

**NUMERICAL ANALYSIS
AND EXPERIMENTAL ASSESSMENT
OF IMPACT WEAR RESISTANT COATINGS:
ELECTRODE, NYLON, PC-ABS AND POLYURETHANE**

OTÁVIO ALMEIDA GOMES PEREIRA

**DISSERTAÇÃO DE MESTRADO EM ENGENHARIA MECÂNICA
DEPARTAMENTO DE ENGENHARIA MECÂNICA**

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RESUMO

Devido a necessidade de aumentar a eficiência de produção, máquinas são submetidas a condições de trabalho cada vez mais severas. Com isso, observa-se cada vez mais o desgaste prematuro de componentes mecânicos, diminuição de sua vida útil e aumento de custos com manutenção. Uma das formas de se prolongar a vida útil de componentes é a utilização de proteções superficiais como por exemplo os eletrodos, polímeros, compósitos e arame tubular.

Este trabalho apresenta um modelo numérico tridimensional para análise de compressão estática em configuração esfera-plano. O comportamento mecânico dos sólidos é modelado segundo o critério de von Mises. São estudados dois materiais de base (aço SAE 1045 e SAE 1020) e quatro revestimentos (Eletrodo Duro, Nylon, PC-ABS e Poliuretano). Testes experimentais são realizados em espécimes com o revestimento eletrodo duro com a finalidade de obter informação adicional sobre suas propriedades mecânicas. Já para o Nylon, PC-ABS e Poliuretano são utilizadas informações obtidas da literatura.

O objetivo deste trabalho é avaliar o comportamento de materiais revestidos submetidos a cargas compressivas severas (2kN). São analisadas a tensão equivalente de von Mises, a deformação plástica equivalente e a profundidade de indentação.

Resultados demonstram que o uso de revestimento pode levar a um aumento significativo da resistência à compressão. Porém, para a escolha do revestimento faz-se necessário avaliar as condições de trabalho. Recomenda-se o uso de eletrodo para cargas maiores que 1kN e o uso dos polímeros para aplicações em que se tem cargas compressivas menores que 500N.

ABSTRACT

Due to the need to increase production efficiency, machines are being subjected to severe work conditions. This leads to an increase of the premature wear of mechanical components, decrease in their mechanical life and an increase in maintenance costs. To extend the life of mechanical components, protection coatings such as electrodes, polymers, composites and tubular wire can be employed.

This work presents a three-dimensional numerical model for sphere-on-plane static compression analysis. Solid mechanical behavior is modeled following the von Mises criterion. Two base materials (SAE 1045 and SAE 1020) and four coatings (Electrode, Nylon, PC-ABS e Polyurethane) are studied. Experimental tests are performed on specimens coated with hard electrode, in order to obtain information on the mechanical properties of this coating. The properties of Nylon, PC-ABS and Polyurethane, are retrieved from the literature.

The objective of this work is to evaluate the behavior of coated materials when subjected to a severe compressive load (2kN). Analyses of equivalent von Mises stress, equivalent plastic deformation and indentation depth are provided.

Results show that the use of coatings can lead to a significant increase in the compression strength. However, the choice of coating must take the workloads into consideration. It is recommended the use electrodes for compressive loads higher than 1kN and the use of polymers for compressive loads lower than 500N.

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Chapter 1

Introduction

This introductory chapter contextualizes the subject of this dissertation: impact wear and ways to minimize damage. In addition, brief general considerations are made about the type of commercial applications that use coatings for surface protection. Finally, the objectives and text structure are presented.

1.1 Motivation and the State of the Art

The use of protective surface coatings have been increasing in various sectors of the industry. For instance, in the sugar and alcohol factories, mechanisms such as chopping knives suffer failure due to wear and tear that represent a significant cost in the operations of sugar mills and alcohol distilleries. Moreover, a reduction in production capacity often occurs due to stops for corrective maintenance [1]. Machines responsible for the maintenance of grassy areas, such as the mower coupled tractors, often experience failure due impact of rock particles with different geometries and weights [2]. However, new types of coatings, welding techniques and consumables (electrodes) are being developed to mitigate this problem. The application of coatings aims to reduce wear, cost and seek to increase the service life of mechanical components, allowing an increase in process efficiency [3].

Therefore, it is extremely important to carry out studies to evaluate the behavior of different surface coatings to protect equipment against premature wear and tear. Figure 1.1 presents some examples of the use of coatings to protect surfaces, in which a) it consists of threads with electrode coating, (b) it consists of a wheel with protective paint and (c) they are FPS with its region of greatest wear coated.



(a)



(b)



(c)

Figure 1.1: Examples of use of coatings
[4][5].

1.2 Research Goals

The general objective of this work is to evaluate the behavior of surface coatings: Hard electrode, Nylon, PC-ABS and Polyurethane, when subjected to compressive load of 2000N. Moreover, benefits and costs of each solution are also analysed to relate their applicability in different scenarios.

