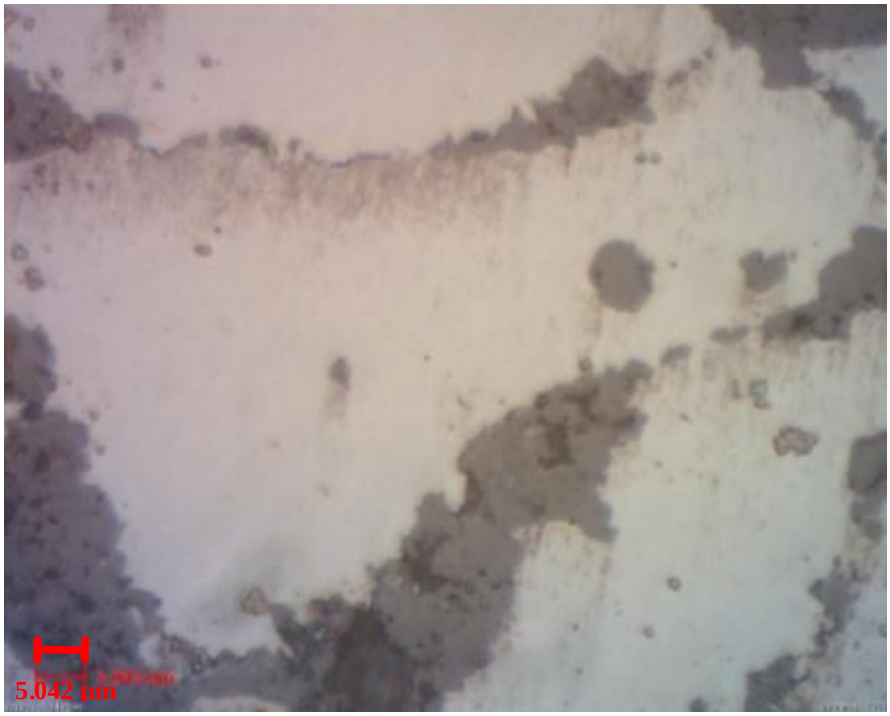
Point 7 at 360x real magnification



Point 7 at 720x real magnification



Point 7 at 3600x real magnification



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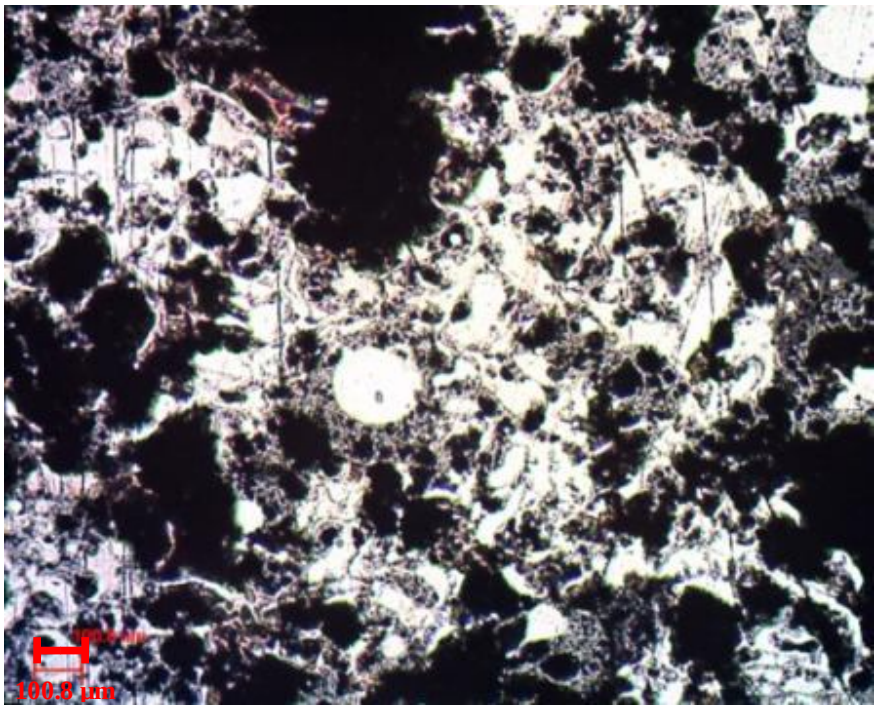
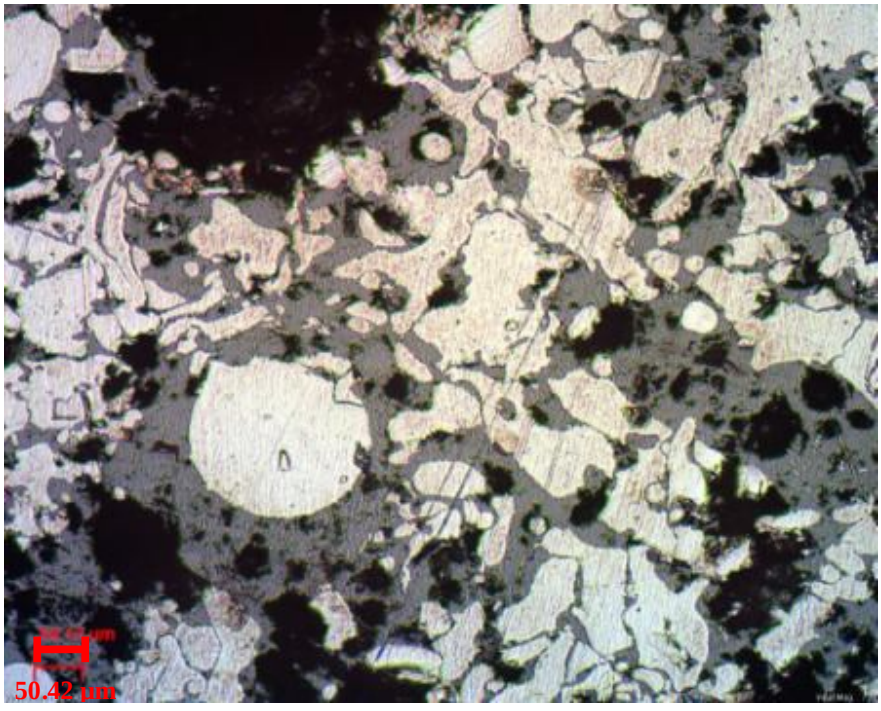
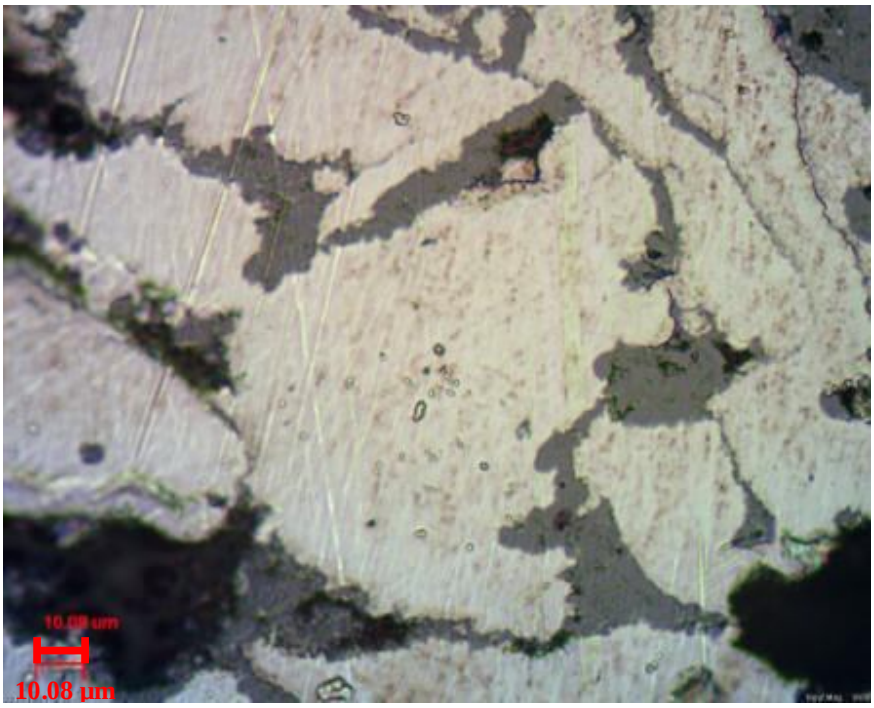


Point 8 at 360x real magnification



Point 8 at 720x real magnification



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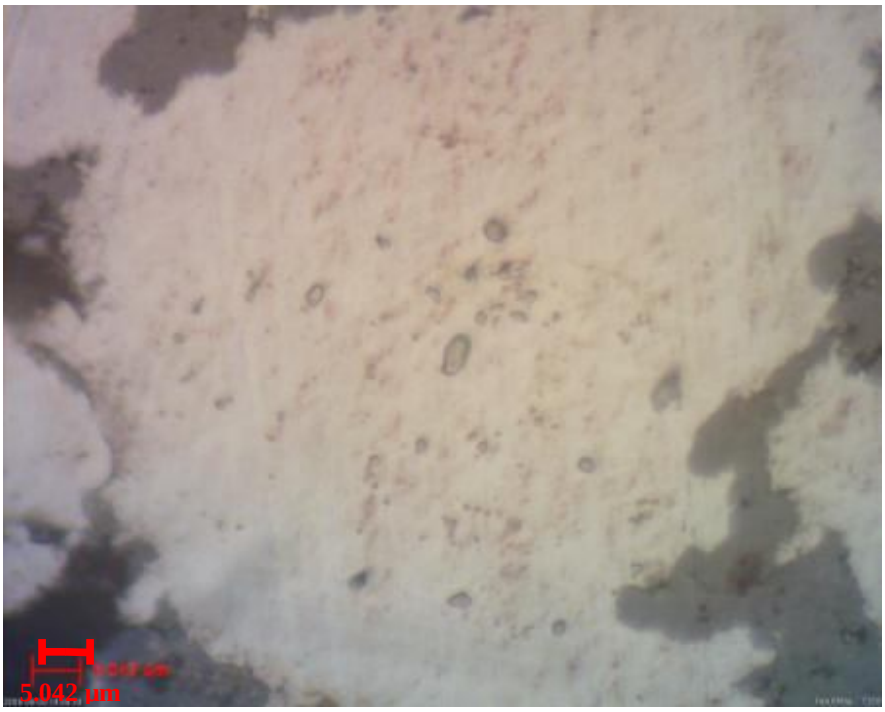

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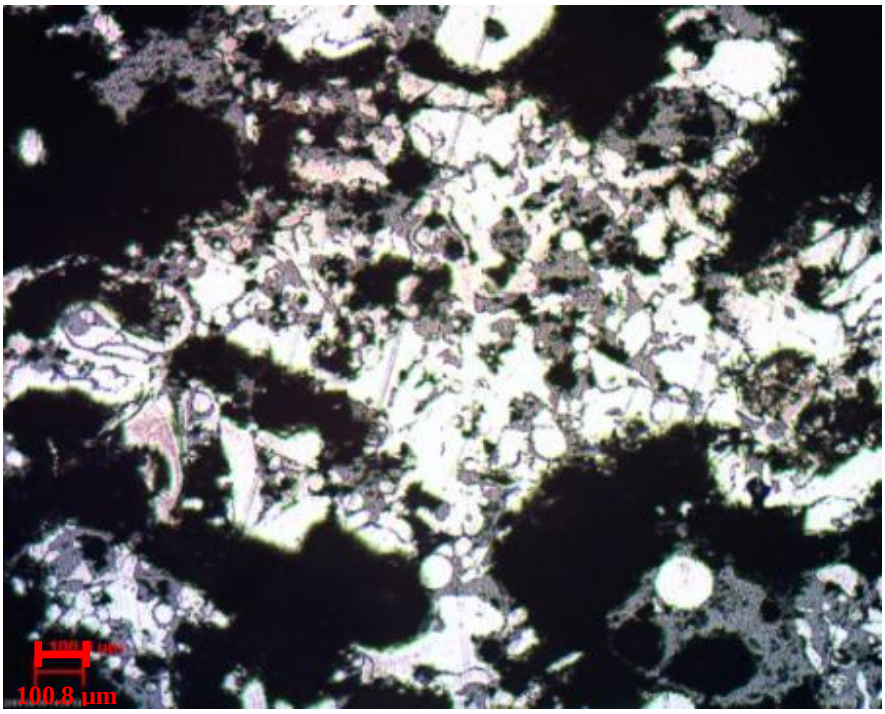
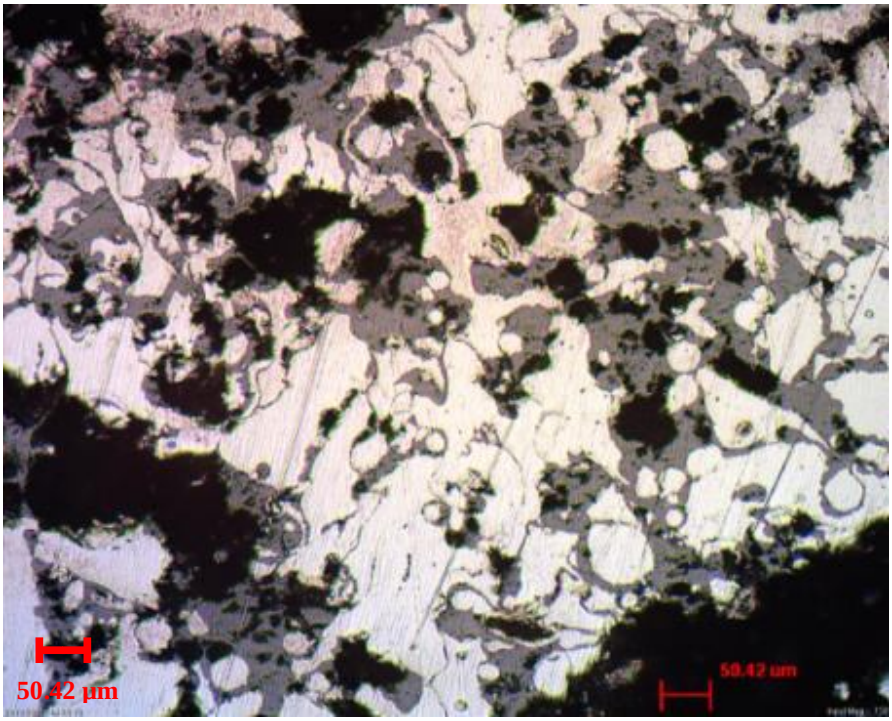


