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# Development of a wear index and its methodology related to mineral processing – Part I

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# Preface

This Master Thesis was performed at Sandvik SRP AB in Svedala in collaboration with the Division of Production and Materials Engineering at the Faculty of Engineering, Lund University, during the spring of 2016.

I would like to thank all people involved that have supervised me during my work both at Sandvik and in Lund.

I also would like to thank Professor Jan-Eric Ståhl who recruited me to this project and who has helped me with valuable knowledge and staff throughout the project.

Special thanks to MSc Per Hedvall and Dr. Hamid Manouchehri who have helped me as contact persons at Sandvik with valuable knowledge and some of the practical parts.

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# Abstract

This Master Thesis was performed for Sandvik SRP in collaboration with the Institution for Industrial Production Faculty of Engineering at Lund University.

Tool wear is one of the main cost drivers in the mining industry. By being able to characterize what kind of rock involved, you can choose a more beneficial tool material to minimize the wear and thereby reduce the maintenance costs.

The purpose of this thesis is to see if there is a correlation between the surface and the wear. The work had to be divided into Part I and Part II due to the size of the project. In Part I nanoindentation was used to get data to models that describes the variation in hardness, different hardness phases and the quantity of each phase for the rock being examined. Nanoindentation examines the rock at nano-scale by forcing a diamond Berkovich indenter into the rock hundreds of times. A part of this thesis was also to find a standard methodology to prepare the samples for the nanoindentation, which requires a good surface roughness.

The work started with a theory study to know the basics about the method and a literature study to see what have been done before.

During the work new experiences were given by using a trial and error method when preparing the samples. The methodology has been described carefully to be able to repeat the process regardless of the rock being examined. However, the grinding and polishing processes can be different depending on the rock, meaning that the time for each process can vary.

The results from the nanoindentation have been put into a table with expected wear based on internal order of the rocks involved. The table is supposed to be a basis used to find a correlation between the surface hardness and the wear after performing Part II. In the end of this thesis different suggestion of how to perform Part II are given.

**Keywords**: Nanoindentation, Berkovich indenter, wear, surface hardness, rock, minerals, manganese steel, mining, comminution.

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# 1. Introduction

*This chapter aims to describe the background, purpose and delimitations. Brief descriptions are given about the working process and the company.*

## 1.1 Report Structure

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## 1.2 Background

There are big differences in energy consumption and equipment wear depending on the type of rock that are being crushed and the product sizes in a mining process. Large differences in crushability can be seen when comparing, for example, magnetite and granite. Varying crushability leads to various wear rates on machine parts that are in contact with the rocks. The wear is primarily dominated by abrasive wear but also material breakaways occur in some of the involved parts. The choice of tool material is mainly determined by the required balance between wear resistance and strength to achieve optimal tool performance at a competitive cost. In current cases the choice of tool material is either manganese steel or cast iron (carbide steel). This is the best way to meet the wear requirements from various rocks.

## 1.3 Purpose and goals

The purpose of this thesis is to be able to characterize a rock in an unambiguous way so that one could pre-select the right type of wear parts and to assess the wear rate on the involved components. The ambition is to be able to correlate the wear rate with the energy consumption so that an overall production cost can be set to a certain product. If this is possible the vision in the end of the total project is to express the cost in SEK/ton. The thesis is supposed to be divided into two different parts. Part I is performed by using a nanoindenter to characterize the rocks according to their material properties at the surface. In Part II friction tests should be performed by using an own developed test machine at the university in Lund. The goal is to try to find a correlation between the two parts to be able to give the rocks a wear index and in the end determine the costs.

## 1.4 Delimitations

- This thesis will involve 6 different types of rocks. The reason for not examine more rocks are that the indentation process is time consuming.

- Every type of rock will be examined with one sample, also due to the time consumption.

- To analyze the results a Weibull distribution model will be used. The choice is based on Professor Jan-Eric Ståhl's knowledge and wisdom obtained by years of experience.

## 1.5 Method

The methodology in this thesis will be based on experiences from cutting processing where abrasive wear has been associated with surface level and distribution in micro- or nano. The distribution in hardness can be determined by making a large number of hardness measurements, 300-400 indents. To begin with there will be a theory study and secondly a literature study of existing articles to get an idea of how far the scientists have come in the concerned area. Furthermore the following points given below should be performed:

- Presentation of the test object (rock body) regarding size, orientation and shape.

- Find a suitable and time efficiency method for preparing the samples.

- The choice of load at surface hardness measurement.

- Make a table containing the rock characteristics by using nanoindentation.

- Give suggestions for further work in the upcoming continuation of the project, Part II.

## 1.6 Sandvik AB

The company Sandvik was founded in 1862 by Fredrik Göransson and is today one of Sweden's biggest companies in industrial production. In year 2014 Sandvik had a turnover of 89 billion SEK and about 47000 employees worldwide (Sandvik AB About Us, 2015). The Sandvik Group operates in five areas illustrated in figure 1.1; Sandvik Mining, Sandvik Machining Solutions, Sandvik Materials Technology, Sandvik Construction and Sandvik Venture (Sandvik AB Business Areas, 2016). The largest business area in terms of employees and turnover is Sandvik Machining Solutions (SMS). SMS is market-leading in tools and tooling systems for industrial metal processing. Sandvik Construction (SC) and Sandvik Mining (SM) are both in the rock industry. SM is a major part of the Sandvik Group and combined with SC the total turnover is about 35 billion SEK representing nearly 40 % of total turnover. Sandvik Materials Technology is market-leading in developing and manufacturing advanced stainless steel and represents approximately 17 % of the total turnover. Sandvik Venture is the smallest business area and is working to create opportunities for growth and profitability in attractive and fast-growing businesses.

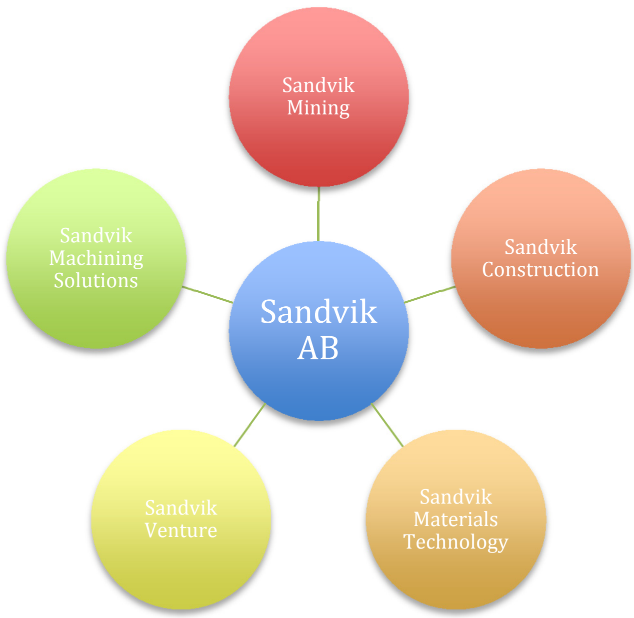



**Figure 1.1 - The business areas of Sandvik AB**

Sandvik Group is an international company with headquarters in Stockholm but with the whole world as a business area. The result of this thesis will be relevant to the mining industry, which means that the affected business areas are Sandvik Mining and Sandvik Construction. Some of the employees working at SM and SC are located in the small town Svedala in southern Sweden. Sandvik is one of the largest employers in Svedala with approximately 350 employees. In Svedala Sandvik is manufacturing crushers and spare and wear parts for their machines.

# 2. Theory

*In this chapter theories and existing articles will be revised. The theories and articles provide the basics for a better understanding.*

## 2.1 Surface hardness

Surface hardness is one of the most important properties for a material. There are several different methods to measure the hardness. The methods are all based on the same fundamental idea, the power consumption required to plastically deform a material. In particular metals properties have been tested in the past because of their ability to apply in many different applications. One of the mining industry's main challenges, in addition to reduce maintenance, is to reduce energy consumption. Therefore new tool materials have to be developed that are not too soft which makes them sticky and not too hard which make them brittle. In addition to the studies made in the past scientists have developed new materials that tries to mimic metal properties. An example is carbon composites, which are very hard for its weight but still it cannot compete against metals properties and the robustness needed in the mining industry.

### 2.1.1 Methods

Some of the most common methods to measure hardness that have been used for decades are Mohs' hardness scale, Brinell test, Knoop test, Rockwell test and Vickers test. A collective name for some of the test methods is indentation. The difference between the methods is primarily the geometry of the indenter that are in contact with the material.

#### 2.1.1.1 Mohs hardness scale

One of the most simple test methods is Mohs hardness scale (Mohs Scale, 2016). In the test process a tool with known hardness is being scratched against the specimen. If there are remaining scratches on the specimen after the test it is clear that the specimen is softer than the tool hardness. By changing to another tool with a different known hardness level it is possible to find where in the scale the specimen should be. However, it is important to know that the Mohs scale is a non-linear scale. Mohs hardness scale runs from 1-10 where nr.1 is softest and nr.10 is hardest. At the bottom of the scale you'll find talc and at the top you'll find diamond. The advantage with this method is that it is a simple technic that does not require advanced equipment. However, there is a problem with the defects on the surface that can be relatively large and visible on the specimen being examined.

#### 2.1.1.2 Indentation

An alternative to measure hardness with a more accurate result is by using advanced indentation equipment. The nanoindentation method is based on the theory from Oliver and Pharr's algorithm that a small area at the micro- or nano scale is being pressed against a specimen during several sequences (Mater, 2004). It requires advanced and costly equipment to carry out the process when a diamond indenter is being used to penetrate the specimen. The indenter is usually a Berkovich indenter, named after its inventor, see figure 2.1. By moving the indenter a small distance between each penetration the results will be more detailed and the hardness is calculated at each point. The result can show the differences in properties between each phase within a rock (Schuh, 2006). To calculate the surface hardness the applied force is divided by the projected area. The projected area is calculated from Oliver and Pharr's algorithm and the hardness is given in GPa.

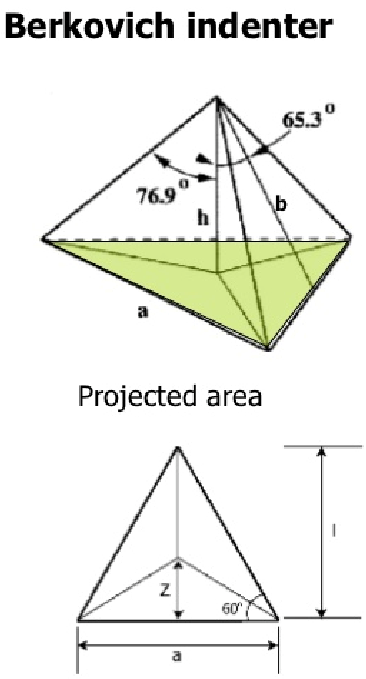



Figure 2.1 - The geometry of a Berkovich indenter and the projected area

### 2.1.2 Abrasive wear

Abrasive wear occurs as surfaces move relatively towards each other (Nötning, 2016). Abrasive wear has always been a problem for mankind, even at the Stone Age. Nowadays different kinds of lubricants help reducing the friction, which is a major part of the problem. The wear rate is affected by various factors such as materials, hardness, sliding speed and temperature. By reducing the abrasive wear the company can save a lot of money because of the reduced downtime thanks to less maintenance and repairs. Problems with abrasive wear occur mainly in the form of torn off material that creates scratches and cavities on the surfaces. The abrasive wear is based on that the materials being in contact have different hardness.

## 2.2 Articles

### 2.2.1 Background Articles

Before the test processes are initiated a literature study was performed. The goal is to see how far others have come in the chosen area. The reason for this thesis is that new research is required to hopefully meet the targets that are set. However, there is still a good chance that some articles contain valuable information concerning the subject. The main target is to see if there exists a connection between the micro hardness and the microstructure. A factor that can cause problem for finding articles is that nanoindentation requires expensive equipment that many cannot afford. Regarding other keywords like *rock* there is plenty of information. In the mining industry several rock types are being processed for the extraction of e.g. gold or iron ore. Each rock type can contain different minerals, which in turn may consist of different substances having different material properties. The construction, distribution and chemical composition of the rock are the basis of the material properties and how easy it is to process. With all these factors in mind there will be a lot of information, which means that some delimitations have to be set.

### 2.2.2 Method Articles

To search for related articles Google Scholar will be used. Google Scholar is a search engine that publishes scientific articles that can be accepted by other academics knowledgeable in the topic. Some of the articles on Google Scholar are also published on sciencedirect.com, which is a website where scientists publish their articles. The search engine contains more than 160 millions articles and to find related information among all the articles one or several keywords have to be used (Orduna-Malea, 2014).

Keywords that were used in this thesis: manganese + steel, manganese + abrasive + wear, manganese + work + hardening, hardness + rock + index, nanoindentation + mapping, rock + hardness + distribution, nanoindentation + rock. In addition to search through Google Scholar the supervisors were also asked for related articles.

To begin with only the abstract of some articles were read through to see if they were related to the topic. Secondly the most interesting articles were read through and totally five reviews were made. The articles being studied in this literature study were published between 1981-2013. However, some of the oldest articles contain information that might not be correct nowadays. One example is that the price of a material was very high in the 80's and not economically feasible to process. Today the situation could be different and the same material could be cheaper thanks to a greater supply on the market.

#### 2.2.3 Result Articles

##### 2.2.3.1 Articles

- Mechanism of Work Hardening in Hadfield Manganese Steel, Y.N Dastur and W. C. Leslie, 1981.