The specific goals are:

- Implement a numerical model for static compression analysis using the Abaqus 6.14 software.
- Simulate the indentation process of the following material configurations: uncoated steel (1020 and 1045) and steel coated with Hard Electrode, Nylon, PC-ABS or Polyurethane.

- Obtain the results of equivalent von Mises, equivalent plastic deformation and indentation depth.
- Compare and analyze the results obtained for the different configurations.
- Identify if there will be gains with the use of surface coatings and what level of compressive load is indicated for their use.
- Evaluate whether the coatings studied in this work can be used for the purpose of surface protection.

1.3 Outline

This work is structured in five chapters as follows:

Chapter 2 presents the review of the most relevant concepts that are related to this study in general and is divided into three sections. Surface coatings: Initially it is presented in a generic way on surface coatings. In the sequence, information on the hard electrode, Nylon, PC-ABS and Polyurethane is briefly presented. Contact Mechanics: This section presents a review of Hertz's theory focusing on the plane-sphere solution.

Chapter 3 presents the methodology for carrying out hardness and tensile tests to obtain information on the mechanical properties of the hard electrode, to be used in the computational model. Finally, the model developed in the Abaqus 6.14 software is presented.

Chapter 4 presents the results obtained from related computer simulations, such as von Mises stress, equivalent plastic deformation and indentation depth followed by discussion and comparison.

Chapter 5 presents a summary of the most relevant conclusions obtained in this work and a recommendation for future work.

Chapter 2

Theoretical Review

The chapter 2 accost about of the surface coatings in this work, the application methods, the mechanical properties of such coatings and some practical applications. Beyond this, the main types of wear are presented, their characteristics and influencing factors. Finally, a review is made on the mechanics of contact.

2.1 Surface Coatings

In the modern industrialized world, the need arose to reduce and control the wear and tear of equipment, with the purpose of extending the useful life of machines and equipment, making them more efficient operationally and reducing their maintenance cost. In order to protect surfaces from wear and other design factors, coating and treatment methods are being developed.

Coating is a layer of material, formed naturally or applied artificially on the surface of a given object, with the objective of obtaining the desired mechanical or technical properties [6]. Currently hard coatings such as titanium nitrite, titanium carbide and aluminum oxide are used in cutting tools, in order to increase their durability. Other coatings such as solid surface films are used and effective [7].

The depositions of the coatings can be: multicomponent, multilayer, gradient layers and surfaces treated in front and back with various combinations of materials [3]. There have been countless attempts to define a procedure for selecting surface coatings a long time ago, but a solution has not yet been reached. Companies still in a simple process, choose, test and meet demand is used. As a result, there is a major economic impact related to wear and tear on various components, machines and equipment.

Estimated that the cost in the USA is in the range of 100 billion dollars related to wear. Adequate coatings and selection procedures result in lower costs and increased operational efficiency and useful life. In the following topics, the coatings adopted in this work are presented: Electrode (Hard coating) and Polymers (PC-ABS, Polyurethane and Nylon) [8].

2.1.1 Electrode: Hard Coating

The use of coatings in several operations is defined by the deposition of metal on a base metal, with the objective of improving the properties for a service condition [9]. One of the surface coatings adopted in this study is the hard coating, applied by welding and will be more detailed below, however, several types of coatings are used according to the properties that are desired for a given service, such as [10]:

- Hard coating: Increase wear resistance;
- Cladding of stainless steels: Increase protection against corrosion;
- Build-up coating: Restore the original dimensions of the part;
- Battering: Application of one or more welding passes.

There are several techniques for the application of hard coating, highlighting fusion welding using processes of Oxyacetylene, Coated Electrode, MIG / MAG, Submerged Arc and Tubular Wires [9]. Most of the alloys to resist wear are produced by consumables deposited by welding and used in critical situations. The hardness range of these coatings is between 40 and 60 HRC [10]. Hard coating is a process of obtaining properties or dimensions from the application of a layer of metal on a surface or base metal, leaving it highly resistant to wear [11].

Hard coating is like an alloy deposited by a welding process on the surface of a material that needs to increase or improve properties such as hardness, wear resistance without losing ductility and toughness of the protected surface [12]. Doesn't have a classification that has all the alloys used for hard coating, however, there are some classifications of these coatings that are based on the chemical composition of the deposited addition metal without any dilution, divided into five classes [13]:

- Class 1: Low and medium alloy steels with 2 to 12% alloy elements;
- Class 2: High alloy steels, including high speed steels and manganese steels;
- Class 3: Iron-based alloys with 25 to 50% alloy elements;
- Class 4: Cobalt, nickel and nickel-chromium alloys;
- Class 5: Tungsten carbide alloys (38 to 60%) in ductile matrix.