Point 9 at 360x real magnification



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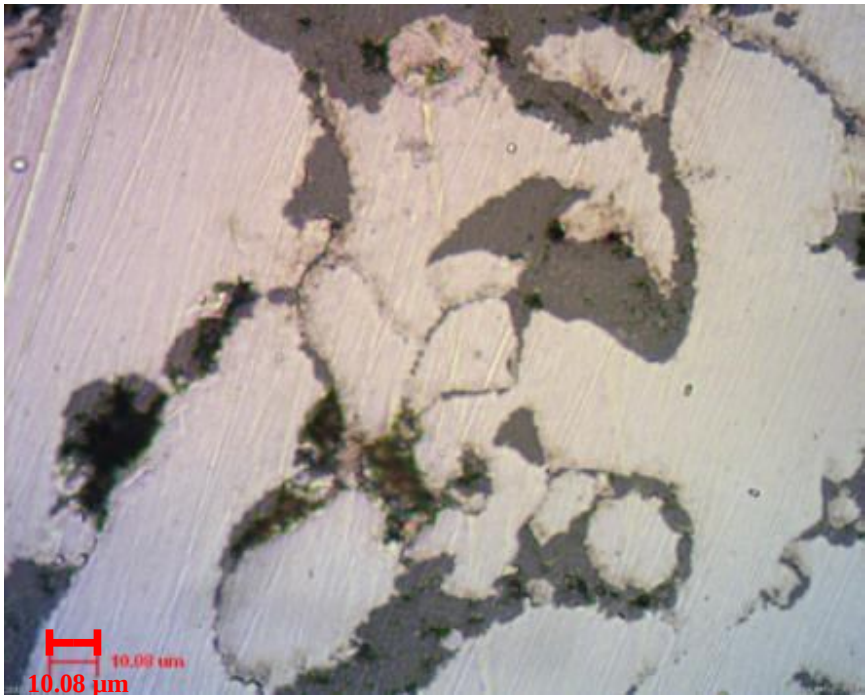
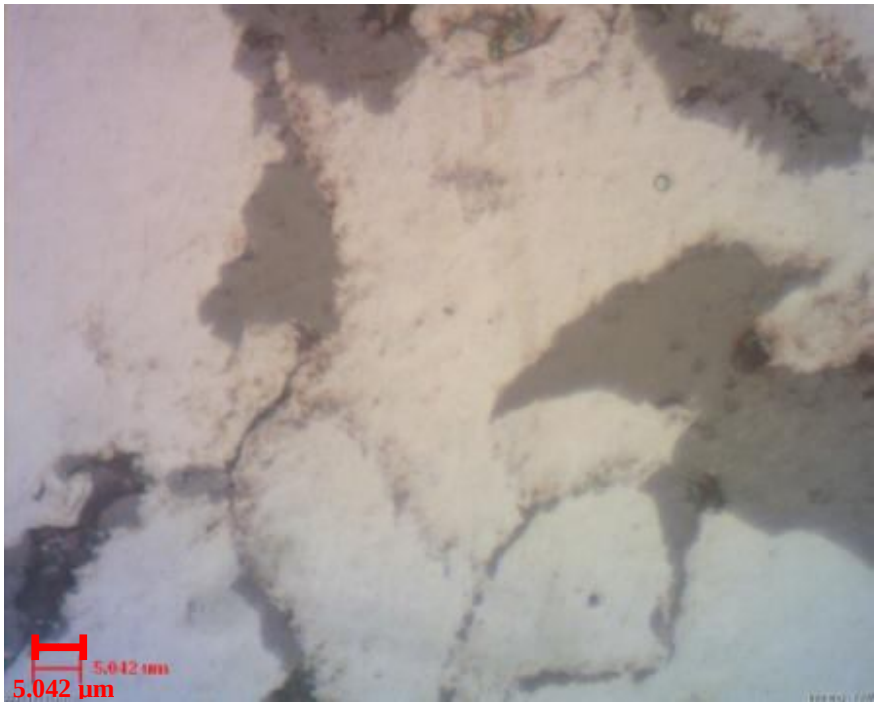
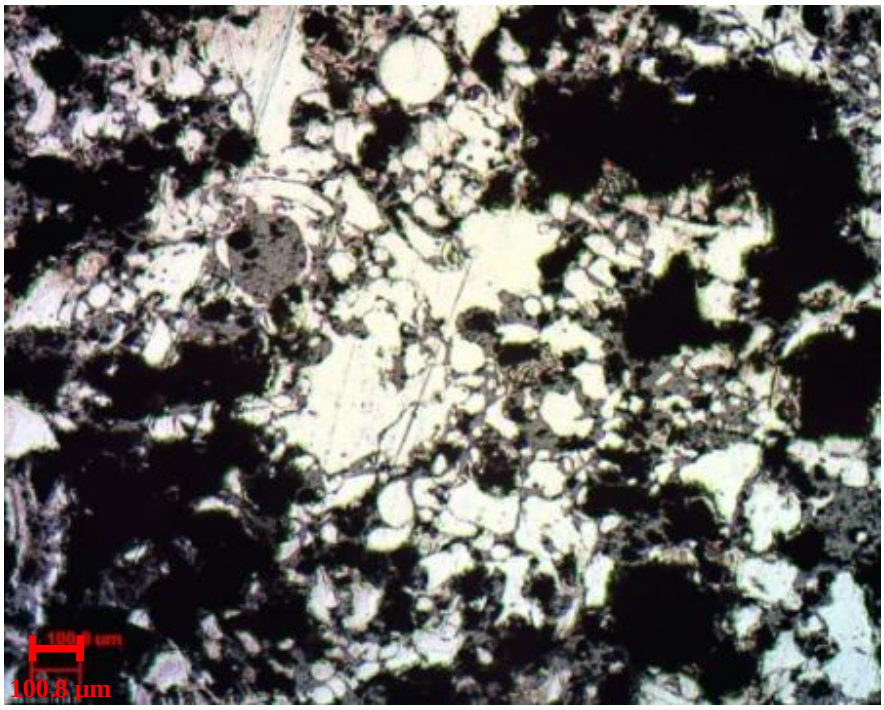