- Micro scale hardness distribution of rock types related to rock drill wear, U. Beste och S. Jacobson, 2003.

- Abrasive wear mechanisms and their relation to rock properties, M. Petracia, E. Badsich and T. Peinsitt, 2013.

- Method of Abrasive Wear Testing in Comminution Processes, Stanislaw F. Scieszka, 1996

- Mapping of mechanical properties of WC-Co using nanoindentation, H. Engqvist and U. Wiklund, 2000.

##### 2.2.3.2 Abstract Articles

***Mechanism of Work Hardening in Hadfield Manganese Steel (Y.N Dastur and W. C. Leslie, 1981)***

This article was published in 1981 and handles the mechanisms and behavior for manganese steel in the single-phase austenitic condition being strained in tension. The result in the temperature range -25°C to 300°C shows an inverted strain-rate dependence of flow stress and high work hardening that is characteristic of dynamic strain aging. The examined manganese steel is also called Hadfield manganese steel after its inventor Robert Hadfield. The Hadfield manganese steel is hard, nonmagnetic and Fe-C-Mn alloy. It is useful for severe work that contains both abrasive wear and impacts. The standard being used in the American Society of Testing and Materials, ASTM, A-128-64 uses this Hadfield manganese steel allows a composition of 1-1.4% C and 10-14% Mn. In the article it is said that manganese steel with more than 12-13% Mn is not economically feasible.

***Micro scale hardness distribution of rock types related to rock drill wear (U. Beste och S. Jacobson, 2003)***

Mining and rock processing involves severe work for the tools being used. Rock processing is often under extreme conditions, which creates abrasive wear for both the tools and the transport equipment. Different material properties of the minerals being processed are a big concern when it comes to choose the best-suited tool. The properties also affect the handling equipment such as excavators, conveyors and crushers, which have to be made of special materials to not wear out too quickly. Even within a single mineral ore, the varying character can lead to several different wear mechanisms on the tool. The need of getting a better characteristics and more knowledge regarding minerals are therefore of great interest. The main cause of wear existing in the mining industry is because of the layer on the surface at microscopic level suffers from fatigue i.e. load at a small level results in a major wear. A common phenomenon when having abrasive wear is called *reptile skin formation*. It is recognized by a pattern of rough plateaus surrounded by valleys and it can be seen as a warning signal before larger cracks arises.

The heat being generated in a tool in action is proportional to the friction between the surfaces in contact. The ratio does not change much between different combinations of tools and rocks. However, the moisture level and the surrounding temperature have a big impact on the results.

In 1977 the international Society for rock mechanics, ISRM, suggested some methods to determine the hardness of a rock. Mainly they suggested Knoop tests and Vickers tests while applying only low loads. The problem by using Brinell tests or Rockwell tests was that the load was too high for the brittle rocks. It was also suggested various dynamic tests i.e. different bounce tests where a diamond indenter is dropped on the specimen and the rebound height is measured. In 2003 ISRM recommended a method called Uniaxial Compressive Strength, UCS. The UCS-method uses a standardized conical tip with an angle of 60 degrees and a radius of 5 mm. Indentation Hardness Index, IHI, is then used to index the rock by dividing maximum load with maximum penetration. The equation to get UCS is: $UCS = 31 * IHI^{1.09}$. The index is based on measurements and is a measure of the rocks ability to withstand elasto-plastic deformation.

The experiments were made with nine different rock types that can be divided into two subgroups. The first group consisting of isotropic characters rocks and the second group with complex rocks. A table were set up with results of the different mines, probability to create reptile skin formation and their ability to withstand abrasive wear. Before the measurements were made the samples were ground with four kinds of grit paper for 30 min each. Two indentations, micro- and nanoindentation, were made where the first used a Vickers tip with a load of 500 g that randomly did 10 indents to get an average hardness. The second indentation was set to a fix penetration depth at 1 μm using a Berkovich-shaped diamond. The diamond did totally 480 indents divided into three parallel lines. A load-displacement graph was given for each of the indents.

The results of the study show the range of hardness and an average. For all rock types the average hardness was higher while using nanoindentation compared to the Vickers tip. The explanation was that the load 500 g using the Vickers tip was to big and didn't gave a good measurement. The measurement with a fix depth resulted in approx. 15% higher hardness.  The fact that it is loading at a low level, which gives highest abrasive wear means that, the rocks hardest areas exposes the tool for most wear. Some of the rock types examined in the tests contained hard particles that worn out the tool even though the rock was defined as soft.

***Abrasive wear mechanisms and their relation to rock properties (M. Petracia, E. Badsich and T. Peinsitt, 2013)***

The article intends to create a better understanding of how abrasive wear tends to occur on tools, which is of great interest for the mining industry. Machines being constantly exposed for dust i.e. in rock processing are exposed for small particles that settle on and between contact surfaces. These particles create abrasive wear, which affects the total lifetime. According to the article 50 % of wear in mining industry consists of abrasive wear. The abrasive wear is either created by 2-body abrasive wear or 3-body abrasive wear. 2-body abrasive wear means that only the two surfaces are in contact i.e. surfaces of two parts in a machine. 3-body abrasive wear is slightly different and a third factor is taken into consideration i.e. small particles like dust or torn of material from the surfaces in contact. It exists models for how to calculate wear when having 2-body abrasive wear. However, 3-body abrasive wear is more common in the industry but it exists no good enough models to calculate the wear rate. The major problem when having 3-body abrasive wear is that it is difficult to predict if the small particles rolls, slides etc. The main focus in this article is therefore to establish a more fundamental understanding of wear and try to create a connection between 2-body and 3-body abrasive wear.

Three rock types where investigated in the study. The rock types where granite, meta-sandstone and sandstone. The main elements in the rocks were quartz and feldspar. Granite with 31 % quartz and 59 % feldspar, meta-sandstone with 66 % quartz and 14 % feldspar, sandstone with 97 % quartz and 2 % feldspar. All samples where polished and grinded to a surface roughness of 1 μm before they where chemically cleaned. To begin with a weigh in and a hardness measurement according to Vickers method were performed on all samples. Secondly two different tests were performed. The first one was Slurry Wheel Abrasion Test, SSWAT, which tests the resistance to withstand 3-body abrasive wear. This is performed with small particles being fed into a rotating chamber. The sample was carrying a load of 216 N and was spinning exactly 358 m against a steel wheel at 33 rpm. To try out the resistance against 2-body abrasive wear the method being used is called Cyclic Impact Abrasion Test, CIAT. The sample is mounted on a rotating disc and hit by abrasive particles with an approximate rate of 10 m/s during 20 min.

After conducting the tests the samples were once again weighed to be able to determine the mass that was lost due to SSWAT and CIAT. To calculate the wear rate the volume loss first had to be calculated by using the weight loss and the density. To study the wear depth a 3D scanner was used.

To calculate mechanical rock properties different methods are used. Uniaxial Compressive Strength, UCS, is a basic method to establish the strength of a rock.

UCS is a standard according to American Society of Testing and Materials, ASTM. Tensile strength is another important property that can be established by using Brazilian Tensile Strength, BTS. BTS reflects the grain bond strength and is also a standard in ASTM. To study a rock's resistance against abrasive wear, the elements in the rock are investigated. It is mainly the hard elements like quartz and feldspar that are critical for the result.

The result after conducting the 3-body abrasive wear test, the SSWAT test, indicates that rocks with high amount of quartz wears the most on a tool. With the help of 3D pictures on the worn surface area the wear pattern can be seen as narrow scratches and grooving. In this case the rock types tears differently because of different amount of quartz and feldspar. Sandstone tears the most, then meta-sandstone and lastly granite. A stunning fact is that when studying 2-body abrasive wear the opposite situation occurs i.e. granite tears more than sandstone. This is explained because of the hard particles, such as quartz, are removed from the surfaces. This means that the amount of quartz is not that crucial. Friction and wear are created when having 2-body abrasive wear. The energy being generated by friction can be connected to the wear. However, with 3-body abrasive wear a specific situation can't be isolated because of the particles movement. By studying the energy consumption to tear of 1 $mm^3$, also called specific wear energy, there is still a chance to get an indication if the rock type has a tendency to abrasive wear.

The conclusion from the tests is that 2-body abrasive wear and 3-body abrasive wear shows the opposite wear properties on the rock types being examined. However, in the mining industry 3-body abrasive wear is the most common situation because of particles like dust constantly is generated when processing rocks. If having the situation of 2-body abrasive wear it is easier to get a hold of the tendency to abrasive wear by using UCS and BTS. The ratio of UCS and BTS is the determined by the factor in the expected abrasive wear of some rock types.

### *Method of Abrasive Wear Testing in Comminution Processes (Stanislaw F. Scieszka, 1996)*

This article deals with different material properties when having abrasive wear by sliding in a comminution process. The mineral used in this study is coal, but the results can still be useful no matter what kind of rock type. A major factor for wear on the tool is the choice of tool material. However, one thing to keep in mind is that the resistance to abrasive wear is not the only factor that reduces the total wear. Other parameters, which also affect the wear resistance, are e.g. toughness and fracture toughness. The main reason to have minimal tool wear is from the economic aspect i.e. the profitability has to be good enough since the machines are suppose to run 100 % around-the-clock. The coal industry is like other mining industries where the costs are primarily affected by the energy consumption and the maintenance.

Twelve different types of alloys were tested and in particular high chrome cast iron Z-1 is of great interest because of its use in ball-and-race type coal pulverizes. Pure coal is relatively soft, but coal extracted from earth also contains hard particles e.g. quartz and slate. It is the hard particles that are creating the most abrasive wear. There are different kind of methods to measure the wear tendency e.g. Hammer impact mill, Dry-sand rubber wheel abrasion test and Tribo-tests (Scieszka mill). No matter what method being used the definition of abrasive wear is still the same; Particles moving relatively each other e.g. at low loads by scratching or by high loads that tears the material off.

To test the wear tendency the Tribo-tests were used in this experiment. The equipment consists of a cylindrical grinding chamber in which a drive shaft is mounted, to one end of which a disc is attached. 30 g coal is positioned in the bottom under the grinding element that is attached to the underside of the disc. Because of different diameter of the disc and the chamber, which results in a clearance, the coal can travel up as the disc goes down. Before the test started all alloys were cleaned carefully with alcohol and weighed. During each test the disc rotated at 100 rpm with a normal force of 2000 N until it almost hit the bottom of the chamber. After the test the disc was ultrasonically cleaned and weighed. The test was then repeated with new coal, but with the same disc.

The results of the tests showed that one could divide the test objects into two groups, brittle and ductile. The actual material, high chrome cast iron Z-1, was hardest with 752 $HV_{30}$ and was also proven to have highest wear resistance measured in unit MJ/g, WR.

A conclusion from the tests was that the method being used was not fully developed, but still a good starting point. However, one should try to further develop the project to enhance the understanding of the relation between WR and other material parameters.

***Mapping of mechanical properties of WC-Co using nanoindentation (H. Engqvist and U. Wiklund, 2000)***

This study uses a nanoindentation equipment to investigate the mechanical properties of each phase of two different WC-Co cemented carbides. A mapping was done with the different phases' of hardness and Young's modulus. A scanning electron microscopy, SEM, took pictures that were compared with the nano mapping. Hopefully a better understanding of each phase properties will result in better mathematical models. Important factors being investigated are distance and depth between the indents to not affect another.

Conventional hardness measurements use a relatively large load at a macroscopic level that gives an average hardness good enough for designers. However, the R&D wants to study the material at a microscopic level. The hardness measurement of a pure material can be an average measure of several grains, but for rocks, alloys and composites the material properties are of greater interest and by using nanoindentation it is possible to study a single grain. A more precise result can give better mathematical models. Nanoindentation also reduces the surface defects that usually occur when performing a hardness test.

Two kinds of WC-Co cemented carbides with different grain size and Co binder layers were tested. Sample 1, WC-0.7, had a grain size of 0.7 μm and a CO binder layer of 0.08 μm. Sample 2, WC-7, had a grain size of 7 μm and a CO binder layer of 0.8 μm. The samples were polished to a surface roughness at nano scale and cleaned with acetone, alcohol and distilled water to remove any impurities. Depending on the choice of parameters in nanoindentation the penetration area can be less than the size of the grain size or binder layer thickness. The results can then be compared to already done tests where microindentation has been used. However, the results from nanoindentation are often higher compared to results from microindentation.

The equipment used for the indents was a XP$^{TM}$ Nanoindenter with a Berkovich indenter and for the images a SEM (Leo 1550). The indenter radius was 200 nm and between each indent in the sample an indent in a fused silica was performed to check the geometry of the indenter. Hardness and Young's modulus were calculated by using Oliver and Pharrs algorithm. The tests were divided into two different parts. The first part tested the resolution according to indent depth and indent distance, test 1 and test 2. The second part focused on the possibility to distinguish the two phases, test 3 and test 4.

In test 1 ten indents were made, with a 30 nm depth, to try to find out what distance between each indent required to not affect another indent. The distance was varying from 0 to 1000 nm. In test 2 every indent lasted for 200 seconds and a try to find out the minimum depth to get reliable data was made. The depth varied from 10 nm to 1000 nm. It was confirmed that a depth of 30 nm was similar to 150 nm. For the second part in test 3 a line of indents crossing several grains were made. There was a fix depth of 30 nm and a 0.5 μm distance between each indent. In test 4 lines of indents were made creating a 15 by 15 μm area of the surface. This area created a 3D image of the material properties. The samples were then scanned with SEM to later be compared with the results.