Four groups classify the coating alloys. Are they [14]:

- Iron-based alloys with less than 20% alloying element;
- Iron-based alloys with more than 20% of alloying element;
- Nickel and / or cobalt based alloys;
- Tungsten carbide alloys.

States that to choose a hard coating, you must take into account weldability, metallurgical compatibility and costs. Iron-based coatings are popular due to their low cost and ease of application [15]. The application of this hard coating has increased in recent years in the industry and in equipment that suffers excessive wear, as we can see in Figure 2.1, where

(a) (b) and (c) are hammers, crushers and disks that were coated with hard electrode in their region of greatest wear.



(a) Hammers.



(b) Crushers.



(c) Crusher discs.

Figure 2.1: Hard coating application.

[4]

The application of this hard coating must follow 5 steps in order to have a greater efficiency against wear: [4]

1. Surface preparation: Impurities such as oils, paint and oxidized regions need to be removed. If there are regions with hardening or cracks, it is necessary that this layer is completely eliminated. The location of the part that will receive the coating must be clean and free from moisture;

2. Dilution: Avoid excessive dilution of the constituents of the addition material in the base metal. Such dilution decreases the quality of the coating and its connection with the surface to be coated;

3. Coating by manual electric arc: The operating conditions are short arc welding, low current welding, welding keeping the electrode perpendicular;

4. Preheating: Reduces the level of cracks;

5. Deposit: Deposit with narrow strands, avoid oscillations and low intensity of the welding current.

Following these steps, several benefits are obtained, such as: increasing the useful life of the coated part, reducing inventory costs and reducing labor costs.

2.1.1.1 Mechanical Properties

The use of coatings provides a significant increase in the hardness of the applied surface and an increase in wear resistance. The properties that the coatings provide can be summarized as: hardness, wear resistance and impact resistance, resistance to high temperatures and friction [10].

The wear of pure materials is proportional to their hardness, however, in coatings this proportionality can be valid up to a certain hardness value, which from that value, the hardness increases with less intensity [13].

The use at Ni-rich alloys promote high mechanical strength and Cr-alloys increase resistance to abrasion, corrosion and moderate impacts [16]. If the impacts were of high magnitude, they need to be rich in Mn. Nickel and cobalt coatings provide high resistance to corrosion and heat along with abrasive, metal-to-metal or impact resistance [17].

The cast iron alloys with high chromium exhibit 20 to 25 times more resistance to abrasive wear than low carbon steel in situations of wear to two or three bodies [18].

The state that the increase in hardness improves wear resistance, as it is a hard coating applied on medium carbon steel substrate, however hard coatings with similar hardnesses may present different wear resistance [19]. The hardness of the coatings is more influenced by the microstructure, which depends on the imposed heat and the chemical composition [20]. Buchely et al [21] studied several coating alloys comparing them to the relationship between wear resistance and hardness, shown in Figure 2.2.

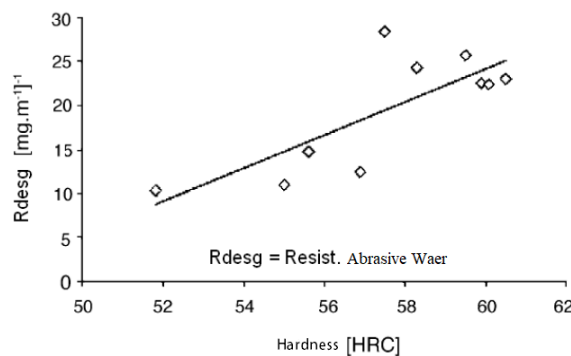


Figure 2.2: Wear resistance versus hardness of the coating.
[21]

2.1.1.2 Hard Coating Used

Actually, two types of hard coating stand out in the market, the coated electrode and the tubular wire, which are characterized by the way of use, hardness and resistance to impact and wear. In this work, the WI DUR 33 - WELD-INOX electrode hard coating will be used, Figure 2.3. The choice was made due to the ease of purchase and the lower cost of purchase / application in relation to the tubular wire.

The WI DUR 33 electrode is coated with chromium carbides for hard coating of parts and equipment subject to severe abrasion with moderate impacts. It is indicated by the manufacturer for preventive use of knives and hammers in the sugar and alcohol plant, buckets, screw conveyors and soil drilling bits. It has a chemical composition of 4.5% Carbon, 4.30% Silicon and 32.50% Chromium and its hardness ranges from 57 HRC - 62 HRC [22].



Figure 2.3: Electrode WI DUR 33.

Generally, the application of hard coatings in the industrial sector has been carried out manually with the coated electrode process or automatically with the Submerged Arc process, when the part is suitable for this application. Studies have already been carried out to analyze the wear resistance of hard coatings, including Carceller [16], Buchelly et al [21], Martins Filho [23], Ribeiro [24], Bálamo [25], Buchanan, Shipway and McCarteney [26], Correa et al [27]. These works were restricted to experiments in laboratories using coated electrodes or tubular wires [1].