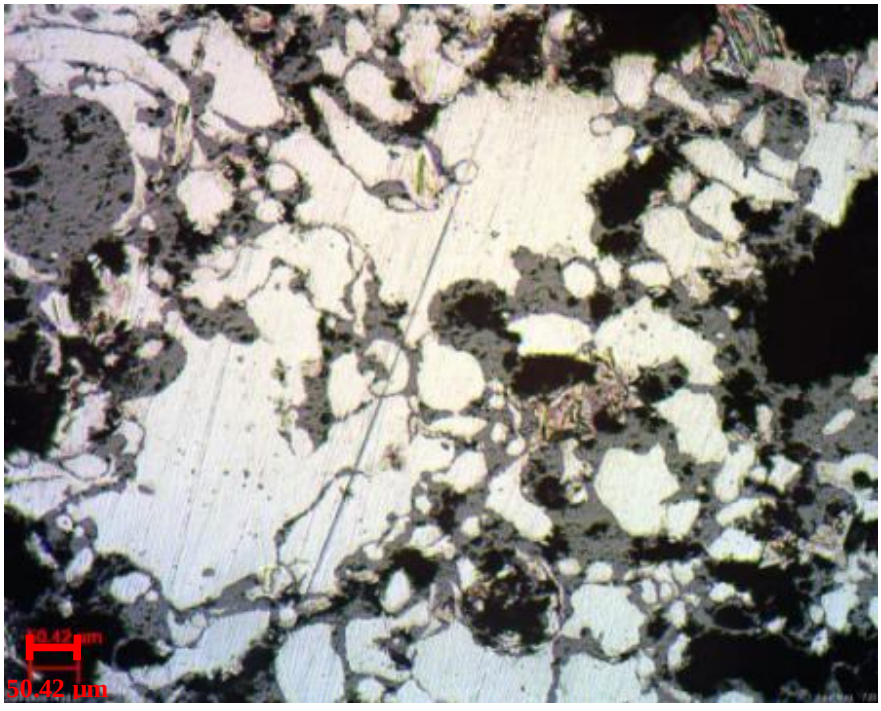
Point 9 at 3600x real magnification



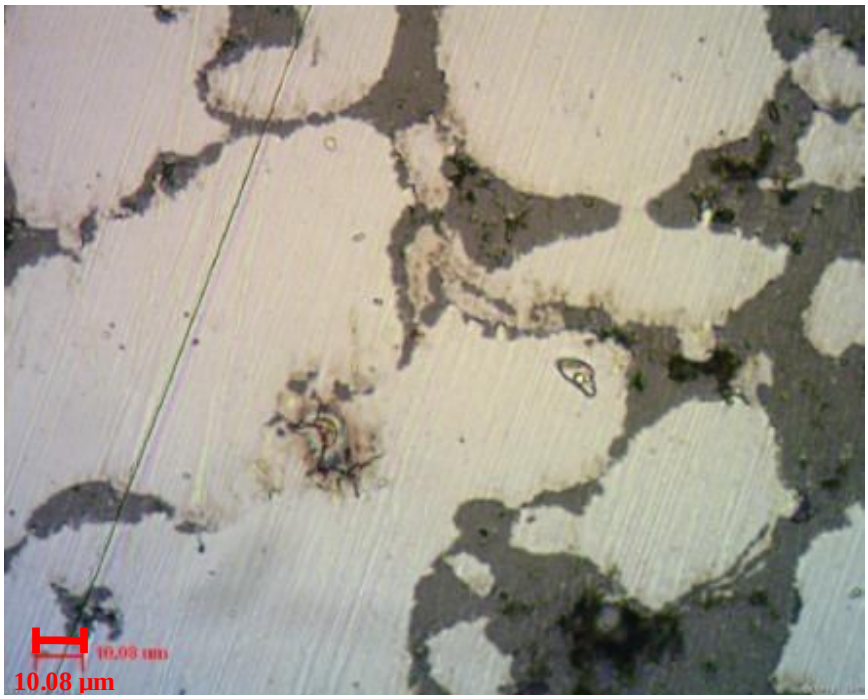
Point 9 at 7200x real magnification



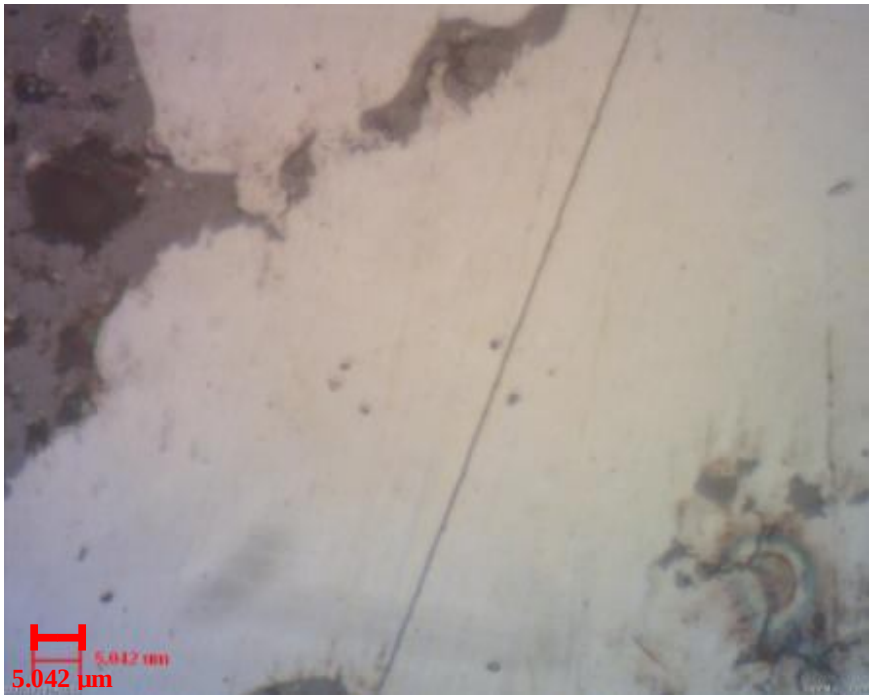
Point 10 at 360x real magnification



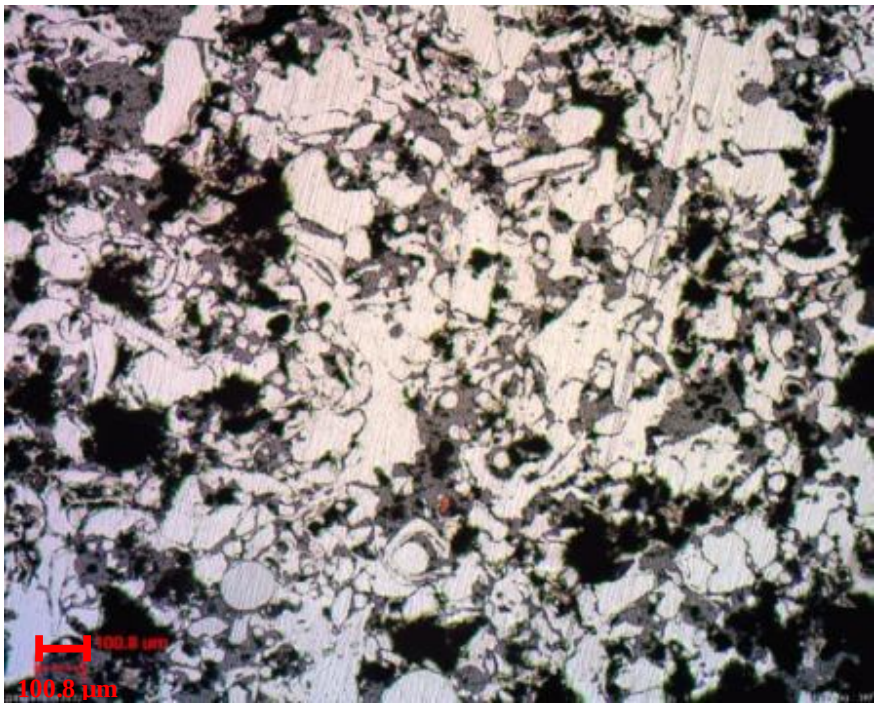
Point 10 at 720x real magnification



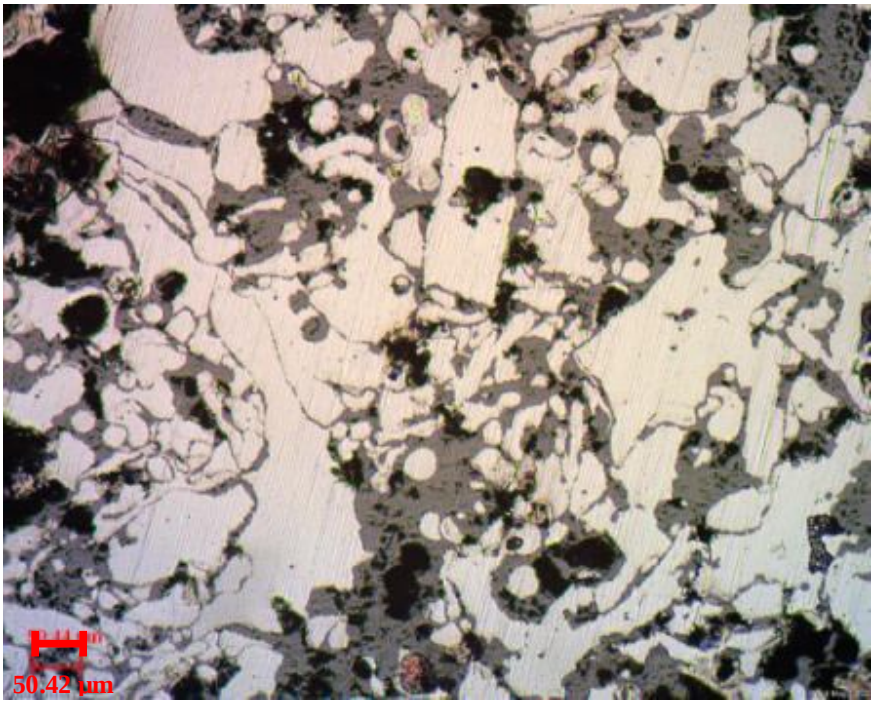
Point 10 at 3600x real magnification



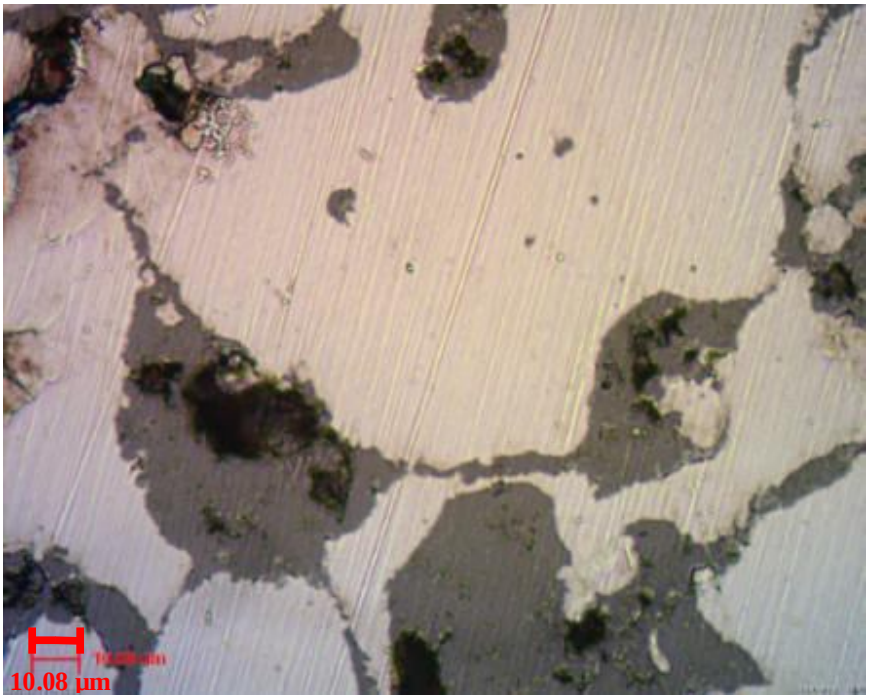
Point 10 at 7200x real magnification



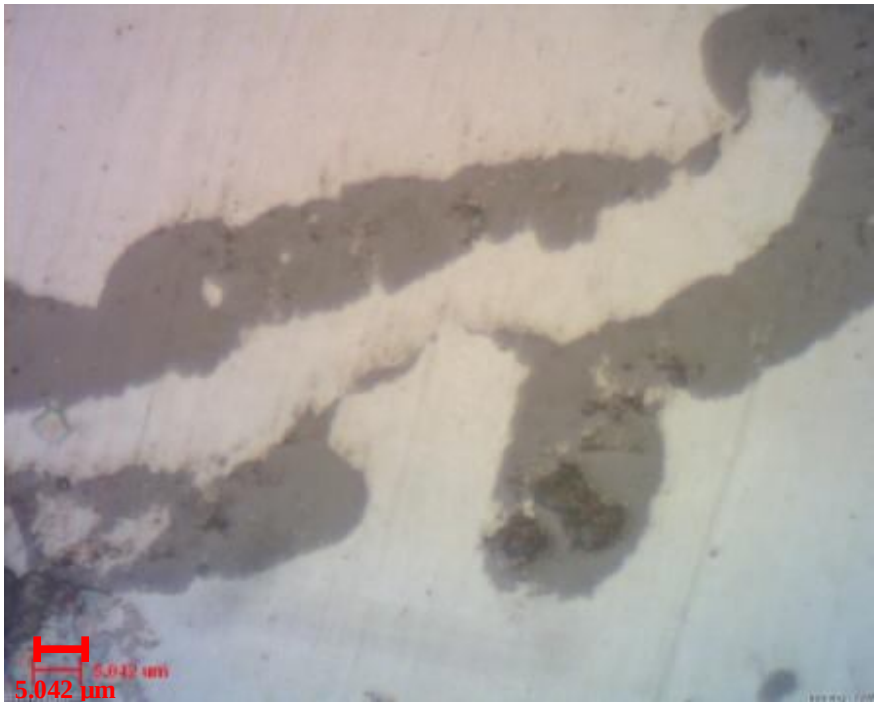
Point 11 at 360x real magnification



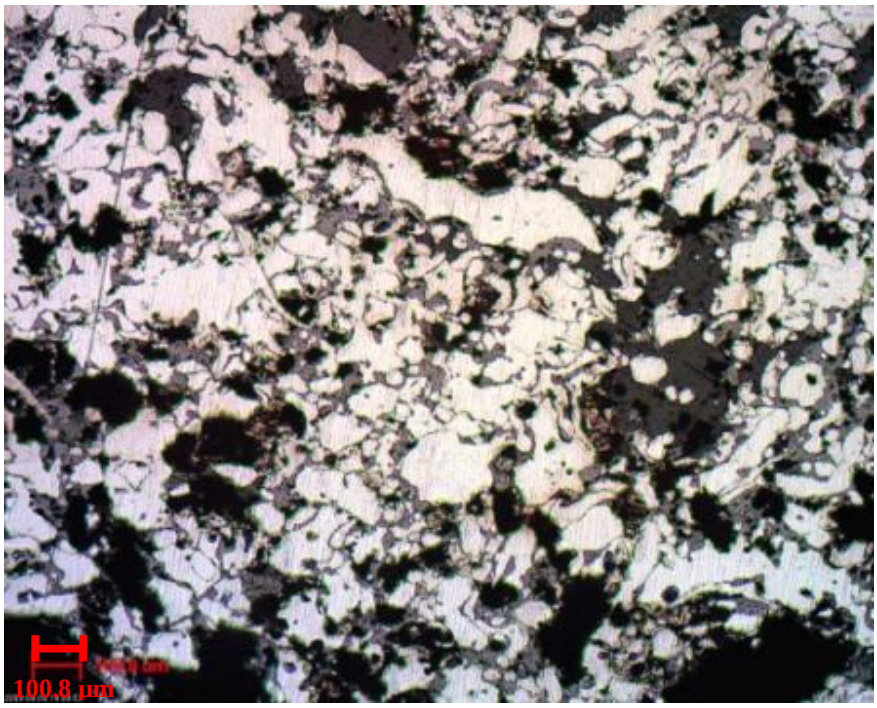
Point 11 at 720x real magnification



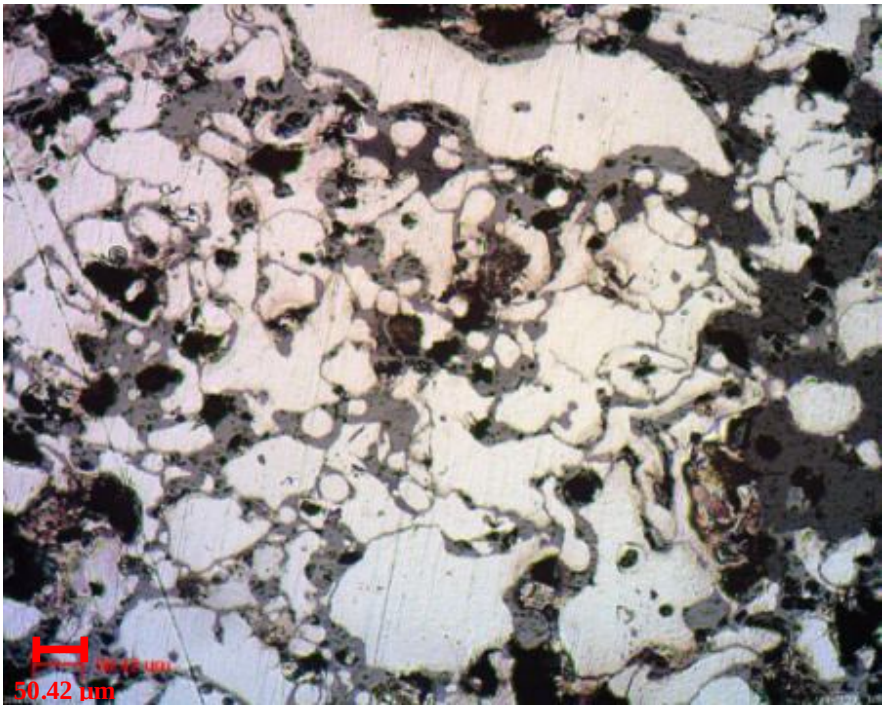
Point 11 at 3600x real magnification



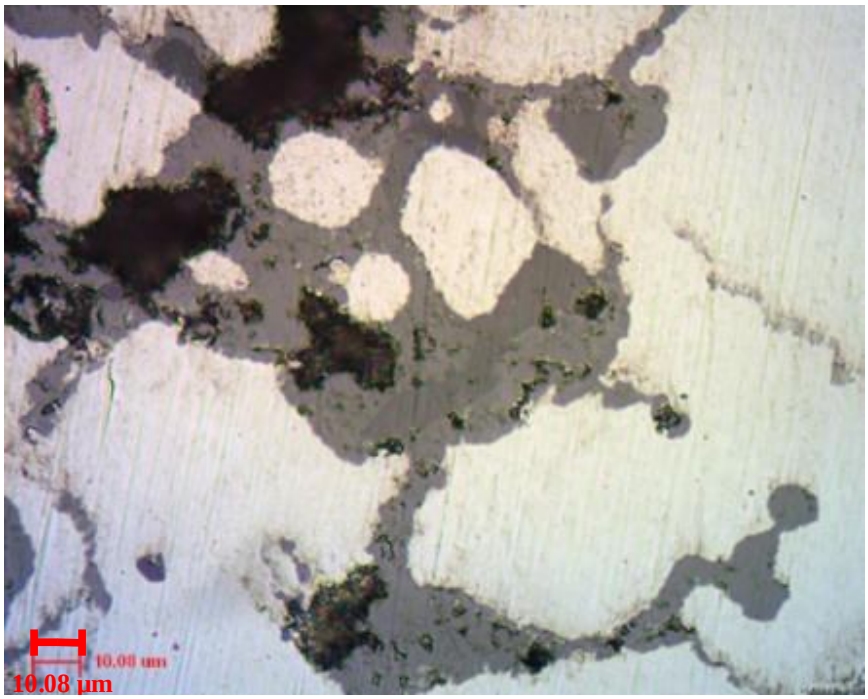
Point 11 at 7200x real magnification



Point 12 at 360x real magnification



Point 12 at 720x real magnification



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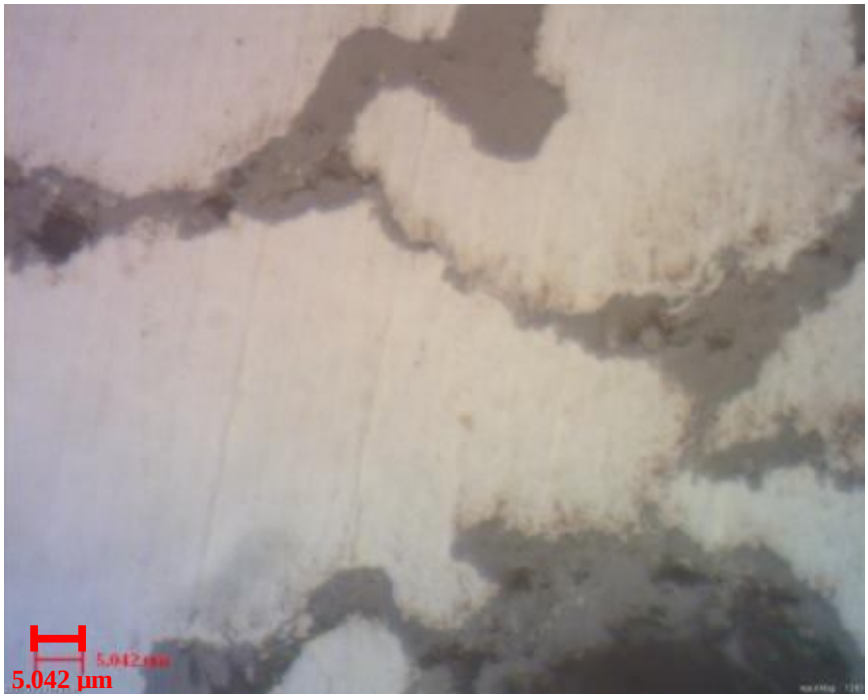
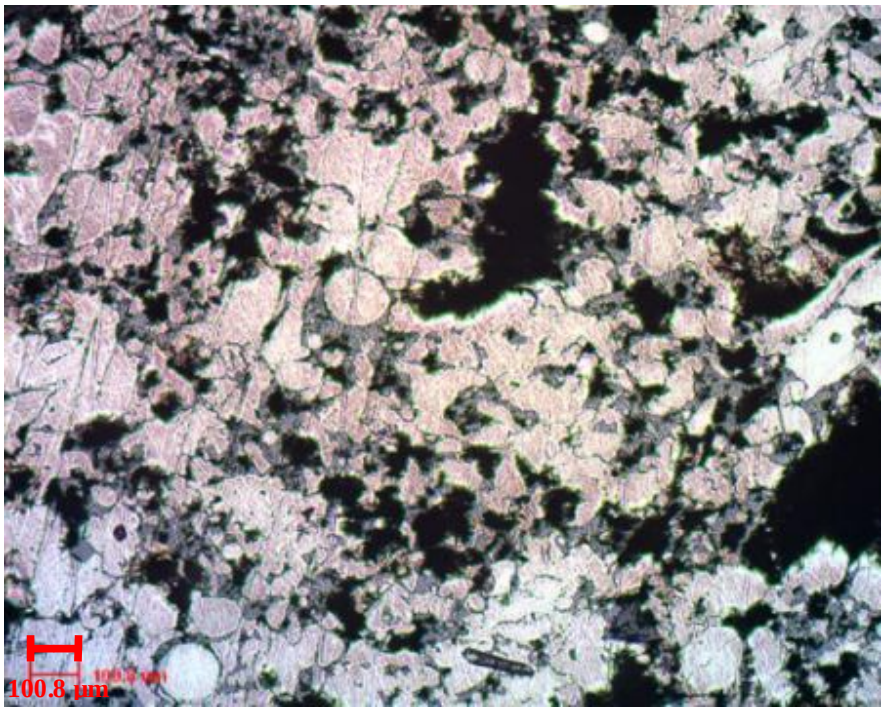
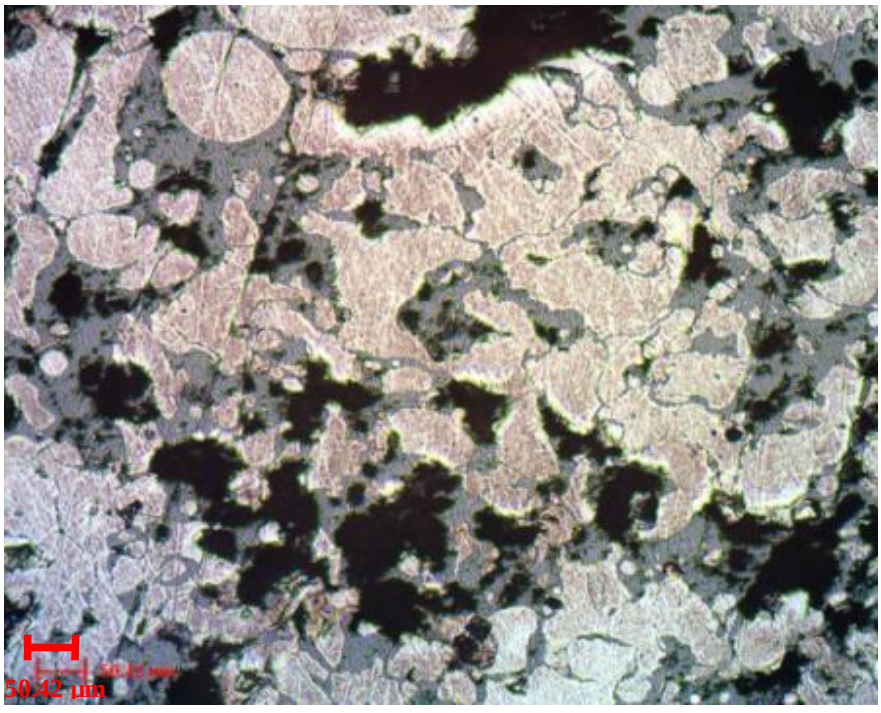