The results from test 1 shows that the distance between each indent does not matter as long as it is larger than 0. Test 2 resulted in a minimum depth of 30 nm, otherwise there was not a reliable results. The results from a depth of 30 nm were similar to 150 nm. Test 3 was not a great success for WC-0.7 since it was impossible to distinguish the two phases. Probably the binder layer was too small. With WC-7 it was possible to distinguish the phases and the results were good according to previous studies. Test 4 resulted in small variations in hardness and elasticity within each phase, but between the phases the results were clear. With the help of 3D images it is easy to understand the properties of the surface. By comparing the SEM image to the 3D image everything seems to be correct.

The conclusions from this article are that a larger distance than 0.5 µm between each indent is not necessary for affecting others and a minimum depth of 30 nm is required. To get a higher resolution the distance should be close to 0. Indentation size effect, ISE, is a theory saying that a nearby area will be affected by an indent and has a change in material properties. However, by using small loads like with nanoindentation this theory can be dismissed. A theory according to the minimum depth of 30 nm can have something to do with water being absorbed into the surface and affects the surface by softening it. Another factor that affects is that small depth may not force the material into plastically deformation.

## 2.4 Discussion Articles

### 2.4.1 Result

There are some factors that have turned out to be essential for a successful experiment. One of the factors that have been discussed in some articles is the distance between the indentations. A penetration can affect the nearby material. However, by having a distance between the penetrations the risks are reduced which means less false results. One distance that was mentioned in one of articles was 0.5µm, but there was no minimum distance except that the penetrations were not allowed to be on top of each other. A smaller distance gives a better result between each penetration i.e. there will be a better resolution.

Another important factor was the choice of load. In the article *Micro scale hardness distribution of rock types related to rock drill wear* a 5 N load was applied in the microindentation test and 7 -377 mN in the nanoindentation test. The choice of load turned out to affect the results since the measured hardness was higher when using nanoindentation. In the article *Mapping of mechanical properties of WC-Co using nanoindentation* the applied load was only 1 mN. The article also had mapping the material properties as an important purpose. The mapping created a better understanding of how the properties change within the material. With the help of a 3D image it is easier for people with less knowledge in the topic to understand the result. However, it is important to first polish and clean the surface while using a sufficient penetration depth to avoid the affects of surface defects. Too small depth can also mean that the material is not being plastically deformed. A minimum depth of 30 nm was recommended since the results of 30 nm and 150 nm depths were similar.

The article regarding the coal tests can be interesting for further work if the method gets further developed. It is an interesting approach of how to make a wear index.

As discussed in the article regarding the Hadfield manganese steel it has been proven that manganese steel becomes harder in severe work. This is a rare material property, which can be useful to extend the lifetime of a machine part that suffers from fatigue.

The article *Abrasive wear mechanisms and their relation to rock properties* compared the cases when having either 2-body or 3-body wear. It is fascinating to see that depending on the situation there will be different results. In 3-body wear there is a third particle that makes a huge different on the wear rate depending on its hardness. The two surfaces can either contain hard particles that are torn off while in action or not. The particles can also come from the surrounding environment and affect the wear rate. While considering that the surfaces contain hard particles it is possible to think that the wear rate will be less if removing the particles i.e. 2-body wear instead. The important factors that the article emphasizes are if the materials in contact contains hard particles as well as the wear situation i.e. 2-body or 3-body wear.

### 2.4.2 Conclusions

In the beginning of the tests some experience from the read articles will be taken into consideration. The principal of how to study the results will be used. Recommended values of a minimum penetration depth of 30 nm and a maximum indentation distance of 0.5 µm can be of great use, but they might not satisfy this thesis tests. A difficult factor to determine to get representative results will be the load and the size of the examined area.

## 2.3 Rocks

The rocks being examined come from mines in the northern part of Sweden. At the beginning there were five types of rocks, which are all listed in table 2.1 in both English and Swedish. Introductions of the rock types are given and most of the information was found on one of the leading websites for earth science (Geology About Us, 2016). Some of the rocks consist mostly of the same components, but with some changes in the distribution.

Table 2.1 - Rocks

| English | Swedish |
|---|---|
| 1. Diorite (D) | Diorit |
| 2. Muscovite slate (MS) | Muskovitskiffer |
| 3. Biotite gneiss (BG) | Biotitgnejs |
| 4. Biotite slate (BS) | Biotitskiffer |
| 5. Amphibole biotite gneiss (ABG) | Amfibol-biotit-gnejs |
| 6. Red gneiss (GG) | Röd gnejs |

### 2.3.1 Diorite

Diorite is an igneous rock used as a base material when constructing roads, parking areas and buildings. In larger size it can also be used as pavers, tile or other stone products in a home. Diorite is a course-grained rock and has a black and white appearance. It is created when magma erupts from the inside of the earth and crystallizes. A generalized chart of the mineral composition of Diorite can be seen in figure 2.2. Diorite is mainly composed of amphiboles, micas, plagioclase feldspar and some minor amounts of quartz, orthoclase or pyroxene (Diorite, 2016).

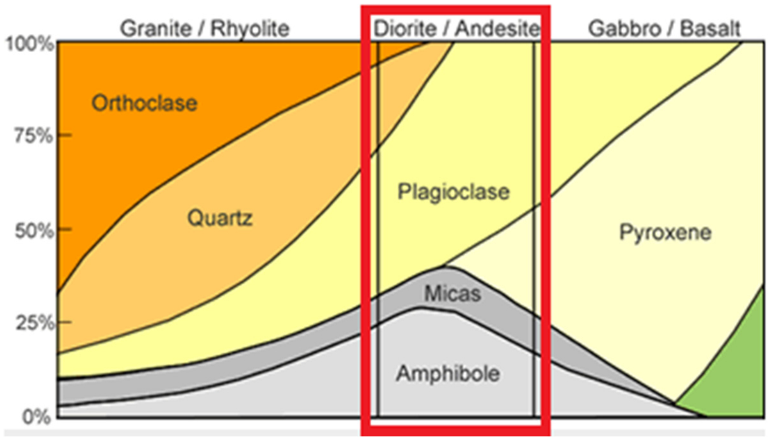



Figure 2.2 - Composition of Diorite

### 2.3.2 Slate

Slate is a metamorphic dark grey rock mostly used as roofing slates. It is also used for interior flooring and exterior paving. Slate is usually mixed with other minerals in the earth and is mainly composed of micas and can contain minor amounts of quartz or feldspar. (Slate, 2016). In this thesis two different kinds of mixes were examined, muscovite slate and biotite slate. Muscovite is the most common mineral in the mica family and has a white appearance, which makes the color of muscovite slate grey and white (Muscovite, 2016). Biotite is also a mica mineral and is often found in igneous and metamorphic rocks. Biotite has a black appearance, which makes the color of biotite slate dark including both grey and black (Biotite, 2016).

### 2.3.3 Gneiss

Gneiss is a metamorphic rock with a black, grey, red and white appearance. An advantage about gneiss is that it does not split along planes of weakness like many other metamorphic rocks. This advantage allows designers to use gneiss as a crushed stone in building site preparation and road constructions. Like many other rocks it can also be used as an architectural stone like a worktop in the kitchen. Gneiss is often mixed with other minerals like biotite and amphibolite and it also contains some minor amount of quartz and feldspar (Gneiss, 2015).

The red gneiss used in this thesis is collected from the small town Dalby located outside of Lund where Sandvik has a test facility (Arvidson, 2006).

## 2.4 Weibull Distribution

Weibull distribution is named after Waloddi Weibull who was a Swedish strength specialist and physicist. The distribution has proved to be useful in reliability engineering when analyzing for example total lifetime and fatigue limit (G. Blom, 2005). The mathematical equation consists of the two parameters α and β, which are shape and scale parameters, respectively, see equation 2.1 (Enger, 2005). Mathematically the result is considered reliable if the error is below 4% when using a Weibull distribution. However, in the industry the error limit is set to 10%, according to Jan-Eric Ståhl. In this thesis the analytical model made by Jan-Eric Ståhl consist of three Weibull distributions.

$$Weibull\ distribution\ \ F_X(x) = \begin{cases} 0 & if\ x < 0 \\ 1 - e^{-\left(\frac{x}{\beta}\right)^{\alpha}} & if\ x > 0 \end{cases}$$

**Equation 2.1 Weibull distribution**

# 3. Methodology

*In this chapter the methodology is described carefully to be able to redo the tests with other rocks. The used equipment is presented with figures for a better understanding.*

## 3.1 Equipment

To prepare the samples, perform the tests and study the surfaces several different types of equipment were used. There are few producers that make lab equipment, but a well-known company is Struers from Denmark. Struers sell both the equipment and the accessories needed e.g. grinding paper and polishing equipment. They have also a website from which the user can get information regarding how to prepare the samples to get a good surface roughness depending on the material.

### 3.1.1 Cutting machine

To cut the drill cores into smaller pieces a cutting machine of type Leco LSM 250 was used, see figure 3.1. To get a good surface roughness after the cut, the blade being used contained diamond grains. The blade can easily cut rocks into smaller pieces as long as the rock is tightened enough.

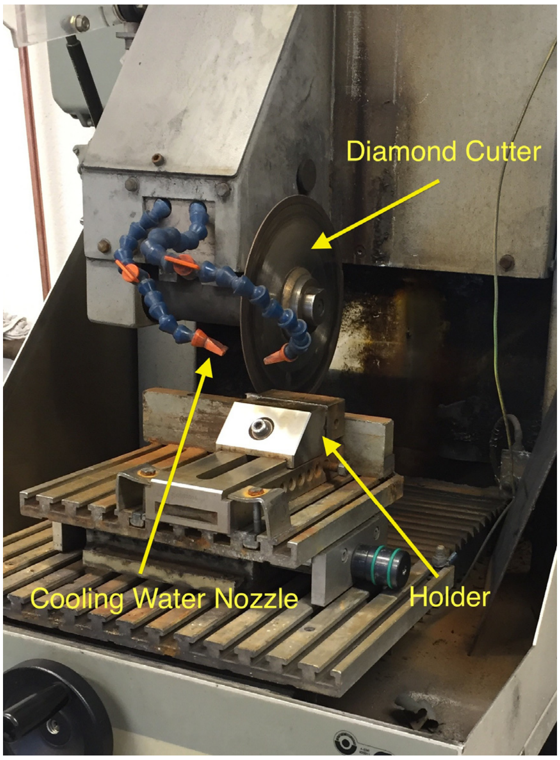



**Figure 3.1 - Leco LSM 250 A2**

### 3.1.2 Pellet machine

To surround the samples with plastics a Predopress from Struers was used, see figure 3.2. When finished, the pellets have a circular shape with a 30 mm diameter.


**Figure 3.2 - Predopress**

### 3.1.3 Grinding/Polishing

The grinding and polishing machine was also made by Struers, which simplifies the process thanks to the same circular shape as in the pellet machine. The grinding/polishing machine was a Rotopol-2 and can be seen in figure 3.3.

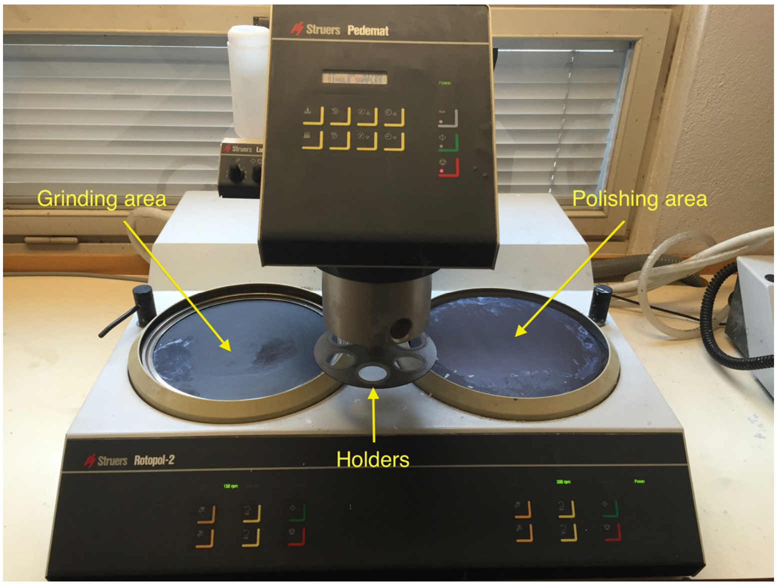



**Figure 3.3 - Rotopol-2**

### 3.1.4 Nanoindentation

To perform the indents a NanoTest Vantage4 from Micro Materials was used. The nanoindenter is a complex machine with an outer casing that covers the most of it, see figure 3.4. The Vantage4 is a high precision instrument designed to provide surface mechanical characterization data by indenting to depths at the nanometer-micron scales. Vantage4 uses a diamond Berkovich indenter to perform the indents. It has a built in microscope, which is used to visually study the examined surface and to take photos (Vantage4, 2016).


**Figure 3.4 - NanoTest Vantage4**

## 3.2 Sample preparation

The rocks arrived as drill cores in a half circle shape from the mining company Boliden from mines in the northern part of Sweden, see figure 3.5. The name of each rock was given from Boliden.