2.1.2 Polymers

Polymers are macromolecules formed from smaller molecules, called monomers [28]. They are popularly known as plastics for several reasons such as lightness, flexibility, low cost, unique appearance and mechanical properties. They can be modified using chemical agents, loads or efforts, or even other chemical compounds, which can generate benefits in several areas of engineering, such as parts in the civil, mechanical, electrical industry, among others [29]. In 1864, the first mixture of polymers was patented, with applications

from picture frames to coatings for electrical cables. Around 1900 there was an increasing development of many synthetic polymers, increasing the production of plastics mainly after the war [30].

Polymers can be classified according to several aspects, such as: their origin (natural or synthetic), preparation reaction (addition or condensation), chemical structure (linear, branched or reticulated), fusibility characteristics (thermoplastic or thermoset), heterogeneity (homopolymer or copolymer) and finally due to its mechanical behavior (plastics, elastomers and fibers) [31]. Polymers have outstanding properties because they are not attacked by acids, bases or atmospheric agents, generally consist of low density, high electrical resistance, temperatures and radiation.

Those of natural origin are those that exist in nature as polysaccharides, proteins and polyhydrocarbons, for example: cellulose, wool, silk, hair, leather, among others. Those of synthetic origin are obtained artificially, for example: acrylic, styrofoam, PVC, polyethylene, polypropylene, among others. In this work, synthetic polymers are evaluated: PC-ABS, Nylon and Polyurethane, as protective coatings for surfaces subjected to compressive loads.

- PC-ABS – Due to the need to seek better mechanical properties in polymers, a combination of polycarbonate and Acrylonitrile-Butadiene-Styrene was performed, which resulted in PC-ABS. ABS with its good processability and PC with good mechanical properties of impact resistance and heat resistance, it was possible to obtain an immiscible, two-phase material with dimensional stability, low shrinkage and moisture absorption, high rigidity and hardness, good resistance to impact at low temperatures, processability, good mechanical properties, flame retardant and heat resistance [30]. The Figure 2.4 shows an example of PC-ABS.



Figure 2.4: PC-ABS.
[32]

- Nylon – Nylon is a synthetic polymer widely used in engineering applications due to its good mechanical properties related to: dimensional stability, good resistance to impact without notching and excellent chemical resistance. Its molecular composition as Nylon 6, 66, 12 and 46 define different types of properties, being able to be chosen according to the application. In general, Nylon is a semicrystalline thermoplastic with low density and high thermal stability. This polymer is among the most important and useful technical thermoplastics due to its excellent wear resistance, good coefficient of friction and temperature properties, and very good impact resistance. Nylon has an excellent balance of properties and is therefore an ideal metal replacement material in applications such as automotive parts, industrial valves, rail tie insulators, and other industrial uses where design requirements include high load, toughness, and heat reduction weight [33, 34]. The Figure 2.5 shows an example of Nylon.



Figure 2.5: Nylon.
[35]

- Polyurethane – Polyurethane ranges from elastomers, fibers, adhesive foams and surface coatings [36]. It is a polymer widely used commercially due to its good resistance to corrosion, abrasion, cutting and hardness. It is a material used to coat parts, buckets in order to avoid the corrosion process of the base surface and thus increasing the useful life of the material in which it is applied. In addition, polyurethane has excellent elasticity, elongation and resistance, replacing the excessive use of rubber [37]. The Figure 2.6 shows an example of Polyurethane.



Figure 2.6: Polyurethane.
[38]

2.1.3 Deposition Processes

The coatings application processes can be divided into four generic groups: gaseous, solution, fused or semi-fused and solid. Two important parameters to be analyzed for the coatings are the thickness and the deposition temperature. Common thickness values are between 0.1 mm to 10 mm with varying deposition temperature ranges [39]. Figure 2.7 exemplifies these parameters. Figure 2.8 shows the techniques of surface coatings.