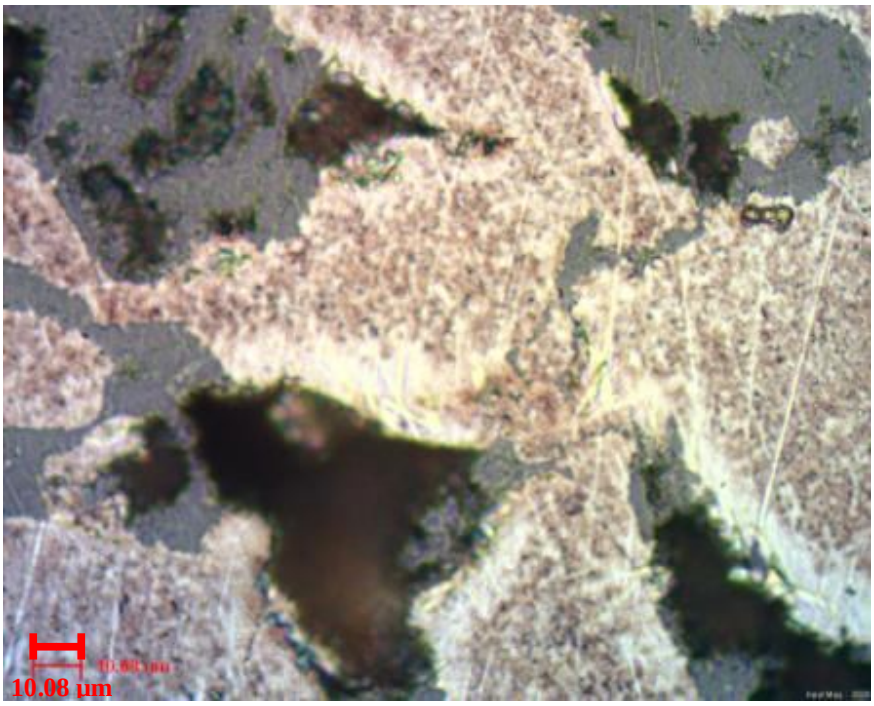
Point 12 at 7200x real magnification



Point 13 at 360x real magnification



Point 13 at 720x real magnification



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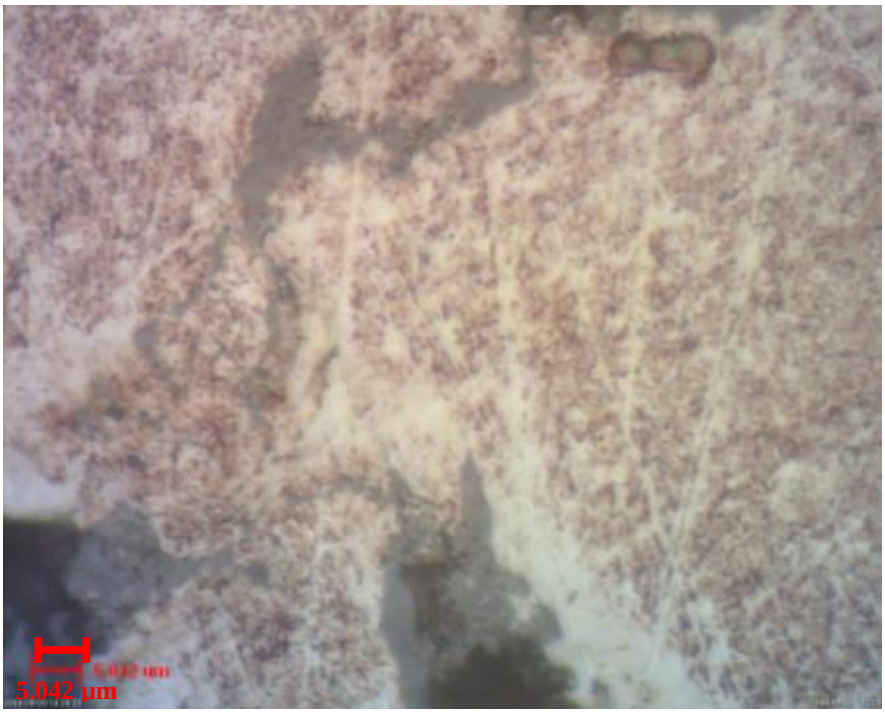
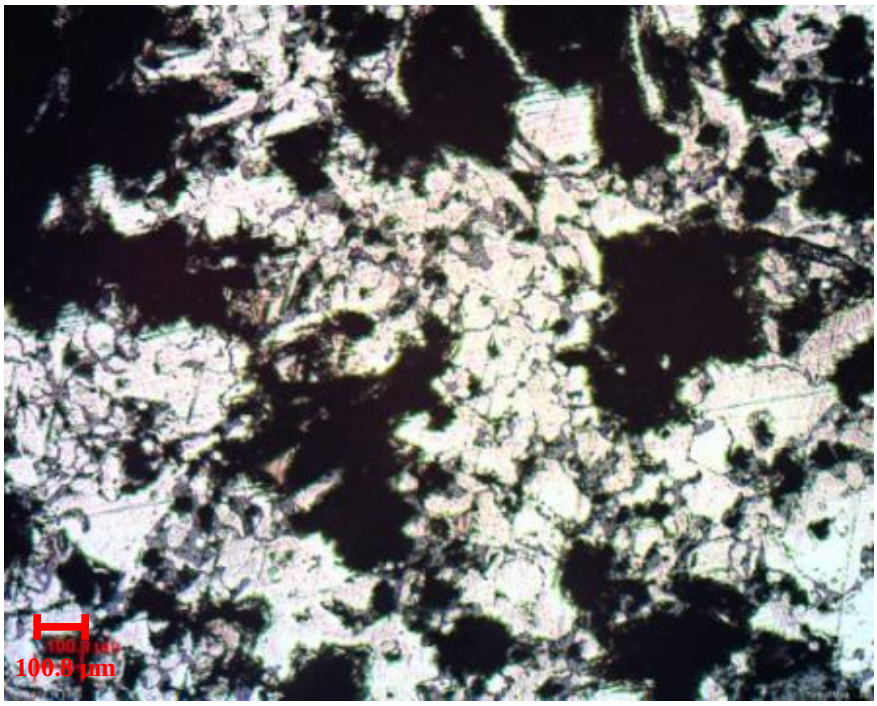
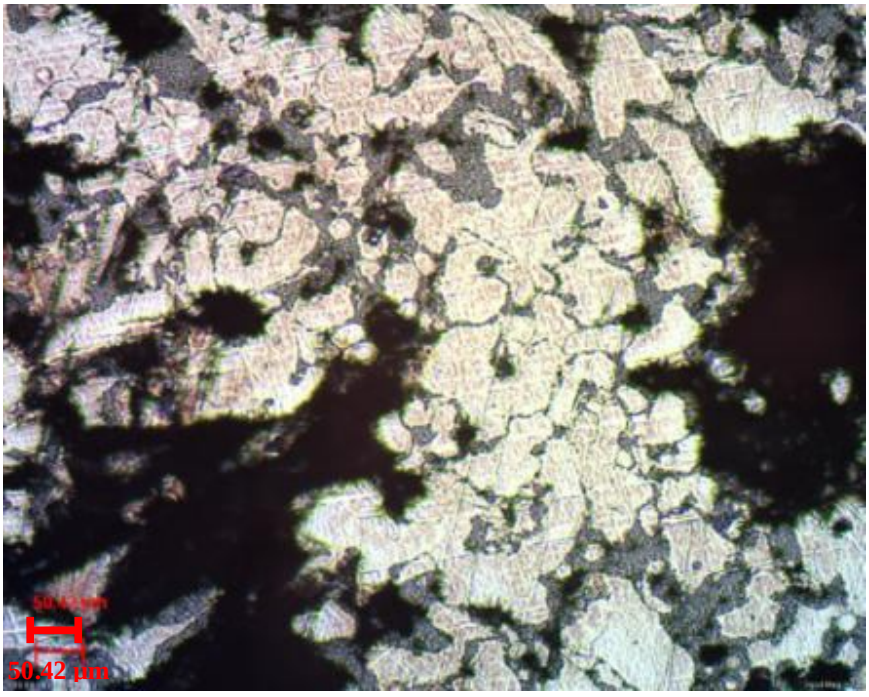