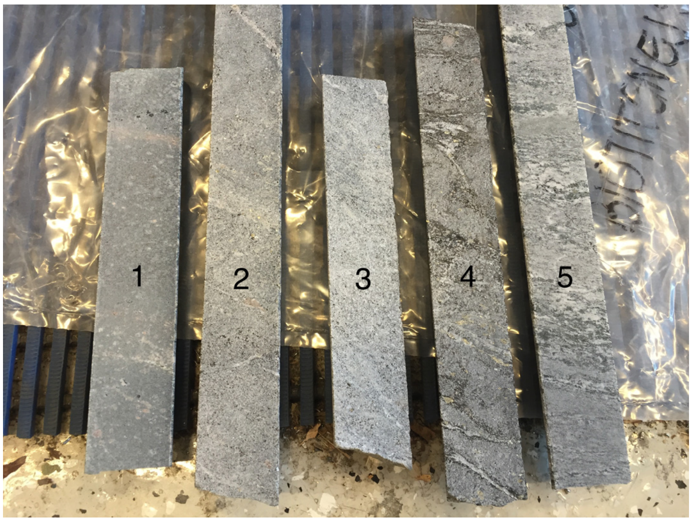



**Figure 3.5 - Drill cores from Boliden**

To analyze the rocks equally they must all roughly have the same size. The size is also important so that the samples fit the holders of the grinding and polishing machine. To get the rocks into the same shape the diamond cutter was used, see figure 3.6.

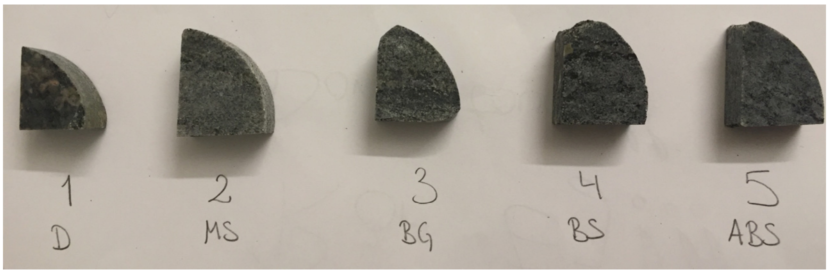



**Figure 3.6 - Samples of equal size**

To fit the holders in the grinding and polishing machine the samples had to be circular with a 30 mm diameter. To achieve a circular shape the samples were put, one by one, into the pellet machine. Due to the price difference two different types of resins were used. The reason for not only use the cheaper resin was because of the resin properties with the expensive one that contained glass fibre, which gives the samples a good hard surface. Placed on top was the expensive resin with a blue/green color, called resin 4, which is a diallyphtalate hot mounting resin with glass fibre filler for edge protection. The cheaper resin with a black color, called resin 5, is an epoxy hot mounting resin with mineral filler for best edge retention and planeness. The five rocks put into plastics can be seen in figure 3.7.

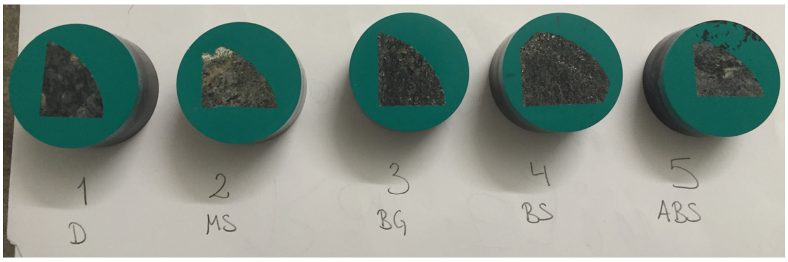



**Figure 3.7 - Rocks surrounded by plastics**

A suggested schedule of how to prepare the rocks was given from Struers. However, some modifications were made to get a better surface roughness. Between each process step the surfaces were studied in a microscope to see whether the surface roughness became better or worse. Given below is the sample process considering the time, choice of surfaces and lubricants. The different surfaces and lubricants were all ordered from Struers.

- **Grinding**
    - 8 min with SiC Foil #800 and water as lubricant, Force 20N, >>
    - 8 min with SiC Foil #1200 and water as lubricant, Force 20 N, >>
- **Polishing**
    - 10 min with a MD-Largo surface with abrasive type 9um diamond grains and DP-Blue as lubricant, Force 20 N, >>
    - 10 min with a MD-Dac surface with abrasive type 3um diamond grains and DP-Red as lubricant, Force 20 N, >>
    - 4 min with a MD-Chem surface with abrasive type 0.04um diamond grains and OP-S as lubricant, Force 10 N, ><

### 3.2.1 Special sample preparation

An exception that required extra work was the sample preparation of red gneiss. The red gneiss arrived as a rock collected directly from Sandvik’s test facility located next to Lund, see figure 3.8.

Figure 3.8 - A red gneiss rock

Compared to the other rocks that arrived as drill cores the red gneiss rock was very irregular, which made the cutting process complicated. To handle the cutting forces in the diamond cutter there must be parallel surfaces on the rock to be able to cut it due to the cutting forces. However, the irregularity made it impossible to find such surfaces. To solve the problem a drill core was cut out of the rock with a special drill. The core was then placed into a plastic tube and glued with epoxy to be in a fixed position. The plastic tube was then tightened in the diamond cutter and a small specimen was cut out. The plastic process was then the same as for the other rocks. In figure 3.9 the process steps are presented.

Figure 3.9 - Red gneiss rock, plastic tube and a pellet

## 3.3 Sample Indentation

To simplify the orientation of the samples, when looking in the microscope, red lines are drawn onto the samples. An example with Diorite is given in figure 3.10. The square was about 12 mm x 12 mm.

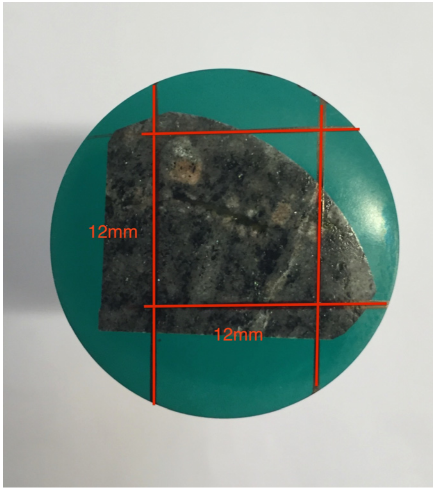



**Figure 3.10 - Sample with orientation lines**

### 3.3.1 Load

Diorite was the first rock to be examined. The results regarding load and number of indents for Diorite was crucial for the rest of the rocks because a standard method is supposed to be determined. To determine the indenter load which to be used, tests with different loads are made with knowledge that the chosen area being tested can affect the result. By visually scanning the sample in the microscope several areas with different appearance can be seen, see figure 3.11. To determine the load, lines of five indents are made and the load increases stepwise within each line. The loads being tested are 5, 10, 20, 60 and 100 mN.

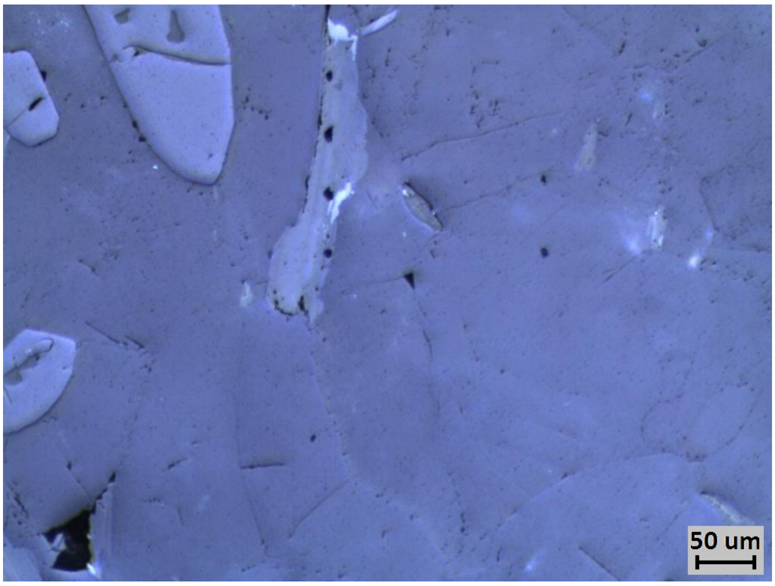



Figure 3.11 - Microscope picture

### 3.3.2 Number of indents

Two different methods are tested to determine the number of indents required to statistically represent the sample. The methods are called Large_Area and Small_Area.

- **Large_Area**
  Due to the fact that the maximum number of indents that previously have been made with the used indenter are 400 indents, the first test being conducted in this thesis was a 20x20 indents area. The distance between each indent was set to 150 um, which gives a total side length of 2850 um. The area being tested was selected randomly on each sample.

- **Small_Area**
  Another approach was to use a 10x10 indents area on four different areas, also resulting in totally 400 indents. The distance between the indents was set to 50 um, which gives a total side length of 450 um. The four areas were selected randomly to cover up a part of all the different types of appearances. A principle indent pattern can be seen in figure 3.12.

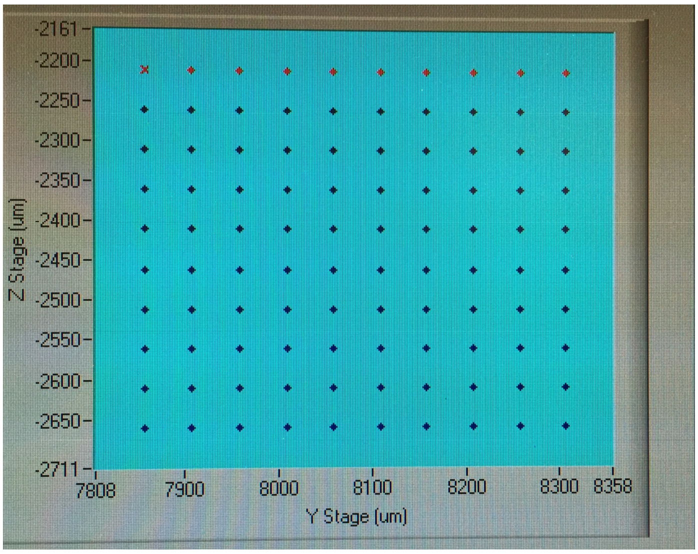



**Figure 3.12 - A 10x10 indent pattern**

# 4. Results

*In this chapter results from the indentation and the Weibull distribution are presented.*

## 4.1 Load

The load vs. depth curves from the load tests can be seen in figure 4.1. Unstable curves indicate a too low load.

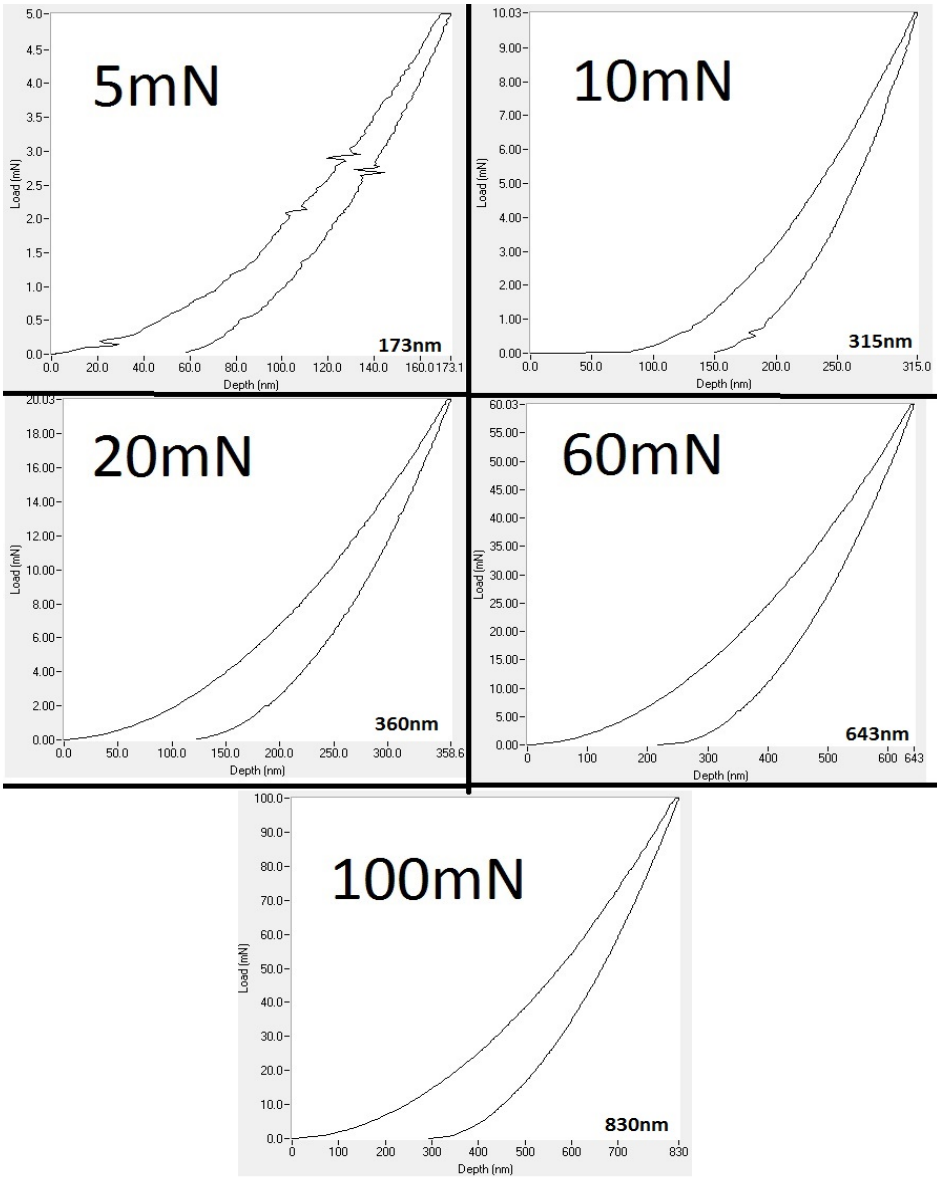



**Figure 4.1 - Load curves**

## 4.2 Investigated areas & Weibull distributions

The investigated areas on each sample are marked in figure 4.2.