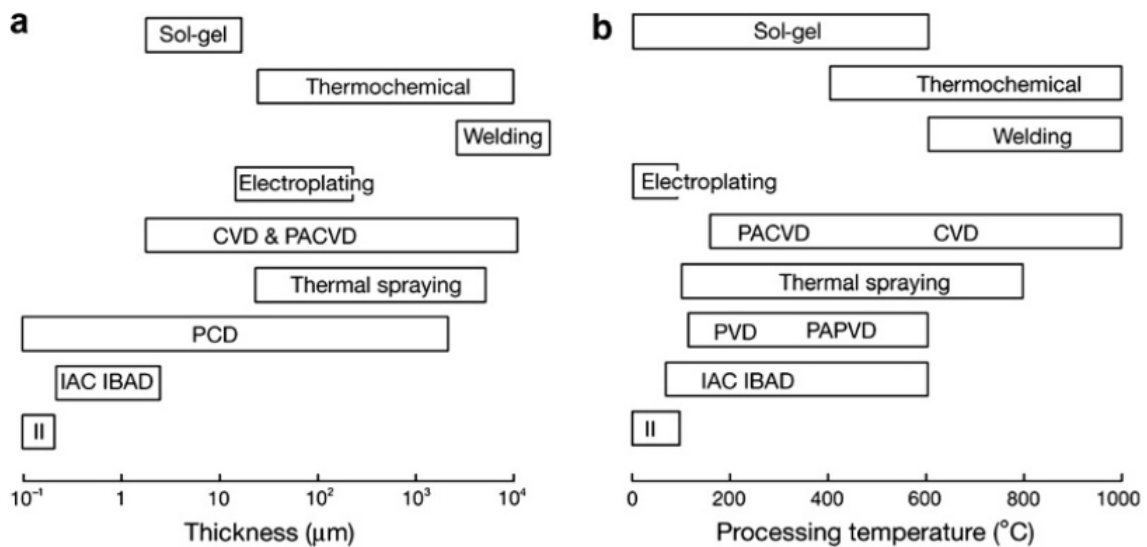


Figure 2.7: (a) thickness of coatings and (b) deposition temperatures. [40]

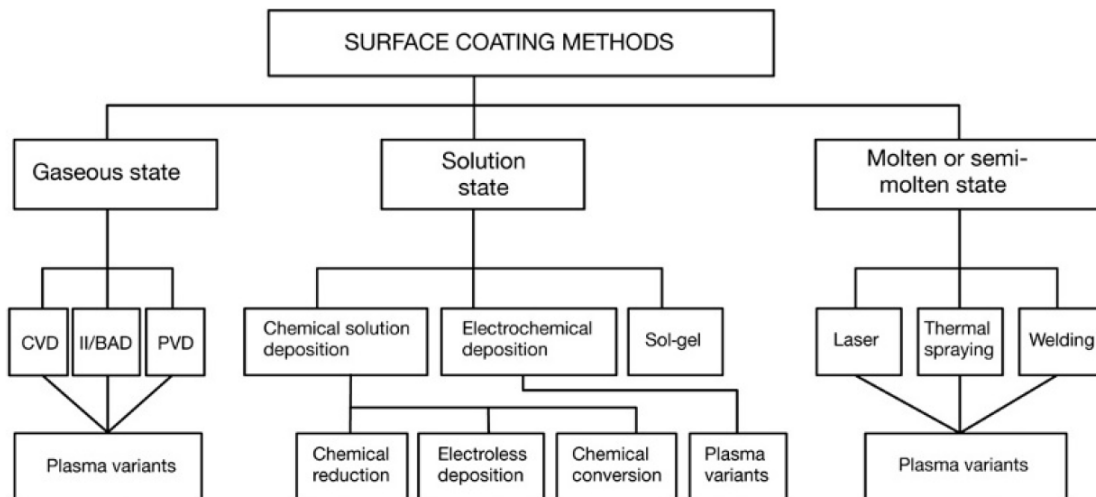


Figure 2.8: General classification of surface coating techniques. [40]

The main deposition methods are presented in Figure 2.7, which we can highlight some:

- PA - Assisted Plasma;
- CVD - Chemical Vapor Deposition;
- PVD - Physical Vapor Deposition;
- IBAD - Ion Beam Assisted Deposition;
- Electrochemical Deposition;
- Thermal spraying;
- Welding.

Then, we will approach with greater emphasis the welding and briefly on some other deposition methods more commercially widespread, both inserted in its state process: gaseous, solution and fused or semi-fused.

- Gaseous State Process: Chemical Vapor Deposition - CVD:

The Chemical Vapor Deposition Process uses gaseous reagents as a source of coating species. Gases that contain the material to be deposited are placed in a reaction chamber and condense on the substrate, forming the coating. High temperatures are generally required, in the 800 to 1200 ° C range. Because the CVD process is at high temperatures, many materials may experience variations in their initial properties. To try to reduce the temperature, electron beams or ion bombardment can be used, and still obtain a dense and well-adhered coating [40].

The CVD method provides coatings of high purity, density and homogeneity, thus minimizing the amount of pores and having strong adhesion to the substrate. This technique has disadvantages related to the high energy cost, as it generally requires high temperatures and, thus, affects the initial mechanical properties of the material to be coated. It is possible to use this process to deposit metallic, non-metallic, composite and intermetallic coating lines. It is one of the most common methods of depositing thin films for the protection of integrated circuits [41].