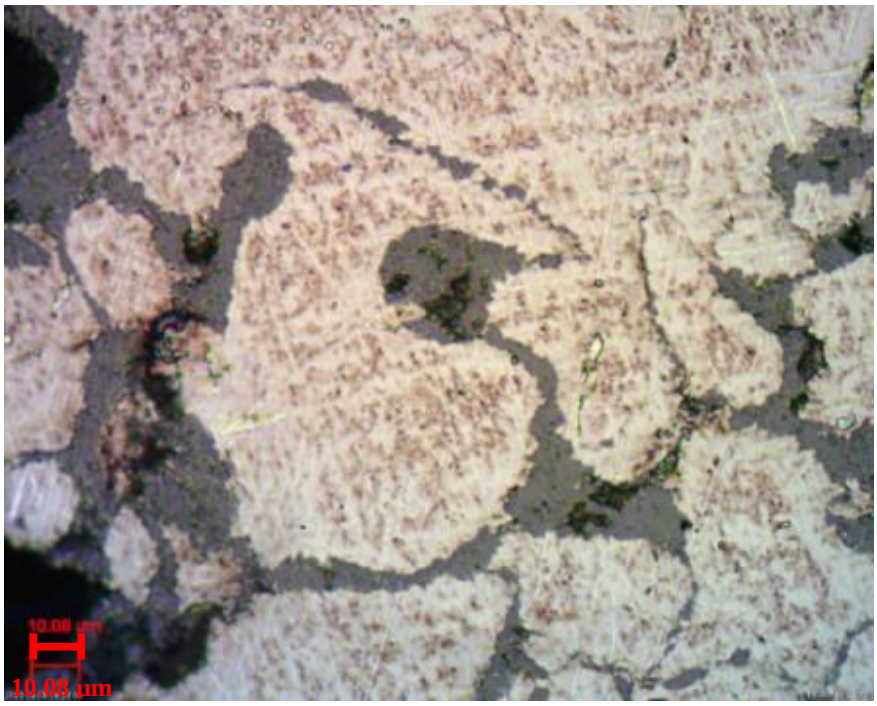
Point 13 at 7200x real magnification



Point 14 at 360x real magnification



Point 14 at 720x real magnification



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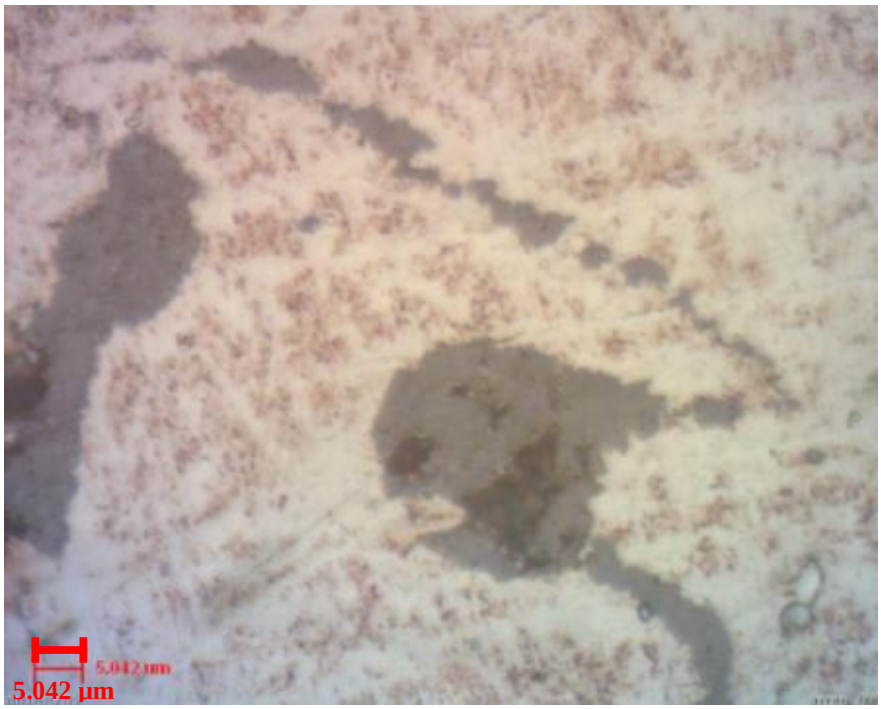
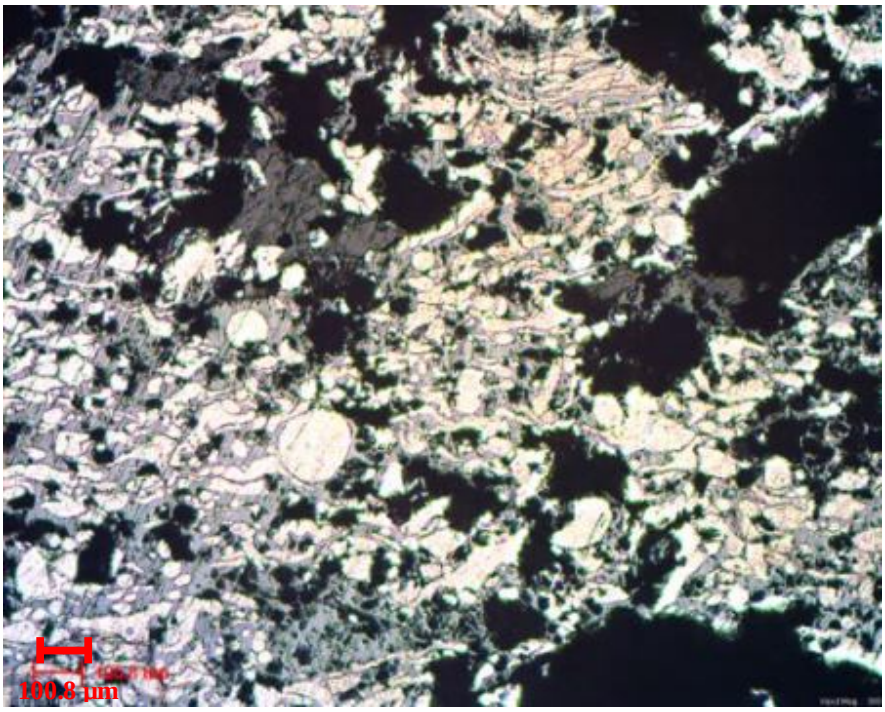
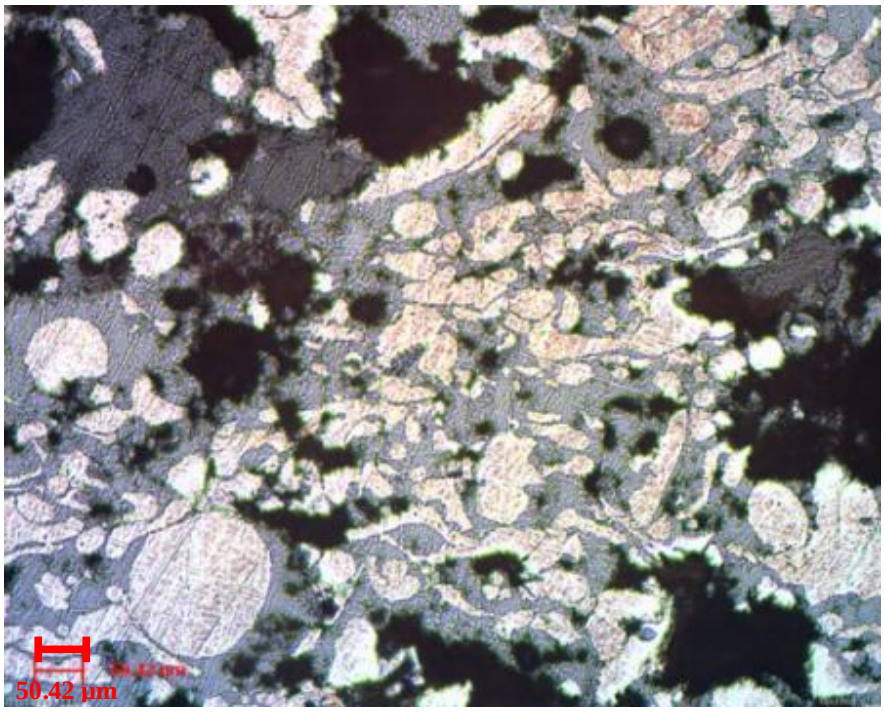


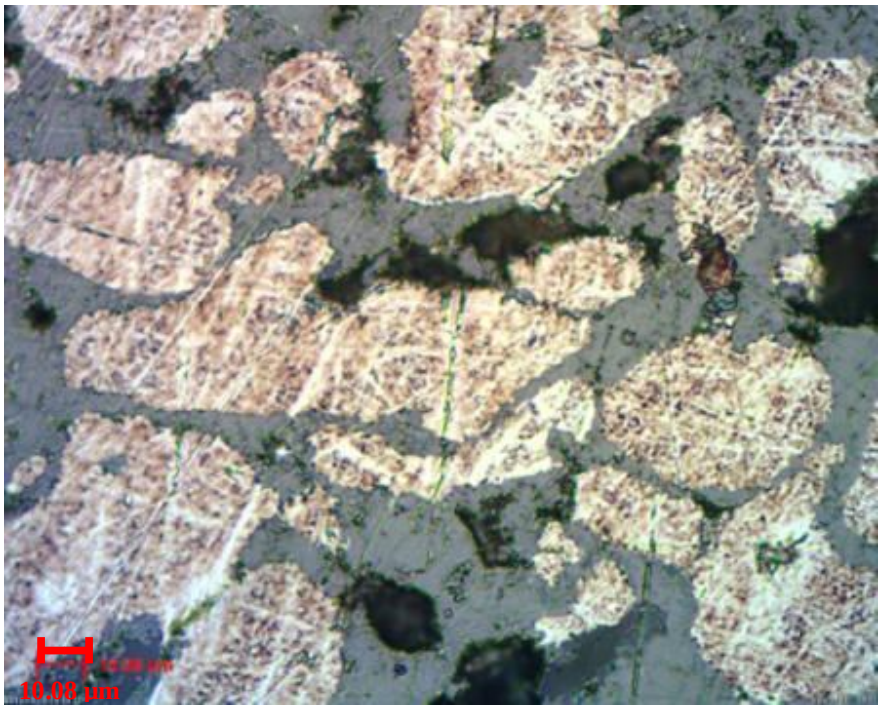
Point 14 at 7200x real magnification



Point 15 at 360x real magnification



Point 15 at 720x real magnification



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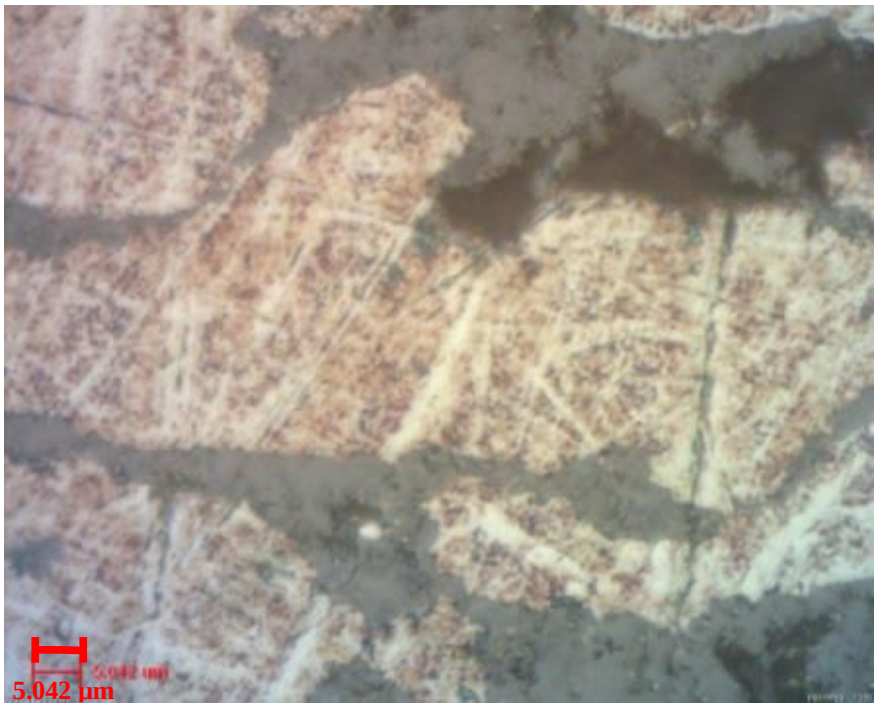
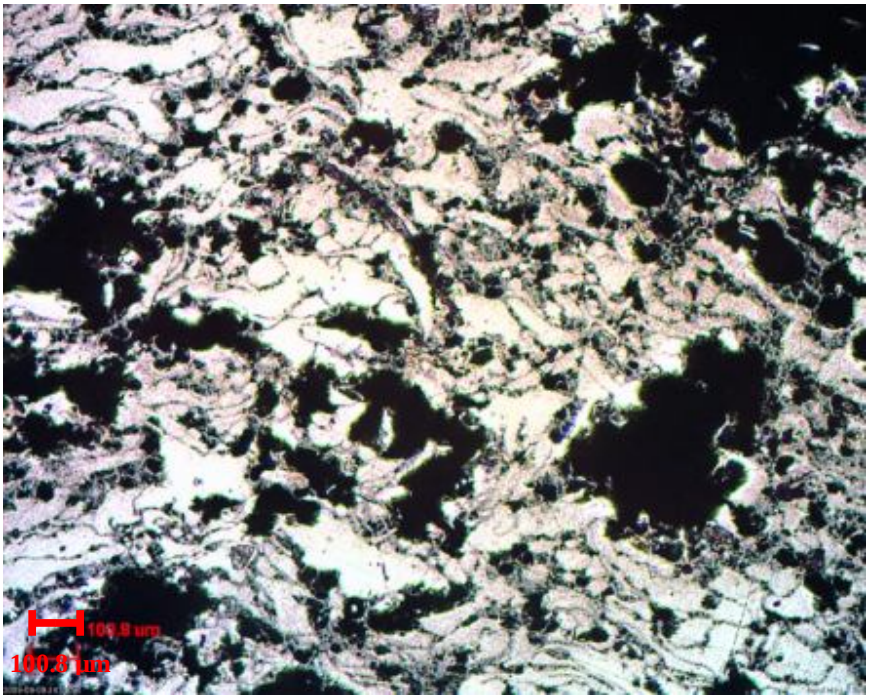
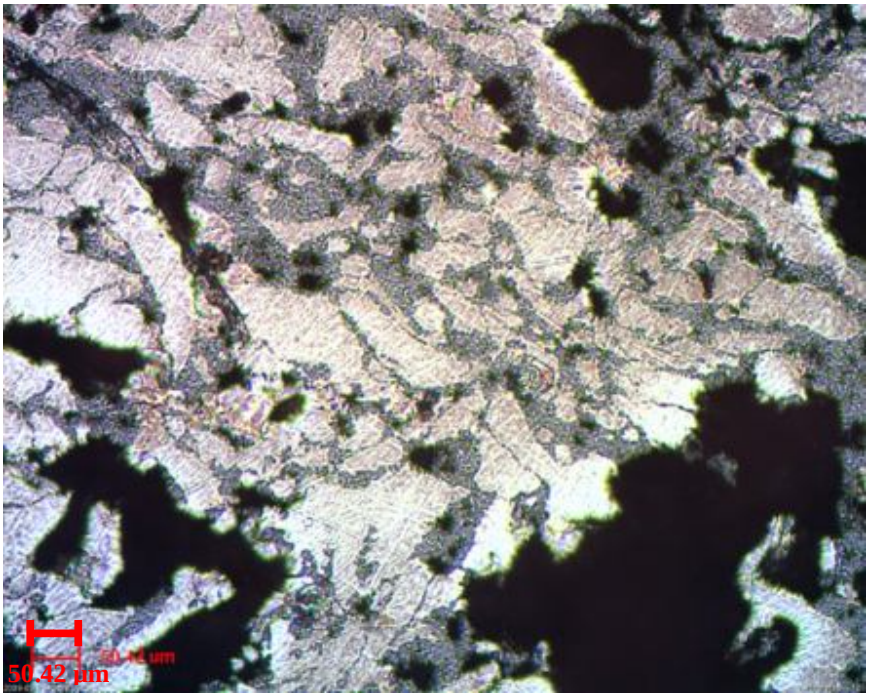