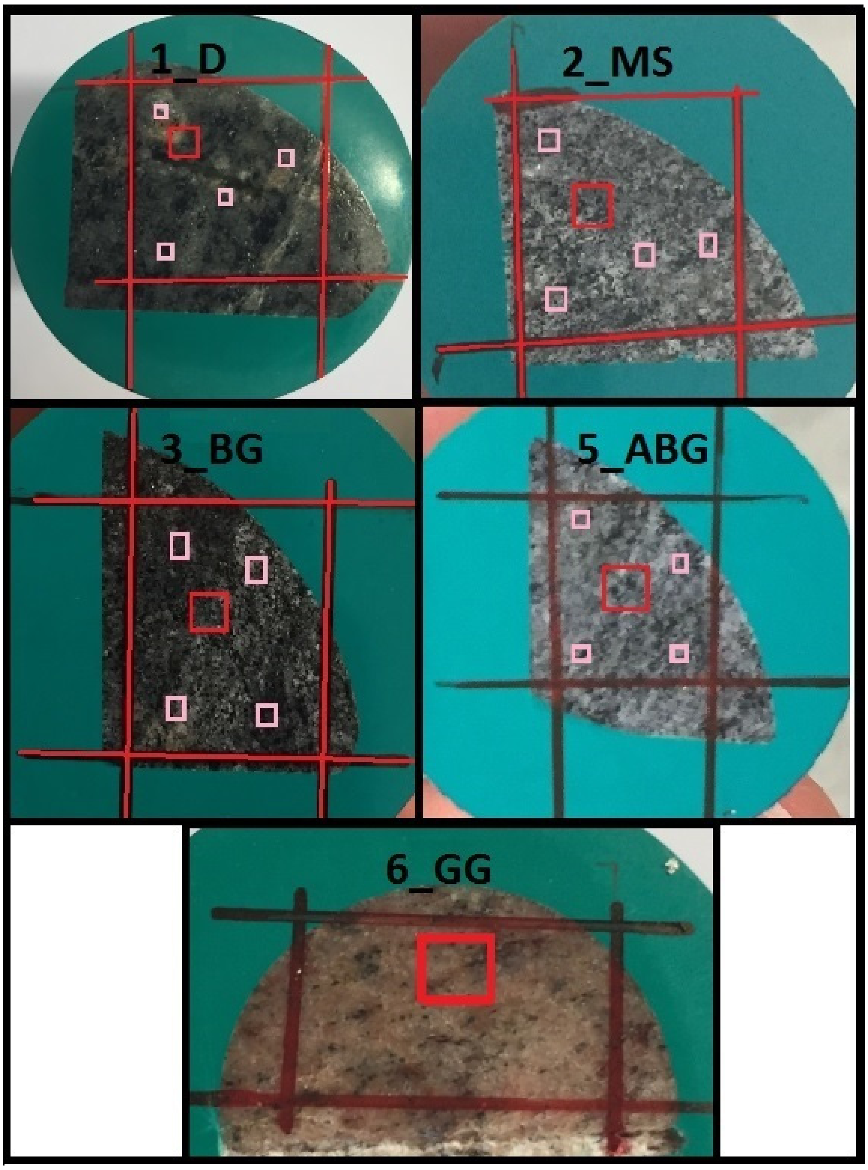



**Figure 4.2. Investigated areas**

### 4.2.1 Diorite

The probability plot (red curve) and histogram (blue dots) for both small_area and large_area for diorite can be seen in figure 4.3.

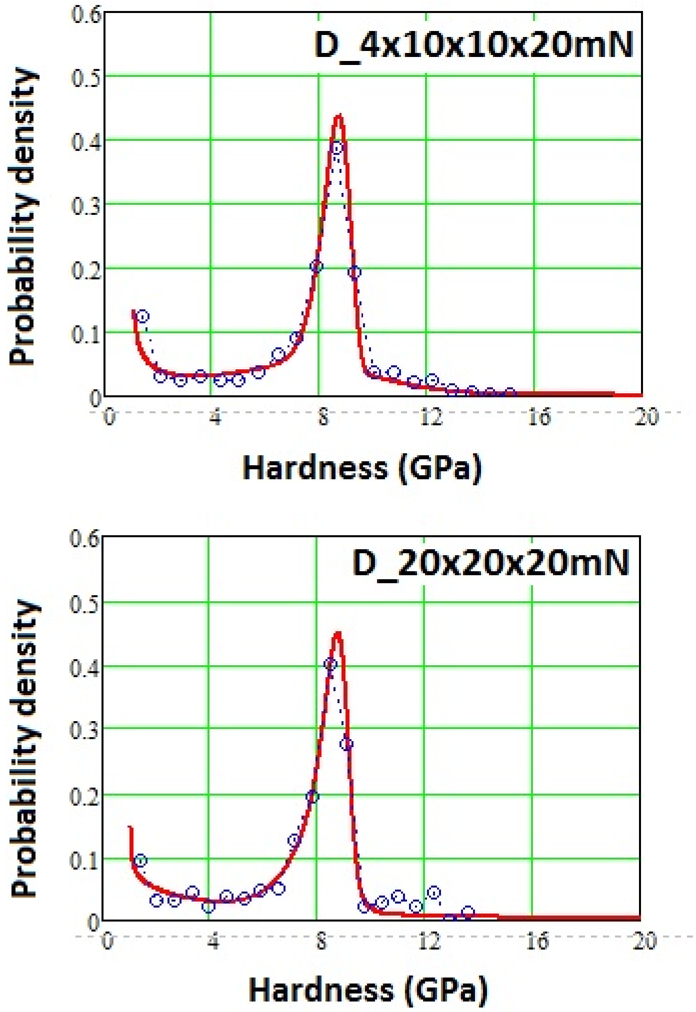



Figure 4.3 - Probability density plot and histogram

### 4.2.2 Muscovite slate

The probability plot and histogram for both small_area and large_area for muscovite slate can be seen in figure 4.4. The reason for conducting test MS_20x20x20mN_Extra is described in section 5.2.

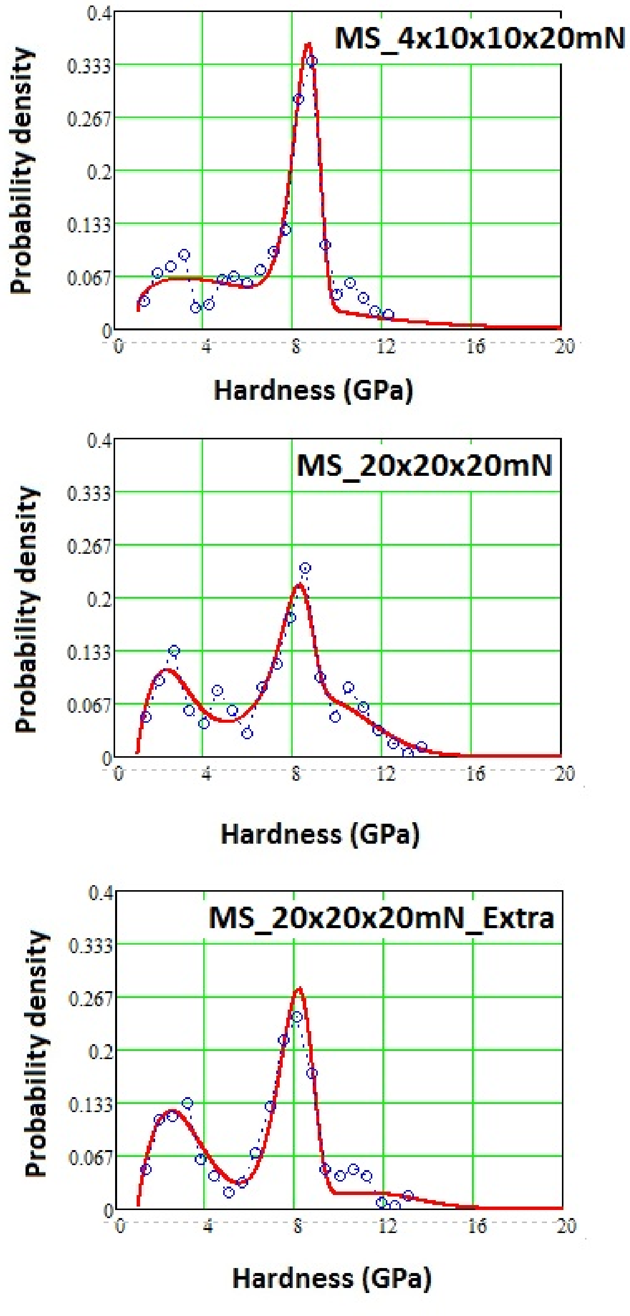
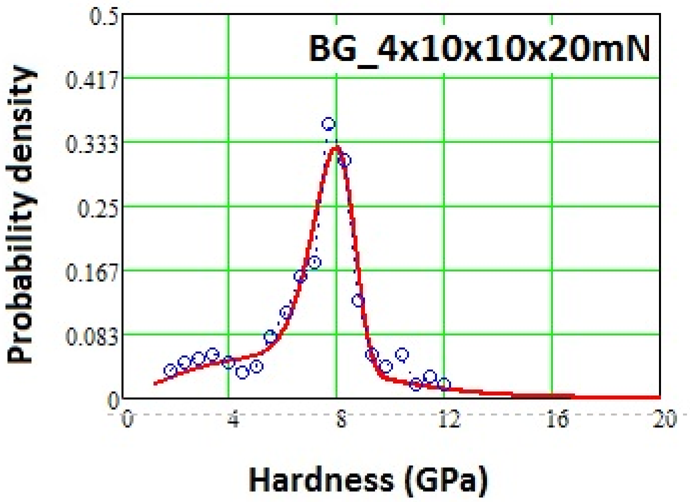



Figure 4.4 - Probability density plot and histogram

### 4.2.3 Biotite gneiss

The probability plot and histogram for both small_area and large_area for biotite gneiss can be seen in figure 4.5.



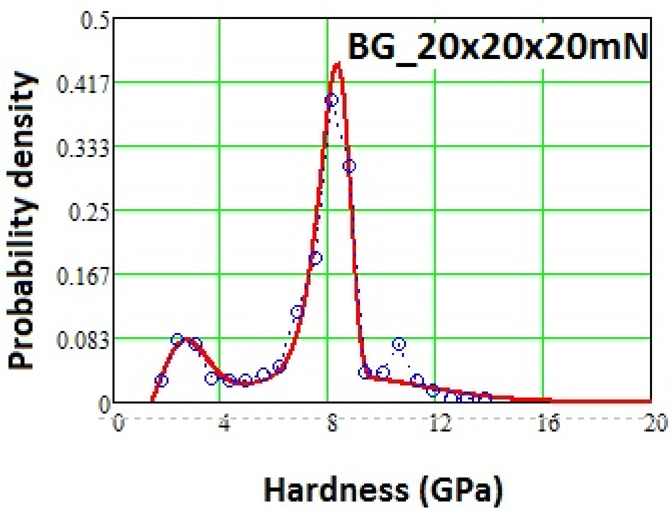




Figure 4.5 - Probability density plot and histogram

### 4.2.4 Biotite slate

No results. See section 5.3.2.

### 4.2.5 Amphibole biotite gneiss

The probability plot and histogram for both small_area and large_area for amphibole biotite gneiss can be seen in figure 4.6.

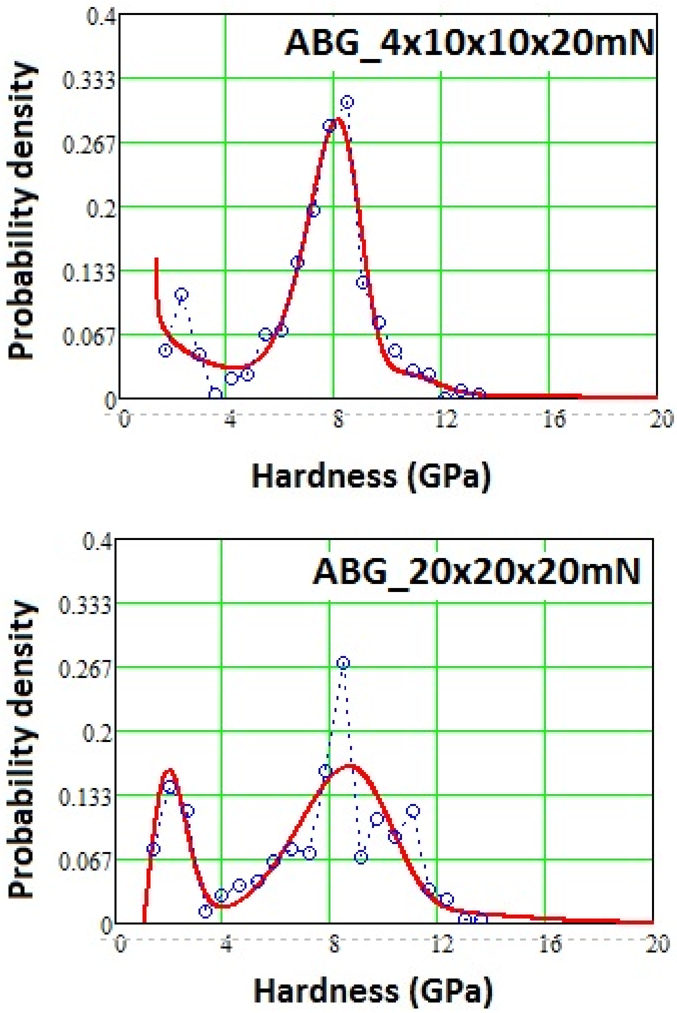



Figure 4.6 - Probability density plot and histogram

### 4.2.6 Red gneiss

The probability plot and histogram for both small_area and large_area for red gneiss can be seen in figure 4.7. The reason for only having large_area is described in section 5.2.