- Gaseous State Process: Physical Vapor Deposition - PVD:

In the process of physical vapor deposition, the coating material is evaporated in a vacuum chamber in a resistive heating medium or bombardment of ionized gas or even an electron gun. The aim is to promote the formation of surface compounds, using chemical reactions. This method has the advantage of occurring at lower temperatures, between 100 to 600 ° C, being indicated for materials that may have their properties altered at elevated temperatures [41, 42].

Various forms of application of the PVD method are presented considering the form of evaporation, such as by cathodic arc, electron beam and spraying. More detailed information can be discussed in Hutchings [42], Burakowski and Wierzchón [43] and other related literature.

- **Solution State Process: Electrochemical Deposition:**

The electrochemical deposition process, known as electroplating, consists of the deposition of a metallic coating on an electrode by an electrolysis process, with chemical changes due to the passage of a current. Some electroplating processes use non-aqueous solutions and some metals were deposited from solvents such as liquid ammonia. The main solvents are organic and molten salts. They have disadvantages such as toxicity, disposal and cost [44]. Electrochemical deposition techniques are described in greater detail by Wills and Walsh [45].

- **Fused and Semi-Fused State Process: Thermal Spraying:**

The thermal spraying process consists of a technique in which the material is heated and projected at high speed on the surface, producing a coating [46, 47]

There is a grouping of thermal spraying processes, the first of which is less energy, called metallization, which includes arc and flame spraying. These are generally applied to metals for corrosion resistance, such as zinc and aluminum. The second group are higher energy processes, such as plasma spraying or high speed spray gun [48].

- **Cast and Semi-Cast Process: Welding:**

Several welding processes can be used to deposit coatings. The two most used are the oxyacetylene torch and the arc welding. These are techniques that can be implemented for most metals, and are not recommended for materials with a low melting point. The thickness range is between 1.5 to 6 mm and has the purpose of resisting various forms of wear [40]

The use of welding to recover and protect parts and equipment such as mills, gears, chippers, brush cutters has increased in several sectors of the economy. Welding technology has evolved to such an extent that today, wear-resistant alloys have been developed and are used as a coating, increasing the life of the coated surface by up to 10 times in relation to the uncoated surface [1].

2.1.3.1 Method Welding: Arc Electric

Electric arc welding with a coated electrode (Shielded Metal Arc Welding - SMAW) is a process in which the union of metals is achieved by heating them together with an arc between the electrode and the part. The electric arc is the most used heat source in fusion welding of metallic materials. This is due to having a good combination of the energy concentration for fusion located in the base metal, easy control, low cost and a low level of risk to the health of the operator [49].

Figure 2.9 exemplifies the electric arc welding process. The coating can be made of clays, fluorides, carbonates, cellulose, ferroalloys, among others and can vary in diameter from 2 to 8 mm. The core (metallic core) can have a length of 250 to 500 mm, conducts the electric current and serves as a filler metal. The coating, when applied, generates slag and gases that protect the region being welded and stabilize the arc [49].

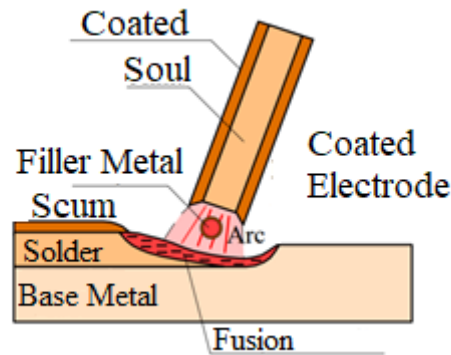


Figure 2.9: Welding process with electric arc.
[49]

In this welding process using electric arc, there are several advantages and disadvantages, described in Table 2.1.

Table 2.1: Advantages and Disadvantages.

Advantages	Disadvantages
1. Simple, portable and inexpensive equipment	1. Difficult application for reactive materials
2. No need for external gases	2. Low productivity
3. Versatile process	3. Requires cleaning after each pass
4. Access to complex areas	

2.2 Contact Mechanics - Sphere to Flat Hertzian Solution

The theory of Heinrich Hertz, known as “Hertz formulae”, consists of the unification of Continuum Mechanics and the Theory of Elasticity and this theory generated satisfactory analyzes of stresses in contact between two elastic bodies [50]. The equations developed by Hertz are related to: contact area, stress distribution, contact pressure and indentation, however, it has some limitations and simplifications such as:

I. The surfaces are continuous and non-conforming;

II. The deformations in the contact region are very small;

III. Each solid can be considered as an elastic half-space, where the contact half-width is much smaller than the radius of curvature of each body, as well as both the lateral and depth dimensions of the bodies in contact;

IV. Absence of friction between surfaces.

For Johnson [50], the contact area must be much smaller than the body radius ($a \ll R$), respecting the limitations described above. The Hertzian contact presents analytical solutions for different types of contact. They are divided into two groups: first - cylindrical and conical indentation solutions in elastic half-planes and second - solutions between elastic bodies, such as cylinders, spheres and planes. The second group is interested in this work, and therefore only this one will be addressed. Contact between two elastic bodies often occurs through the application of a force F or a displacement z [50].