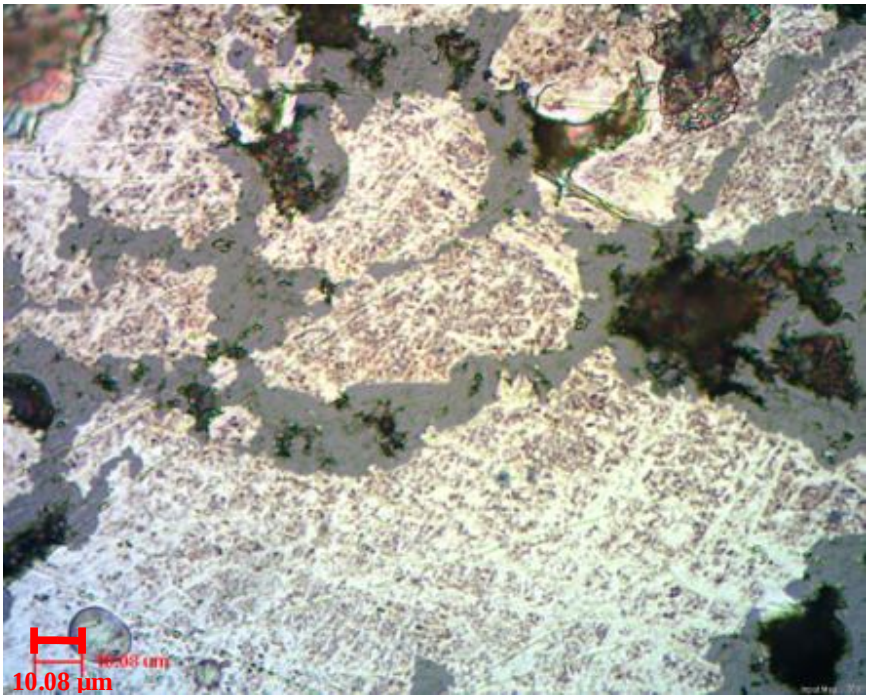
Point 15 at 7200x real magnification



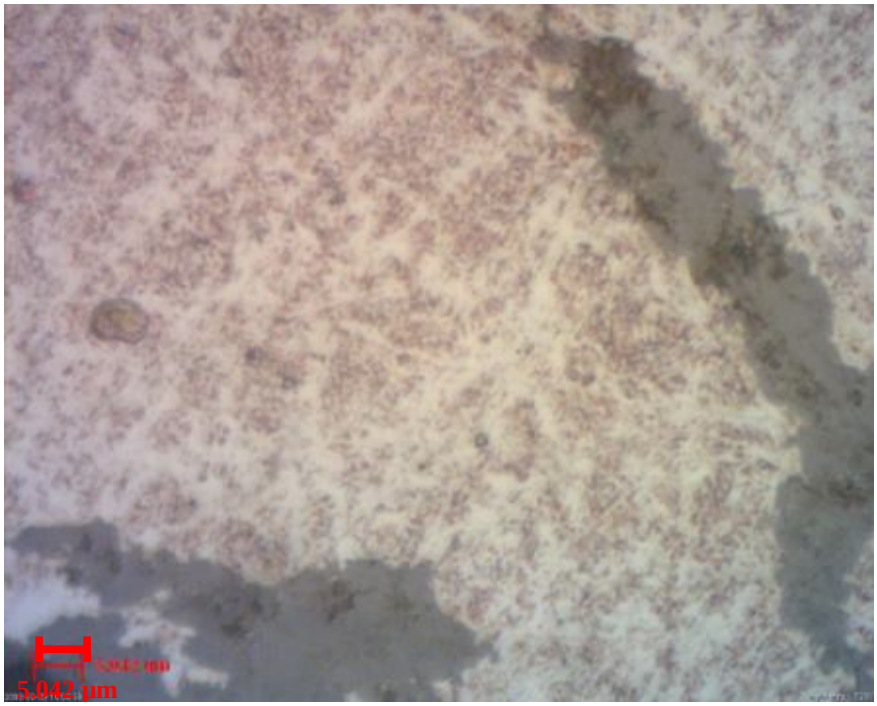
Point 16 at 360x real magnification



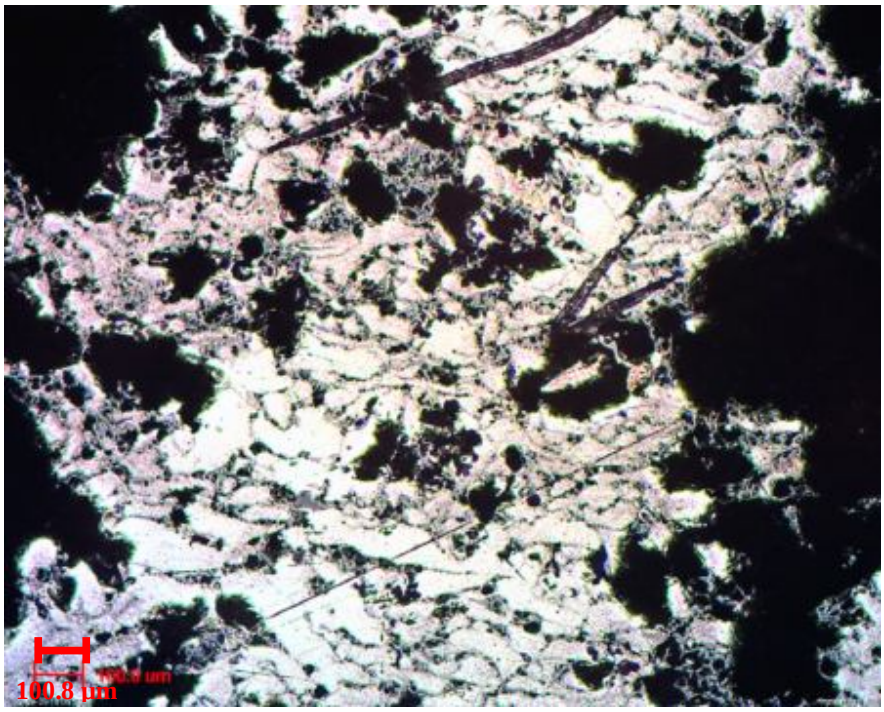
Point 16 at 720x real magnification



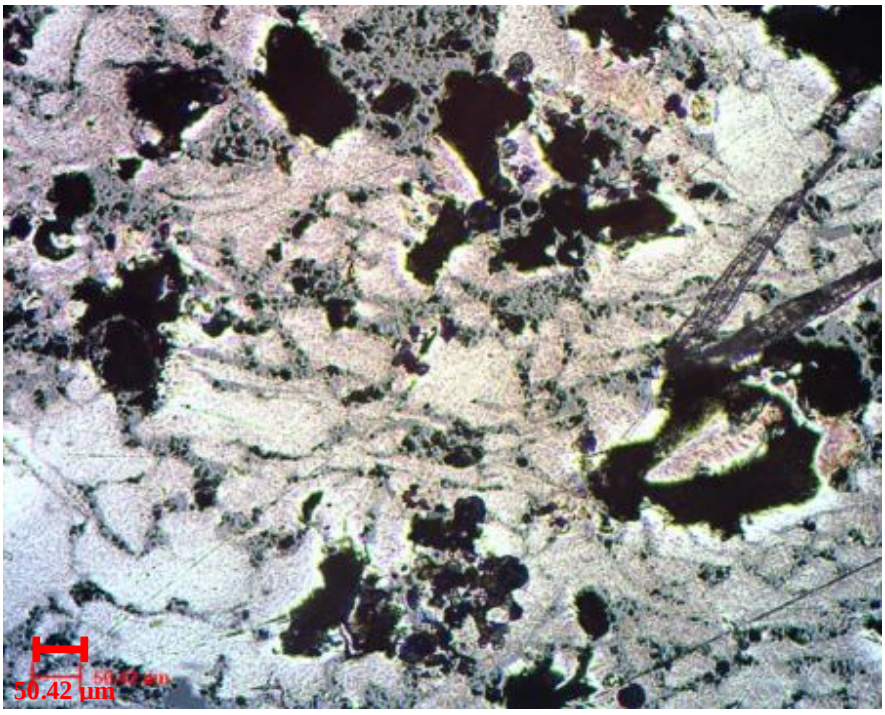
Point 16 at 3600x real magnification



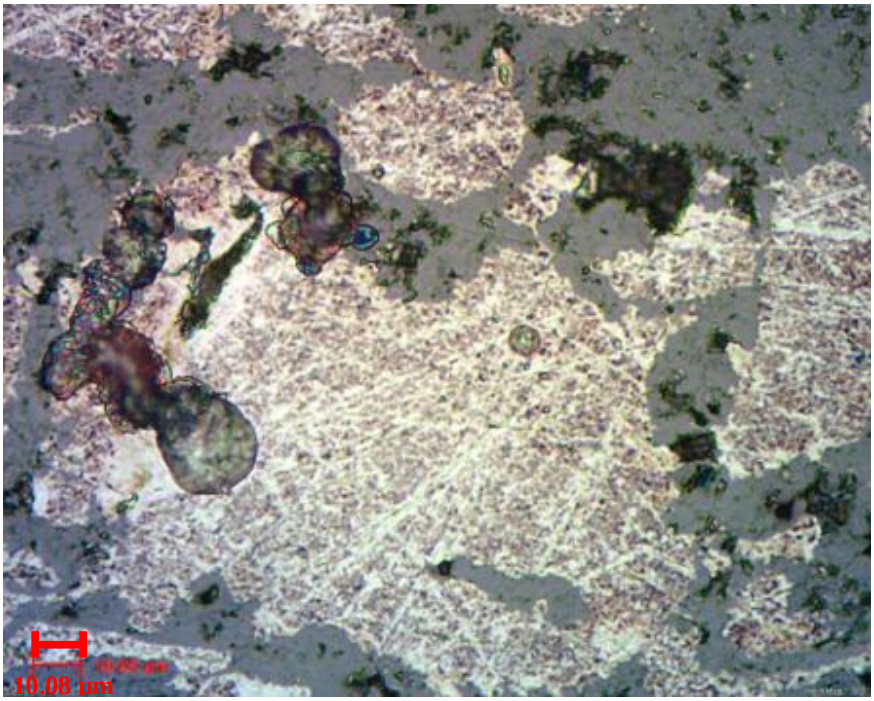
Point 16 at 7200x real magnification



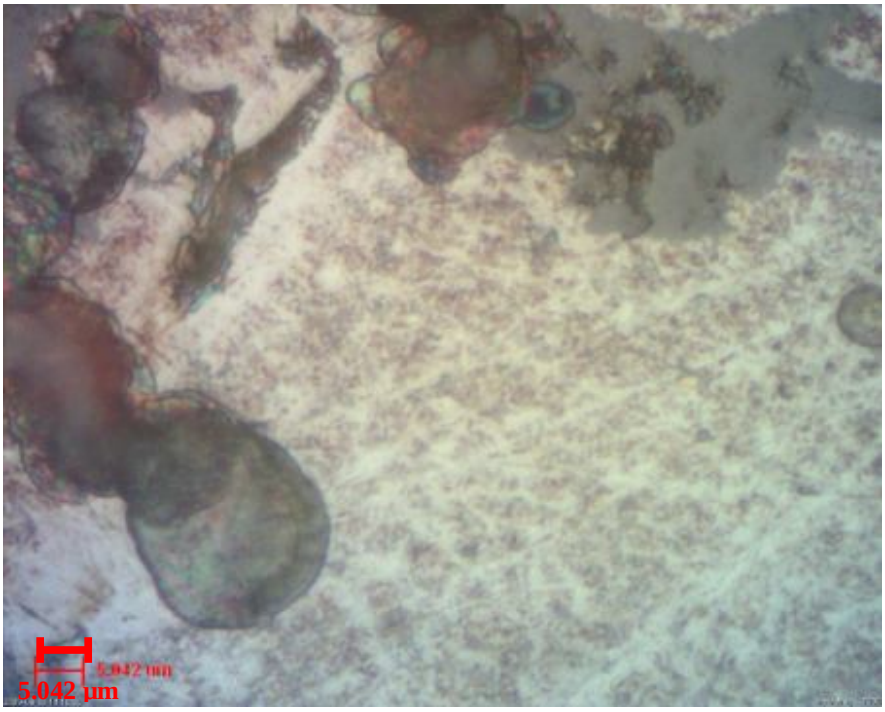
Point 17 at 360x real magnification



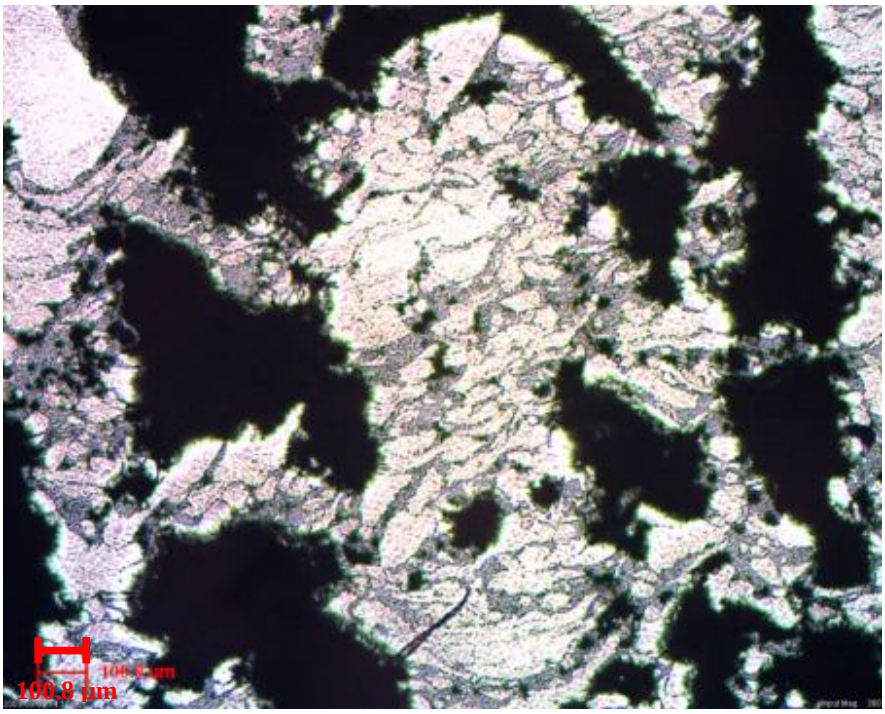
Point 17 at 720x real magnification



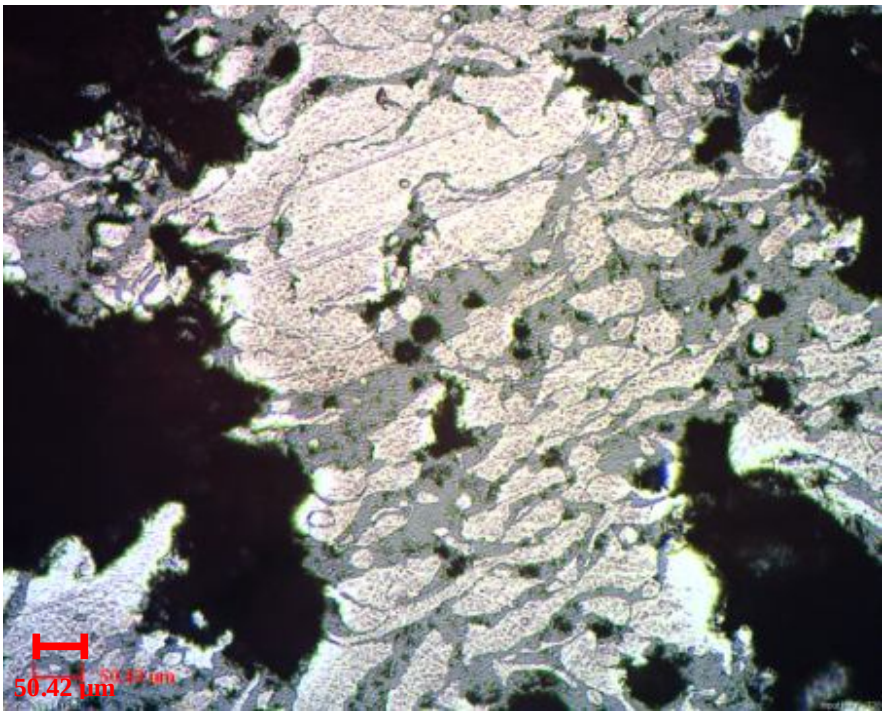
Point 17 at 3600x real magnification



Point 17 at 7200x real magnification



Point 18 at 360x real magnification



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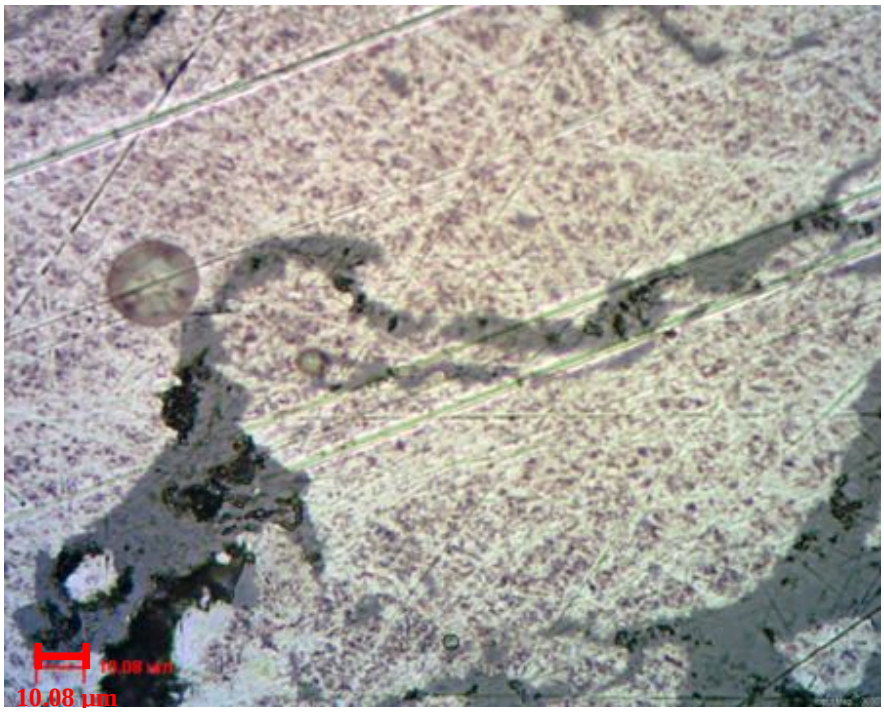