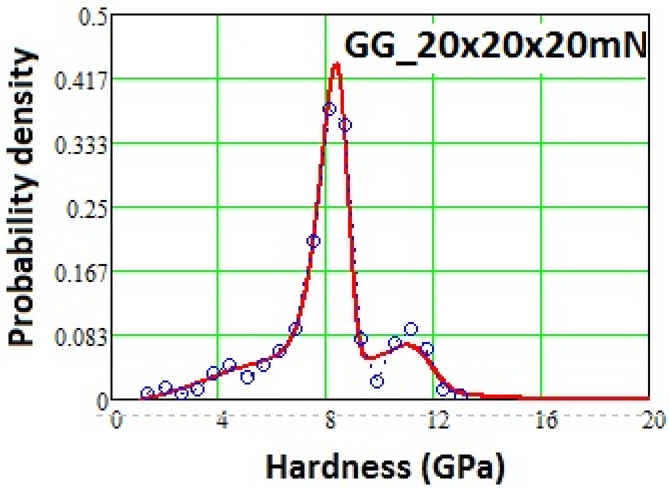



Figure 4.7 - Probability density plot and histogram

# 5. Analysis and discussion

*In this chapter the load, number of indents, statistical results and errors are analyzed and discussed.*

## 5.1 Load

After performing the load tests with different choice of load in the range of 5 mN-100 mN, analysis curves with load vs. depth were given. As can be seen in figure 4.1 in chapter 4 the load curves were not stable when using a load below 20 mN, meaning that the load has to be at least 20 mN. The result curves when using the load 20 mN-100 mN were all good, but the differences in depth were large, between 360 nm-830 nm. With these factors in mind the decision was to use 20 mN to avoid affecting a too large surrounding area of the indent. The fact that the diamond Berkovich tip penetrates 360 nm with 20 mN and 830 nm with 100 mN has a big impact on the projected area on the sample. A larger projected area requires a larger distance between the indents and the process when using 100 mN is therefore more time consuming compared to 20 mN.

## 5.2 Number of indents

To analyze the results a statistical model created by Professor Jan-Eric Ståhl was used. The model consists of three Weibull distributions with Alfas and Betas that were adapted in each analysis to get reliable results with small errors. Two analyzes were made on each rock to compare the results from 4x10x10 indents and 20x20 indents. All results had an error less than 4 %, which is within the limit. For most of the rocks the results were unambiguously regardless the choice of method, small_area or large_area. However, the choice to use large_area is seen as better because it covers a larger area and do not risk to only do tests on one phase, which can occur with small_area. Totally the small_area covers 1.8 mm x 1.8 mm and the large_area covers an area of 2.85 mm x 2.85 mm. Due to the fact that red gneiss came late in this project, an exception during the tests was made. The red gneiss was only investigated with the large_area method due to lack of time because the nanoindenter were used in other projects as well.

When analyzing the results it was shown that Muscovite slate had different results depending on the choice of method. Therefore an extra test was made with a large_area indent pattern. The results from the extra test proved that the first 20x20 result was correct and therefore no further extra tests were made on the other rocks.

The total indentation time for each 10x10 indent pattern was around 9 hours, resulting in totally 36 hours. For the 20x20 indent pattern the retractions distance for the diamond Berkovich indenter was increased in case of large differences in height and also the distance between each indent was increased. The total time for the large_area was around 46 hours.

To get a better understanding of how the surfaces looks, pictures are presented on some of the investigated small_area. The reason for showing small_area is that the microscope could not take just one single picture of the large_area. Photos on respective rock can be seen in appendix A, all with 10x magnification.

## 5.3 Errors

### 5.3.1 Sensitivity

During the analysis of the tests some errors were found in the results. The reason for having errors was that the rocks had some pores in their structure. When the diamond Berkovich tip went down into a pore the registered result became wrong and a possible explanation might be that it was because of the sides of the tip that touched the rock before the tip it self reached the bottom. The sample of muscovite slate had a big pore that resulted in several errors, see figure 5.1.

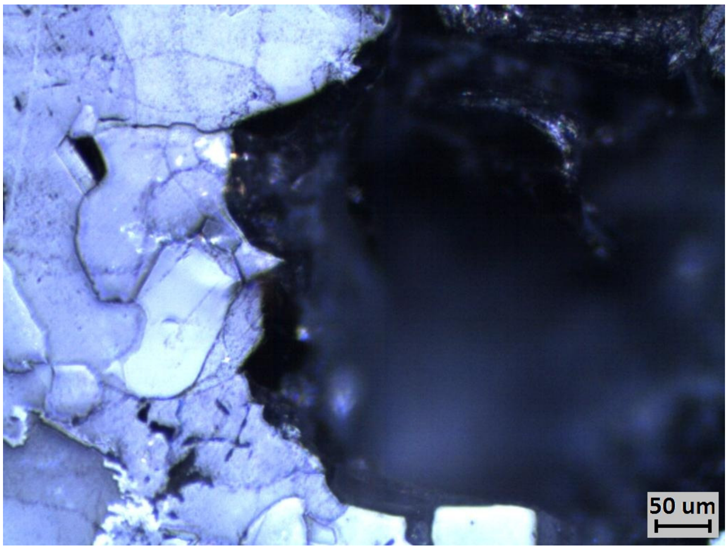



**Figure 5.1 - A big pore in muscovite slate**

To eliminate the errors all indents were sorted by size and the hardness measurements below 1 GPa and above 14 GPa were seen as incorrect and were deleted. The reason for using the range 1 GPa – 14 GPa was because of single indents was made and there were no surface hardness measurements below 1 GPa or above 14 GPa. The total numbers of indents that were within the range for each sample are given in table 5.1.

Table 5.1 - Number of analyzed indents

| | OK | Error |
|---|---|---|
| **D** | 400 | 0 % |
| **MS** | 368 | 8 % |
| **BG** | 392 | 2 % |
| **BS** | - | - |
| **ABG** | 385 | 4 % |
| **GG** | 399 | 0 % |

The indentation method can be seen as relatively stable when studying the low percentage of errors. However, in the beginning of the test process all test preparation in the indenter was made during the days and the tests were performed during the nights and weekends. The reason is that the indenter can be sensitive to other noises such as doors slamming and vibrations from other machines. However, due to the need of the indenter equipment for other purposes the last tests were performed no matter the time of the day. Still this does not seem to have affected the results because the red gneiss was the last sample and only one single indent was an error. To be almost completely sure that nothing affects the results recommendations are that the equipment should be placed in the basement away from other machines.

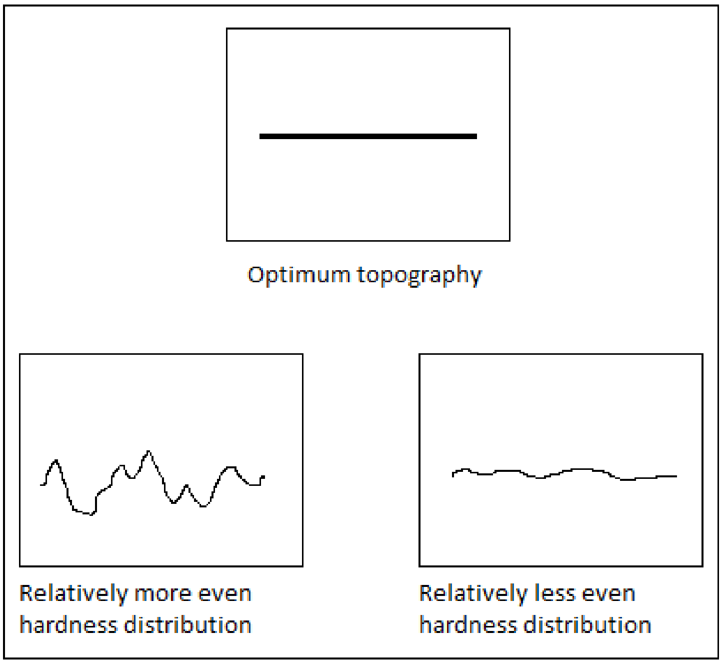
### 5.3.2 Biotite slate

Biotite slate was the only rock that could not be prepared properly. When using the diamond cutter there were nozzles that cooled the cutting blade with water. The water was also in contact with the rocks, but biotite slate was the only rock that became very porous during the cutting process, almost like coarse sand. Still it was possible to cut the BS into smaller pieces and surround it with plastics. However, the grinding and polishing processes were impossible to perform because the sample came into contact with water and large flakes fell off. This lead to enormous pores and it would have been a risk for the expensive equipment to try to put it in the indenter.

## 5.4 Expected wear

In the mining industry processed rocks contains both soft and hard phases, which leads to abrasive wear. A possible theory might be that it is mainly the soft phase that is being torn off and the hard phase remains and creates peaks on the surface of the rock. It is the peaks that lead to most wear on the wear parts. As can be seen in this thesis the results show that the rocks consist of different surface hardness. The theory is that it is the range of hardness within a rock that decides how much tool wear there will be. A more even surface on the rock will lead to a more even surface on the tool as well. To explain the theory better an example is given.

Example:
Rock A consists of 100% 12 GPa and rock B consists of 50% 3 GPa and 50% 12 GPa. Initially the idea is that rock A results in most wear because it contains more hard particles than rock B. However, according to the possible theory rock B should lead to most wear because the soft phase is torn off and the hard phase remains as sharp peaks. A surface pattern with high peaks and deep pores occur. For rock A there is no soft phase to be torn off easily, which means that the wear will be more even and the surface will therefore be more even with lower peaks and not as deep pores as for rock B. Figure Ex.1 shows the expected topography of rocks with different hardness distributions.




**Ex.1 – Expected topography**

As can be seen in chapter 4 the probability plot and histogram are given for each sample. For some of the rocks there are some smaller differences between small_area and large_area. The risk by doing small_area is that the examined area might only consist of one surface hardness phase due to its small size. The large_area gives a more representative result for the surface hardness distribution because it covers a larger area and it is less likely that the indenter only hit the same hardness phase in each indent. By only analyzing the large_area further it can be seen that some of the plots and the corresponding histogram might not always look the same. To simplify the results and be able to put the rocks into a wear table, the distribution of surface hardness is divided into four ranges. The ranges are 1-4 GPa, 4-7 GPa, 7-10 GPa and 10-14 GPa. In figure 5.2 a comparison with all of the rocks is visualized. The individual analyzes with the corresponding percentage of each range can be seen in appendix B.

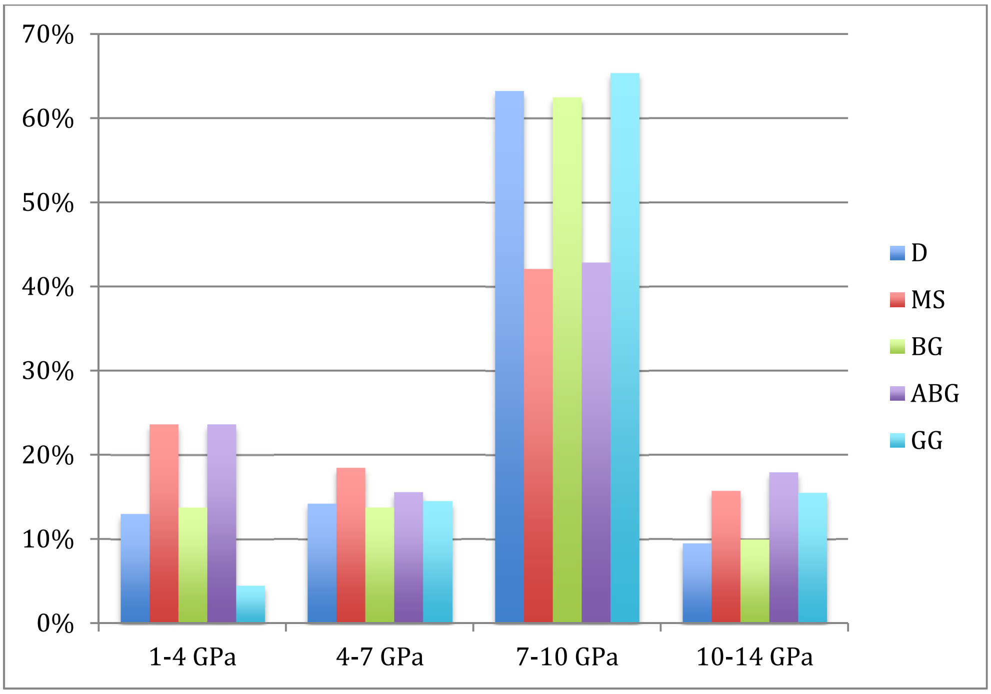



**Figure 5.2 - Comparison of hardness distribution**

The analyze shows that MS and ABG are similar in their hardness distribution. There is difference between MS and ABG in the hardest range 10-14 GPa. If their soft phases are torn off slightly the same it is possible that there will be more hard peaks in ABG, which also leads to more wear on the tool when crushing ABG than MS. When crushing the ABG it will therefore be a higher cost per ton due to the maintenance costs. Because of the relatively same distribution between each range for ABG and MS, respectively, they will have a larger wear effect compared to the rest of the rocks.