Now, a sphere-plane contact is shown in Figure 2.10. We consider an initial force F , where Z is a displacement due to the applied force, the term a represents the length of the semi-arc of contact. Considering that the sphere has radius R_1 and R_2 tends to infinity due to being a flat surface, the equivalent radius is calculated by the equation 2.1, which R_{eq} will be the radius of the sphere, since the radius of the flat surface tends to infinity.

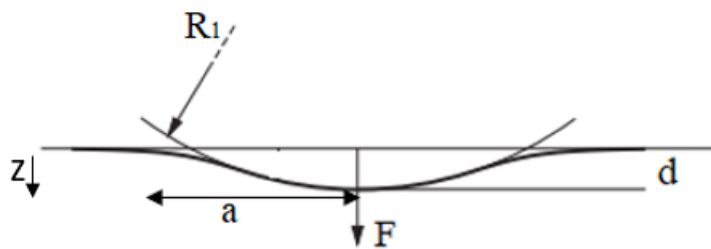


Figure 2.10: Sphere-plane contact.
[51] adapted

$$\frac{1}{R_{eq}} = \frac{1}{R_1} + \frac{1}{R_2} \quad (2.1)$$

And the contact half-length, a , is obtained from equation (2.2).

$$a = \sqrt[3]{\frac{3FR_{eq}}{4E_{eq}}} \quad (2.2)$$

Where E_{eq} is obtained by the Young's modulus of the two bodies, E_1 and E_2 , and the respective Poisson coefficient, v_1 and v_2 :

$$\frac{1}{E_{eq}} = \frac{1 - v_1^2}{E_1} + \frac{1 - v_2^2}{E_2} \quad (2.3)$$

The indentation depth is obtained by:

$$d = \frac{a^2}{R_{eq}} \quad (2.4)$$

The force, F , is given by equation (2.5).

$$F = \frac{4E_{eq}\sqrt{R_{eq}}\sqrt{d^3}}{3} \quad (2.5)$$

And Finally, the maximum pressure, P_0 , can be calculated by equation (2.6).

$$P_0 = \frac{3F}{2\pi a^2} \quad (2.6)$$

2.2.1 Indentation Test

The indentation test consists of applying a known compressive load to a defined material surface. The tool used for this purpose is called indenter, which can have different geometries. Its best known application is in hardness testing, used to identify the mechanical behavior of the material to which it is subjected to testing [52]. The indentation process is a versatile and essential mechanism for contact mechanics, using the Hertzian solution and its concepts even in more complex situations when relating some type of wear. The indentation test can involve simplicity of the equations of the Hertzian solution, but also complex ones composed of stresses and deformations [53].

Effects related to indentation size began to be observed, and the use of this type of evaluation grew. However, their results were somewhat uncertain, due to measurement uncertainties and because of the geometry of the indenters. With the passage of time and evolution of technology, these errors have been reduced. The effect of indentation size is related to the morphology of the material and the plastic path in the contact zone. It is shown that in the case of conical and pyramidal indenters there is a fixed relationship between the measured properties with the indentation depth, in contrast, for spherical indenters the relationship is with the indenter diameter [54, 55, 56, 57].

2.2.2 Hardness

Hardness is a mechanical property that measures the resistance of a material to localized plastic deformation [58]. Qualitative and quantitative techniques exist to obtain a material hardness. In the qualitative system it is made by a Mohs scale, which varies between 1 (soft) to 10 (diamond). Quantitative techniques is done with a use of a small indenter, which is forced against the surface of a material to be tested, under conditions of controlled load [58].

Hardness Tests can be destructive, when they cause the material to become unusable after the test, and non-destructive. Non-destructive tests are generally used in quality control, verification of manufacturing conditions such as heat treatments and uniformity of materials.

The main objectives of the hardness test are [59]:

- Knowledge of wear resistance;
- Approximate knowledge of mechanical strength through the use of correlation tables;
- Quality control of heat treatments;
- Quality control in plastic forming processes and bonding processes;
- Research and development of new alloys and materials.

The main types of hardness testing:

- Risk Hardness (Mohs scale);
- Shock Hardness (Shore);
- Penetration Hardness (Brinell, Rockwell and Vickers).

2.2.2.1 Risk Hardness

First standardized hardness test method (Mohs scale). It is based on the standard mineral scribing process. It consists of a scale of 10 minerals.

Features of this test are:

- Qualitative method (Comparison with other minerals);
- Little used (Due to inaccuracy);
- Application in mineralogy.

2.2.2.2 Shock Hardness

It consists of a dynamic test (Shore), in which the impression is caused by the free fall of a piston. The test uses a steel bar (plunger) weighing 2.5 N, with a rounded diamond tip. The hardness value is proportional to the energy consumed to form the mark on the specimen [59].