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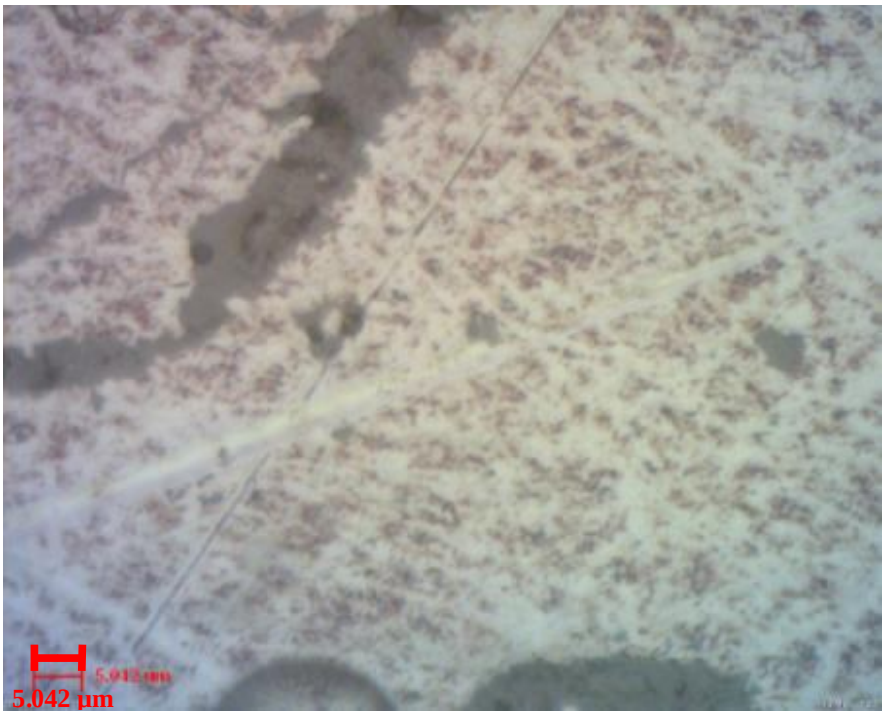
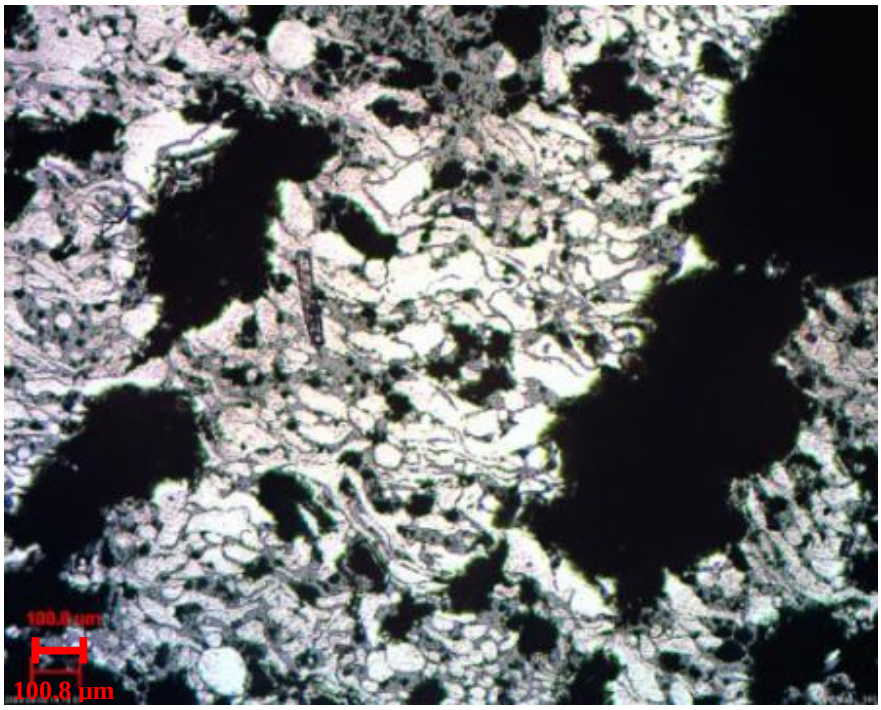
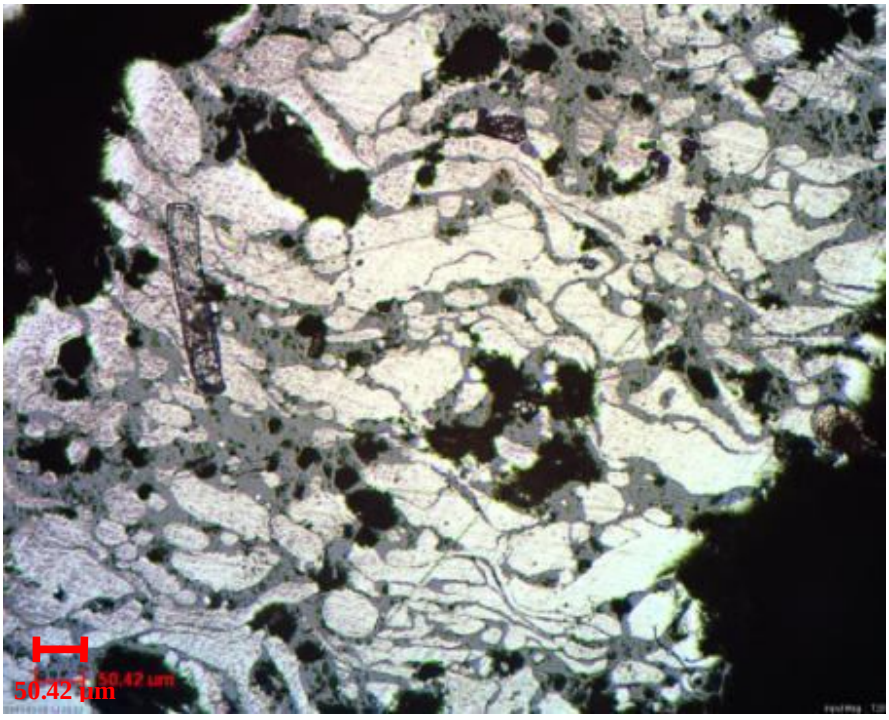