From the same analysis similarities are shown between D, BG and GG. D and BG very much look the same and no further separation between them can be made without performing further tests as in part II. However, the comparison with GG indicates that GG have a smaller amount of the softest phase, but higher amount of the hardest phase. There is a bigger possibility to find hard peaks in GG than D or BG and this will lead to more wear.

After analyzing the results the predicted wear are presented in table 5.2. The rocks with least wear are presented first and most wear are presented last.

**Tables 5.2 - Expected wear**

| | |
|---|---|
| **Least wear** | • Diorite<br>• Biotite gneiss |
| | • Red gneiss |
| | • Muscovite slate |
| **Most wear** | • Amphibole biotite gneiss |

# 6. Conclusions

*In this chapter conclusions and suggestions for further work are presented.*

## 6.1 Recommendations

Without performing part II of this project it cannot be confirmed that nanoindenter is the most appropriate method to use. However, the results were all good for the rocks that could be indented and is seems that even if the surface looks porous in the microscope it is possible to use the indenter.

The nanoindenter equipment is expensive due to its complexity and there is no major economic benefit by investing in similar equipment at Sandvik. Instead a closer relationship between the company and Lund University should be established to perform the tests. A closer relationship is beneficial for both parties since Sandvik does not have to make large investments and for the university that receives additional industrial project for both students and faculty.

Special recommendations for Sandvik are to invest in equipment that can cut out a drill core from a small rock and also conduct their abrasion index (AI) test with the involved rocks. The core equipment will ease the process due to the fact that no advanced equipment is needed on site to cut out cores, instead single portable rocks can be taken into the lab.

## 6.2 Conclusions

- The body size of the rock is not allowed to exceed a 25 mm diameter. It has to fit the pellet machine and the plastics surrounding the rock must be able to bond all around. The shape has no influence of the results, meaning that the sample can for example be a square, triangle or circle.

- A load of 20 mN has proved to be good enough to get a stable *load vs. depth* curve while the depth is minimized to not affect a too large area.

- A suitable method of how to prepare the samples has been presented in the methodology. The total time to examine one sample with 400 indents in a 2.85 mm x 2.85 mm area is around 46 hours. The test can be performed around the clock as long as no nearby machines that create major vibrations are planned to be run at the same time as the test process itself.

- According to the results from the indenter tests, the wear is expected to be greatest when crushing amphibole biotite gneiss and least when crushing diorite.

- If part II confirms the results of this thesis a huge advantage to predict the wear on the wear parts can be established. Rocks from all over the world, where mines are planned, can be collected and examined. The results can help the designers to predict the wear on the wear parts more correctly, by knowing the rock wear, and the right type of manganese steel can be used. Ultimately a reduced tool wear results in cost savings for the buyer and Sandvik gets a reputation that their products have low maintenance.

## 6.3 Suggestions for further work

A new methodology has to be developed to standardize the tests with rocks in the Tribotester in Lund. Plates have to be made of different types of manganese steel that is used in the crushing chamber. An important factor is that the manganese plates have to fit the Tribotester at Lund University to be able to conduct the tests. Sandvik have some plates already made up, but they have to be cut into the right size to fit the machine. Maybe some other technique has to be tested to cut the cores due to the problems with biotite slate.

The pressure in the Tribotester is a major factor in the test process. It is important to use the right pressure when conducting the tests and a suggestion to use three different pressures might be good enough. The three pressures that should be tested are the minimum, median and maximum value of the pressure in the crushing chamber, which should be known by experts at Sandvik.

In some way the drill cores from Boliden have to be cut into smaller and uniform pieces so that the results can be compared between the rocks. In the Tribotester the sizes of the rocks are crucial that they are almost exactly the same. The reason is because of the contact surface between the manganese steel and the rock has to be the same for each rock. It is in the contact area that the wear is created. This has to be done to confirm the nanoindenter tests.

Another proposal that also can be tested is to randomly place the rocks in the Tribotester. This will lead to different contact areas and it is possible to test each of the rocks several times. A random test is a more realistic test because during the crushing process in the mines the rocks are randomly placed in the crushing chamber.

It might also be interesting to study the heat generation with a heat camera in the contact area to see if it has influence on the wear. Maybe the contact area on the manganese steel changes its structure during the tests due to the heat.

It might be possible for Sandvik to try different types of rocks in their test facility in Dalby. Results can then show if the rocks have different wear effect on the manganese steel. The rocks can then be cut into smaller pieces and put into the nanoindenter. The only problem with this approach is that it requires 1000 kg of each rock type for Sandvik to test it. This makes it a more costly project if Sandvik wants to test for example 10 rocks.