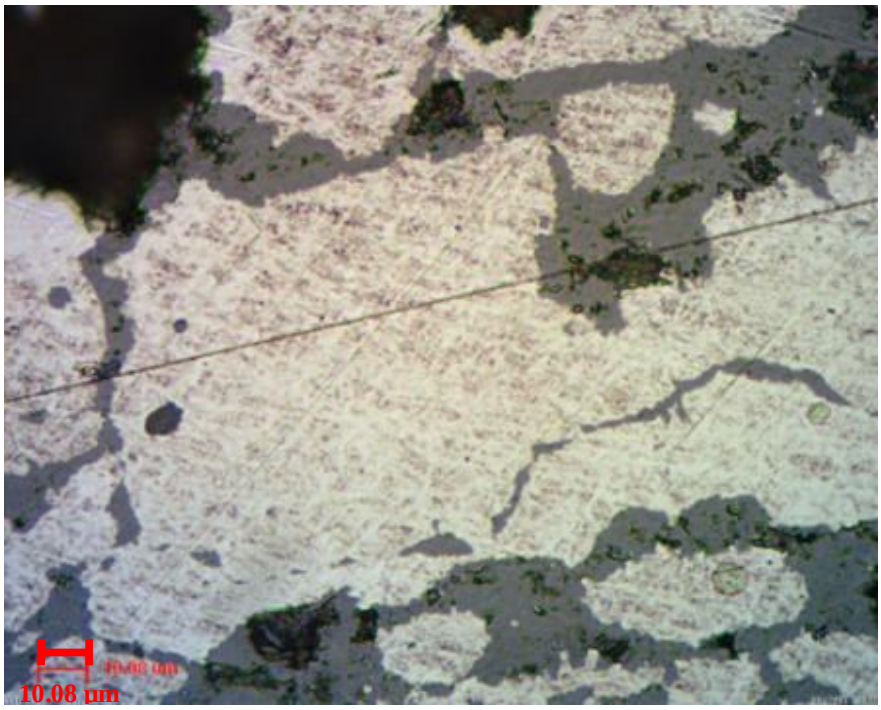
Point 18 at 7200x real magnification



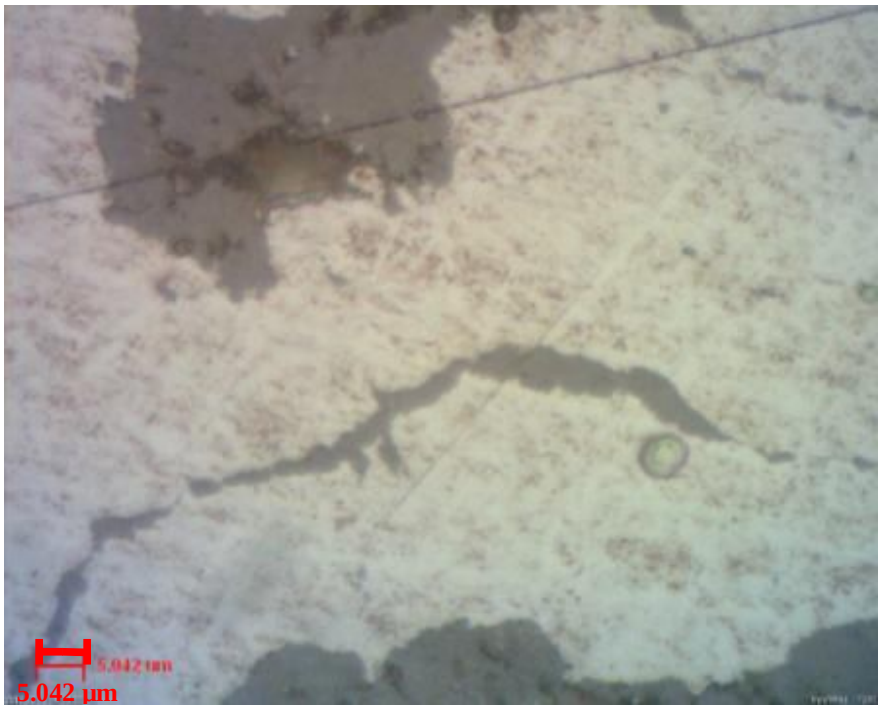
Point 19 at 360x real magnification



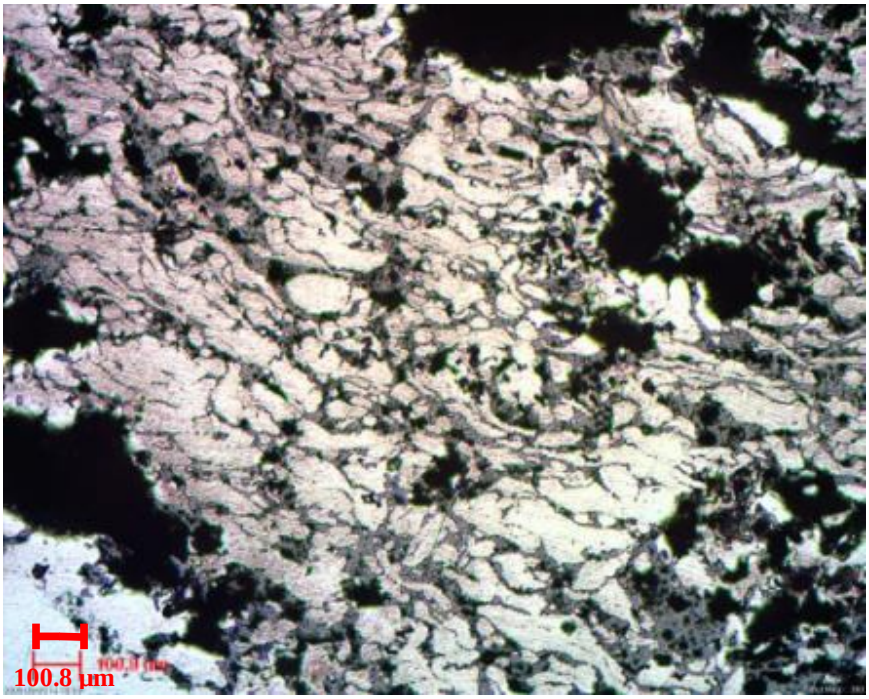
Point 19 at 720x real magnification



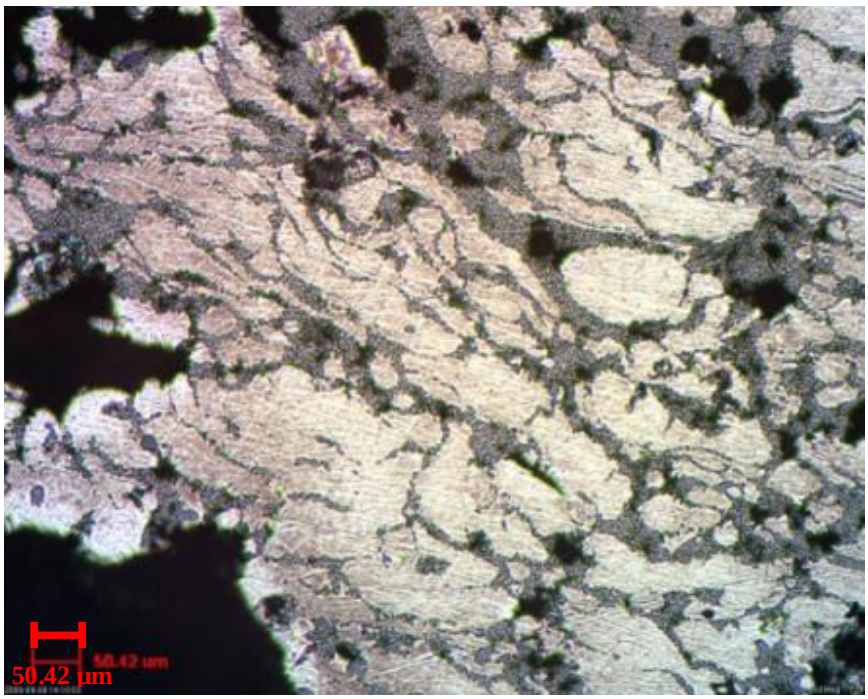
Point 19 at 3600x real magnification



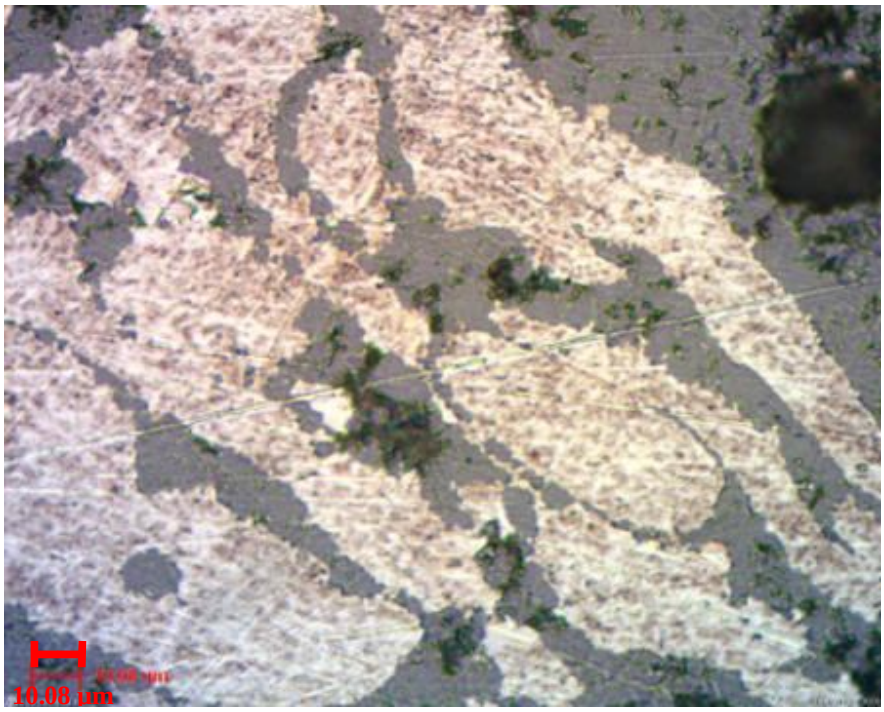
Point 19 at 7200x real magnification



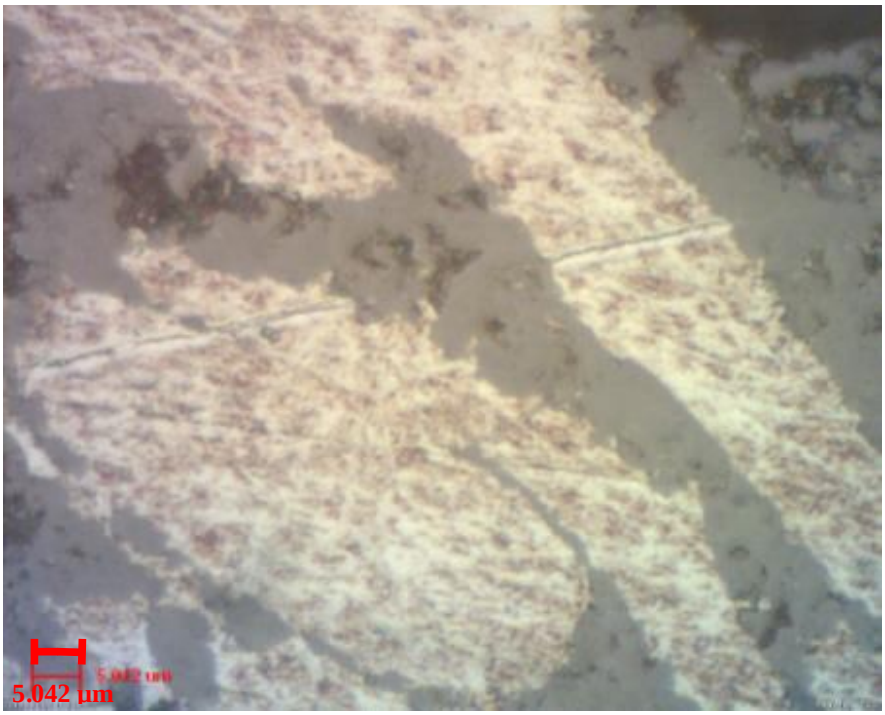
Point 20 at 360x real magnification



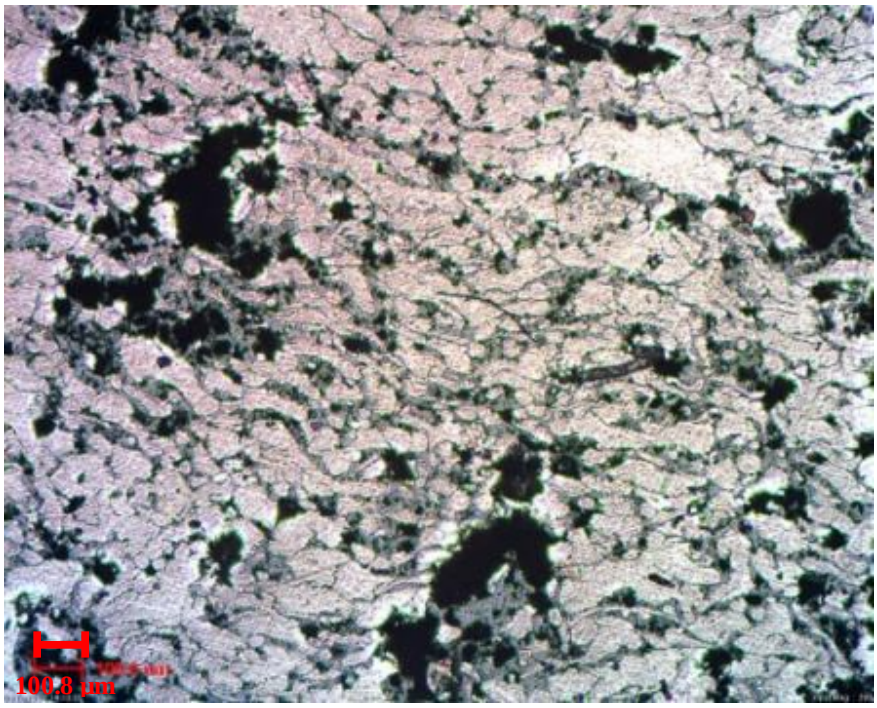
Point 20 at 720x real magnification



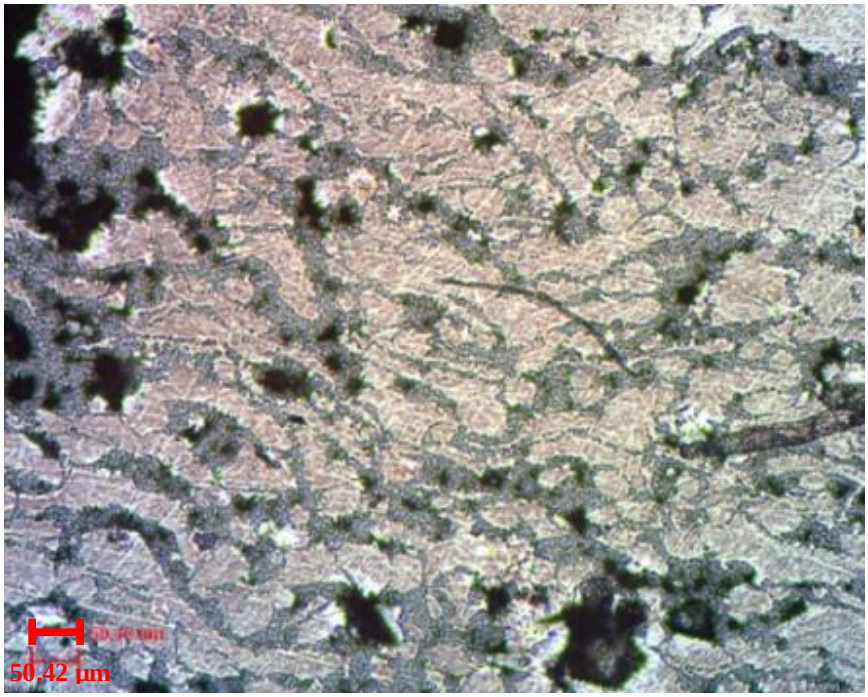
Point 20 at 3600x real magnification



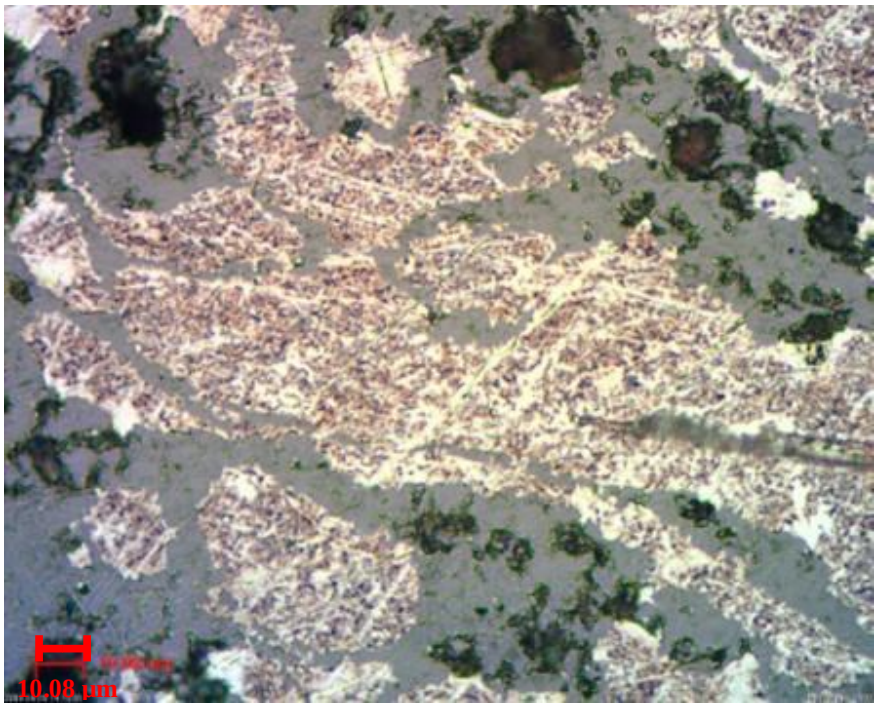
Point 20 at 7200x real magnification



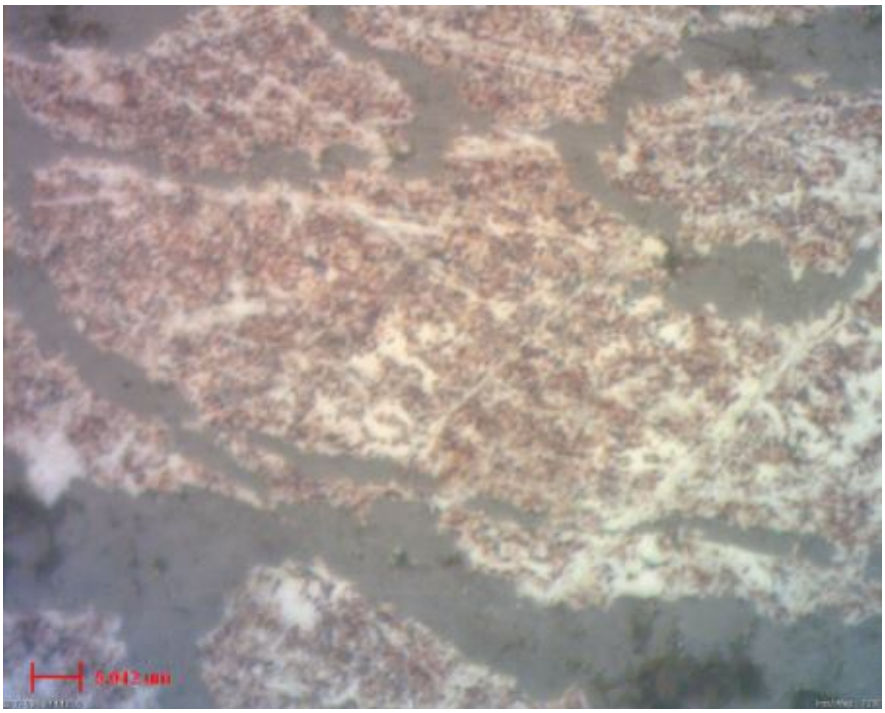
Point 21 at 360x real magnification



Point 21 at 720x real magnification



Point 21 at 3600x real magnification



Point 21 at 7200x real magnification

APPENDIX V – RESULTS FOR HARDNESS TESTING

Point of interest	Sample hardness value (HV)			Average hardness value (HV)	Average hardness value (HB)	Tensile strength (MPa)
	1	2	3			
1	90.8	96.8	95.5	94.4	94.4	335.0
2	115.3	129.1	106.7	117.0	117.0	415.5
3	146.3	101.9	139.1	129.1	129.1	458.3
4	244.1	254.2	206.9	235.1	235.1	794.5
5	163.3	174.1	169.7	169.0	169.0	600.1
6	145.1	100.7	144.0	129.9	129.9	461.3
7	160.8	163.0	163.4	162.4	162.4	576.5
8	245.6	289.5	271.0	268.7	268.7	908.2
9	255.8	205.3	215.4	225.5	225.5	762.2
10	198.6	183.8	206.3	196.2	196.2	663.3
11	210.2	212.6	200.4	207.7	207.7	702.1
12	310.5	146.4	181.2	212.7	212.7	718.9
13	313.3	209.8	250.0	257.7	257.7	871.0
14	61.0	153.3	176.2	130.2	130.2	462.1
15	264.0	268.6	209.9	247.5	247.5	836.6
16	184.3	148.6	153.4	162.1	162.1	575.5
17	175.6	223.5	204.6	201.2	201.2	680.2
18	134.4	146.7	168.1	149.7	149.7	531.6
19	180.8	239.6	187.2	202.5	202.5	684.6
20	53.7	100.5	131.6	95.3	95.3	338.2
21	245.2	214.3	226.5	228.7	228.7	772.9