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# Appendices

## Appendix A

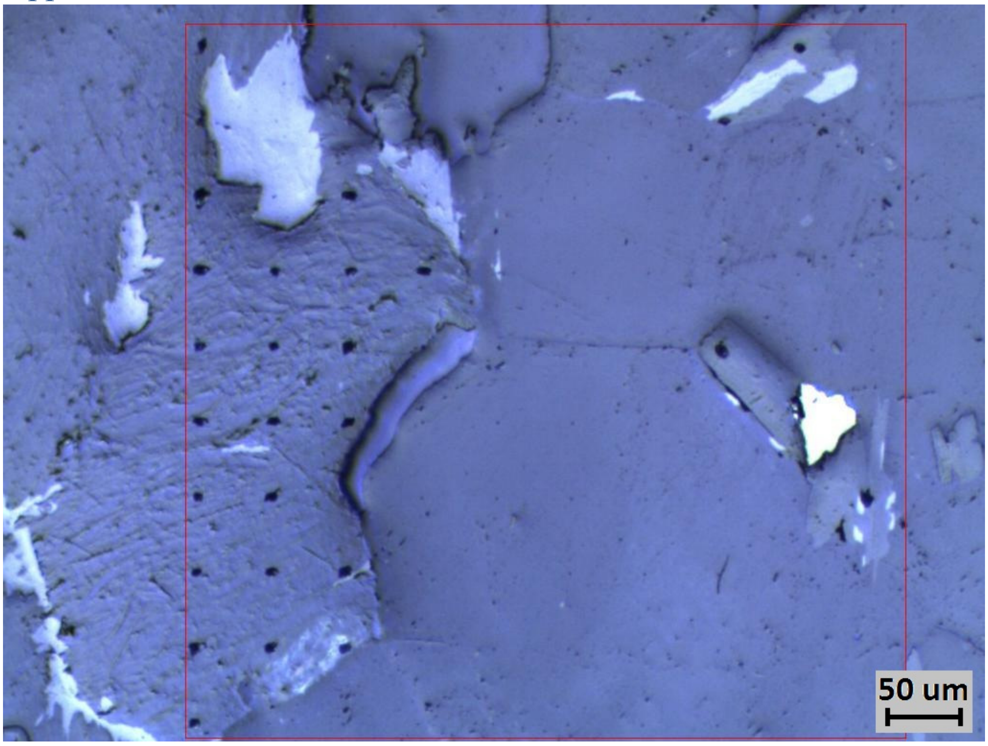


**Figure A.1 - Microscope picture of diorite**

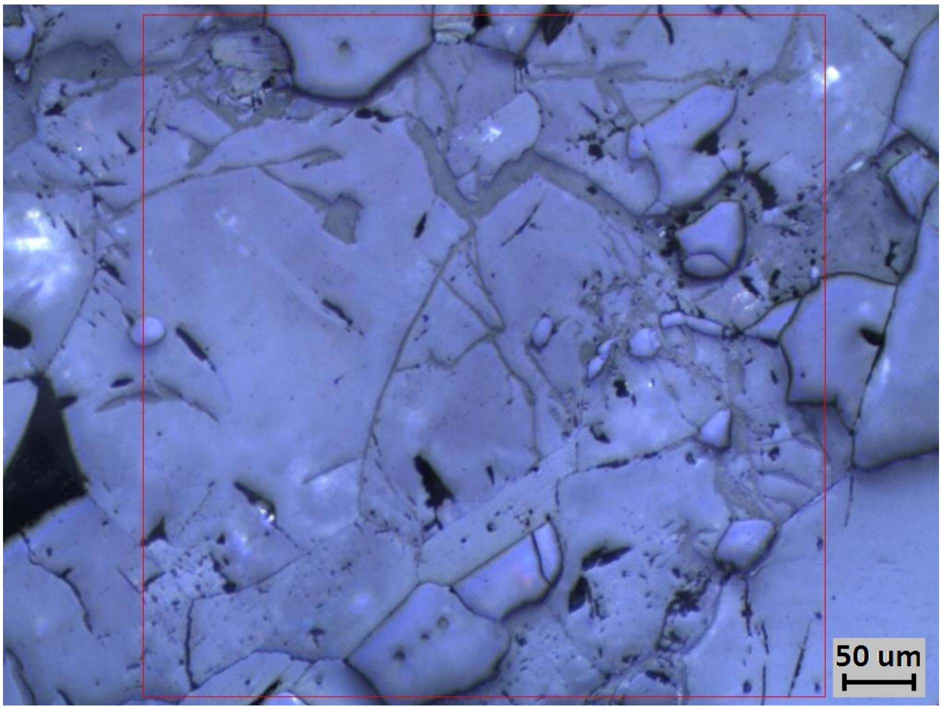


Figure A.2 - Microscope picture of muscovite slate

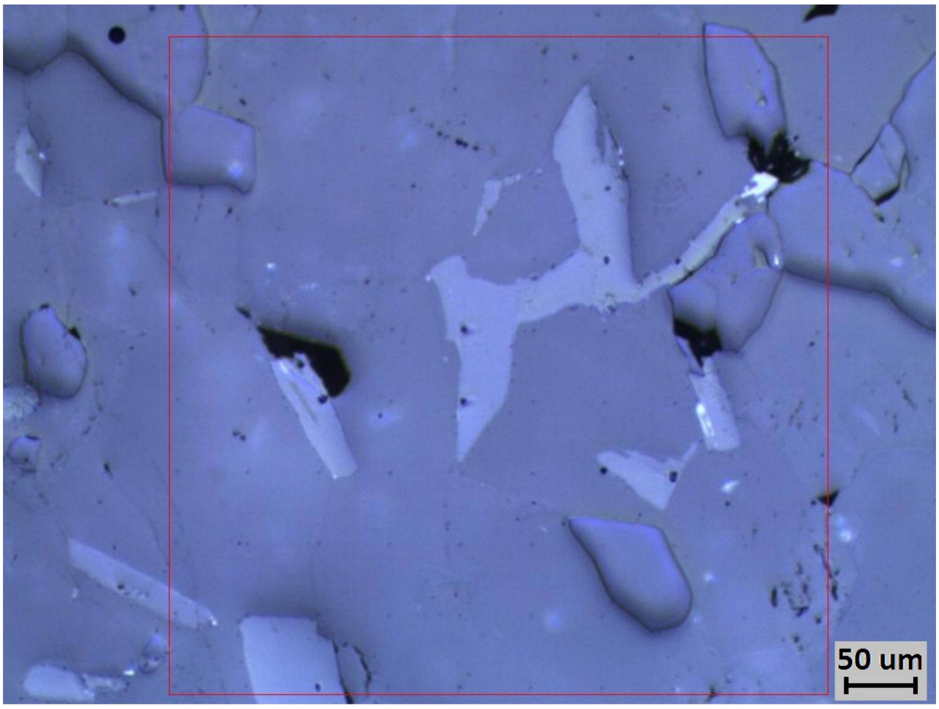


Figure A.3 - Microscope picture of biotite gneiss

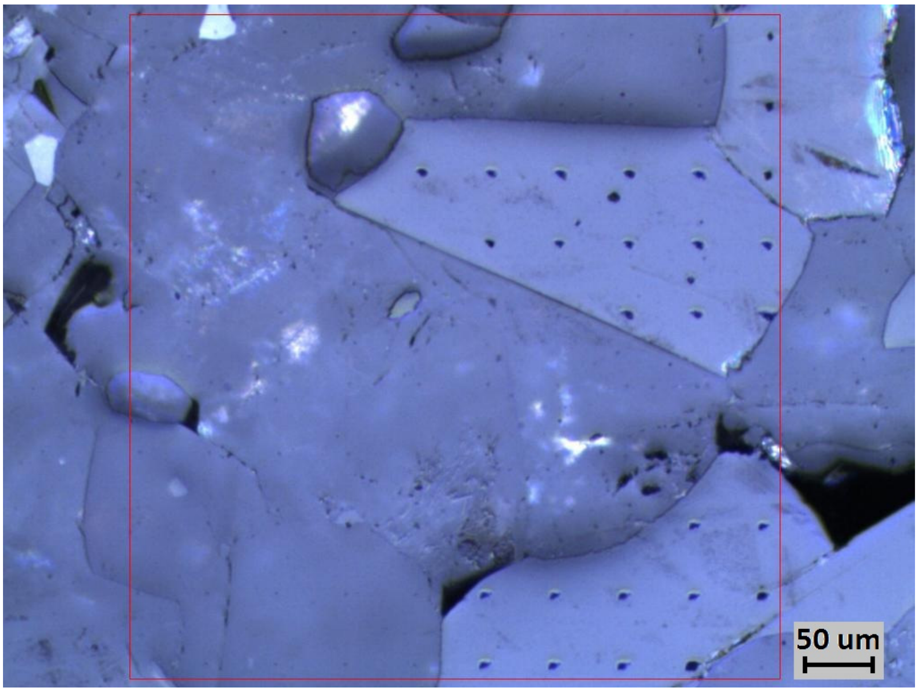


Figure A.4 - Microscope picture of amphibole biotite gneiss

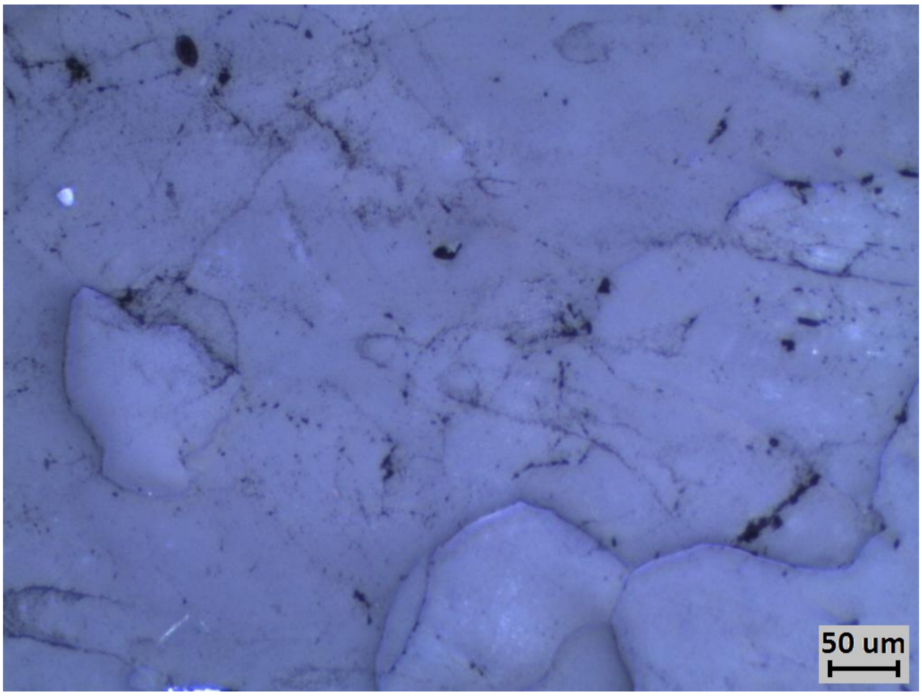


Figure A.5 - Microscope picture of red gneiss

## Appendix B

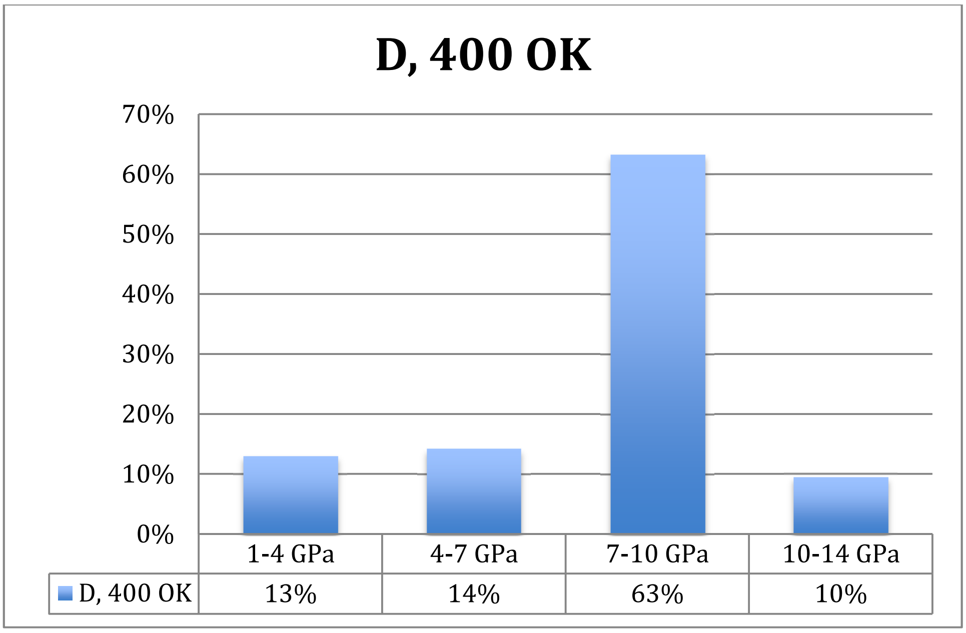


Figure B.1 - Hardness distribution in four ranges of D

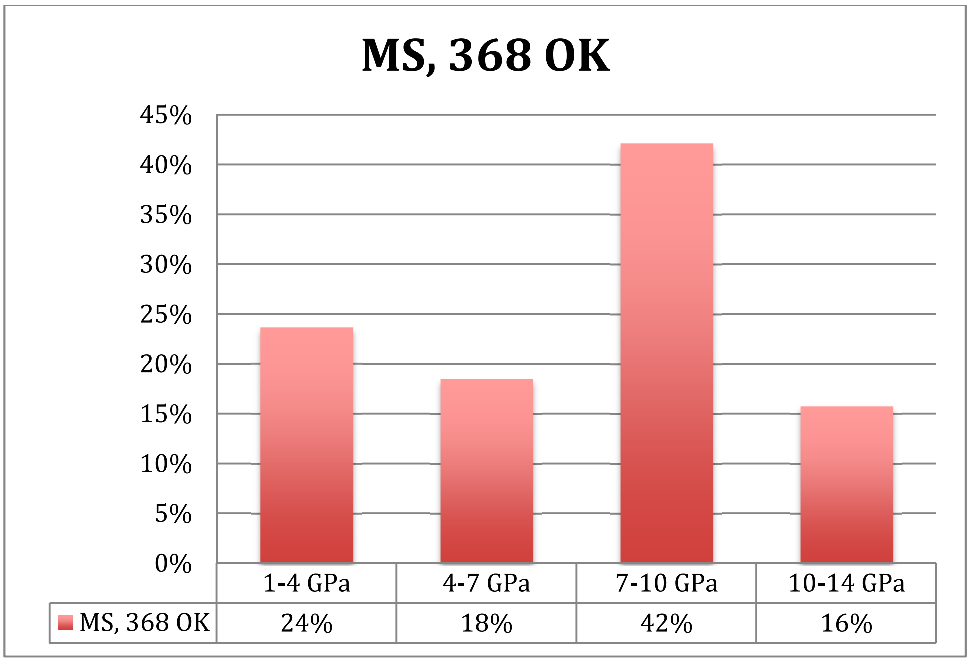


Figure B.2 - Hardness distribution in four ranges of MS

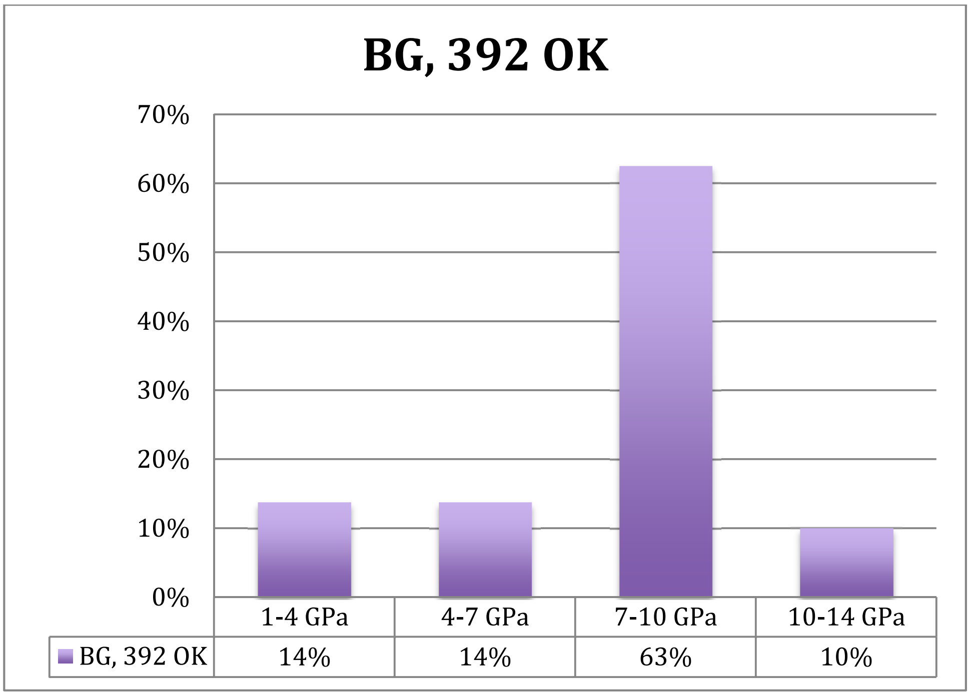


Figure B.3 - Hardness distribution in four ranges of BG

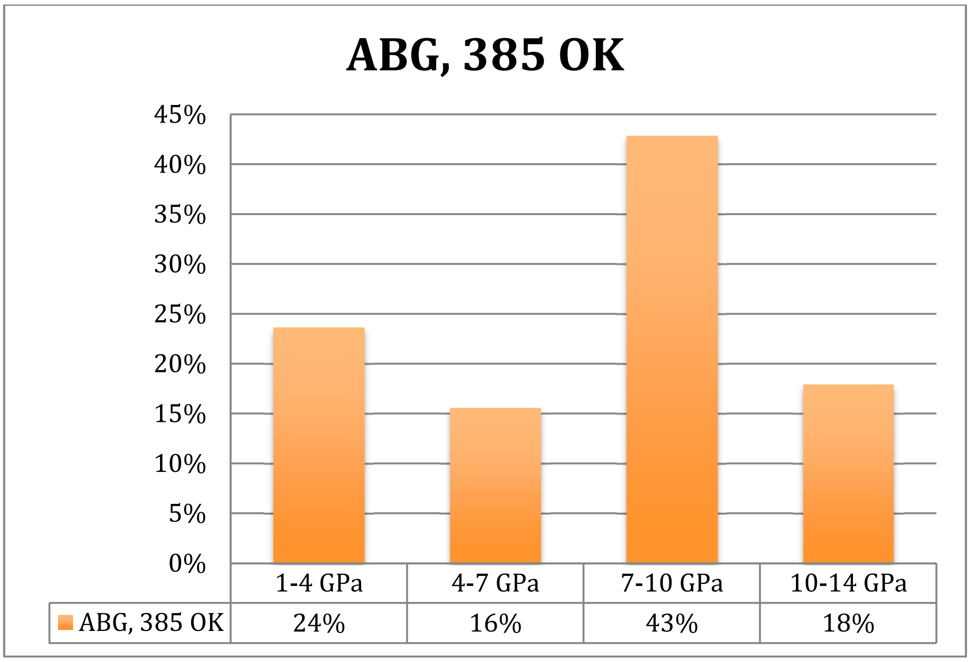


Figure B.4 - Hardness distribution in four ranges of ABG

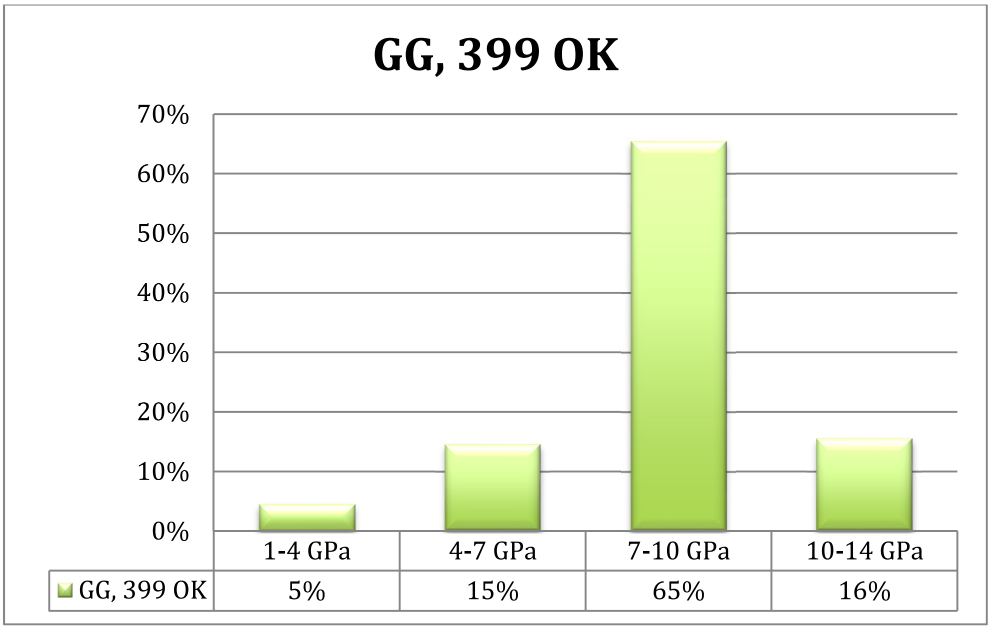


Figure B.5 - Hardness distribution in four ranges of GG