The advantages of this type of test are due to its ease of use, the possibility of measuring the hardness of large parts and the Shore impression caused on the part is small, allowing the test to be carried out on already finished parts. Disadvantages are that there is difficulty keeping the measuring equipment aligned and thin parts can vibrate on impact.

2.2.2.3 Brinell Hardness

In Brinell hardness testing, a spherical indenter is forced against the metal surface. The loads vary between 500 and 3000 kgf and during the test the load is kept constant for a time between 10 and 30 s [58].

The ASTM E10-12 [60] standard guides the execution of the test, from the selection of the indenter and the relationship of force with the diameter of the indenter. Figure 2.11 represents the variables present in the test.

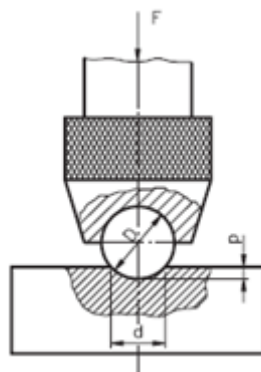


Figure 2.11: Brinell Hardness Test.
[61]

The Brinell hardness (HB) is the ratio between the load and the area of the spherical cap printed on the tested material (A_c), according to equation (2.7).

$$HB = \frac{F}{A_c}, \quad (2.7)$$

where the area of the spherical cap is given by equation (2.8) and P is the depth of the cap and D is diameter.

$$A_c = \pi DP \quad (2.8)$$

Substituting equation (2.8) in equation (2.7), a mathematical relationship between depth (p) and diameter (D) is used, arriving at equation (2.9), which allows the calculation of HB hardness.

$$HB = \frac{2F}{\pi D(D - \sqrt{D^2 - d^2})} \quad (2.9)$$

This type of hardness test has advantages due to its low cost, it requires little time to prepare the surfaces and the two main disadvantages are the possible measurement error by the operator and the unusability of the tested part due to large impressions.

2.2.2.4 Rockwell Hardness

It was developed in 1922 by Rockwell, consisting of a hardness test method that uses a preload system. The Rockwell hardness method, HR (Rockwell Hardness), considers the depth that the indenter reached, discounting the elastic recovery, due to the removal of the greater load, and the depth reached, which is due to the smaller load. In this method, the result is read directly from the testing machine. The advantages of this method are speed, smaller print marks, detection of small differences in hardness and reliability [59].

The ASTM E18-94 [62] standard determines basic conditions for the Rockwell hardness test, such as: flat surface perpendicular to the load and application of preload for 3 seconds, the minimum thickness of the tested part must be at least 10 times greater than the depth of the dent caused in the test.

Rockwell hardness is subdivided into two groups: Normal Rockwell and Superficial Rockwell. The difference between one and the other is basically the load used to carry out the test. The most applied scales for Rockwell hardness are usually A, B and C. For surface hardness, the most used are N and T.

2.2.2.5 Vickers Hardness

The Vickers hardness method, represented by the abbreviation HV (Hardness Vickers), is a test in which a pyramid-shaped diamond indenter with a square base and an angle between faces of 136° is compressed against the piece to be tested by a pre-determined force. After removing the force, the diagonals of the print are measured and the Vickers hardness number is calculated by dividing the value of the test load F by the print area Equation (2.10) [59].

$$HV = \frac{F}{A} \quad (2.10)$$

Equation (2.10), after mathematical manipulation, can be represented by equation (2.11), where F is given in kgf and d in mm.

$$HV = \frac{1,8544F}{d^2} \quad (2.11)$$

The load for the Vickers test must be applied progressively, without shocks or vibrations, by means of a piston moved by a lever, and maintained for a period of 10 to 15 seconds. This method of hardness testing has the main advantage of being applicable to the entire range of hardness found in different materials.

Chapter 3

Methodology

This chapter presents the experimental tests carried-out for the evaluation of the mechanical properties of the electrode and the necessary steps to implement the proposed numerical model within the software ABAQUS CAE 6.14.

3.1 Characterization Tests

The hard electrode was selected as one of the coatings of this study. To evaluate its properties hardness, impact and tensile tests are carried-out. These tests are used to infer the stress-strain curve of this material. The base material is SAE 1045 steel and the coating is the WI DUR 33 hard electrode, a commercially available to coat often employed to minimize wear.

3.1.1 Hardness Test

Firstly, for the hardness test, a specimen of SAE 1045 steel material was prepared. Its surface was properly sanded, polished and cleaned to receive the superficial coating, the WI DUR 33 hard electrode, shown in Figure 3.1-a. For the specimen with and without coating, the Rockwell C hardness test was performed on the DUR 150 machine [63], Figure 3.1-b. The load used was 150 kgf, a pre-load of 10 kgf and a 120° tapered diamond penetrator.

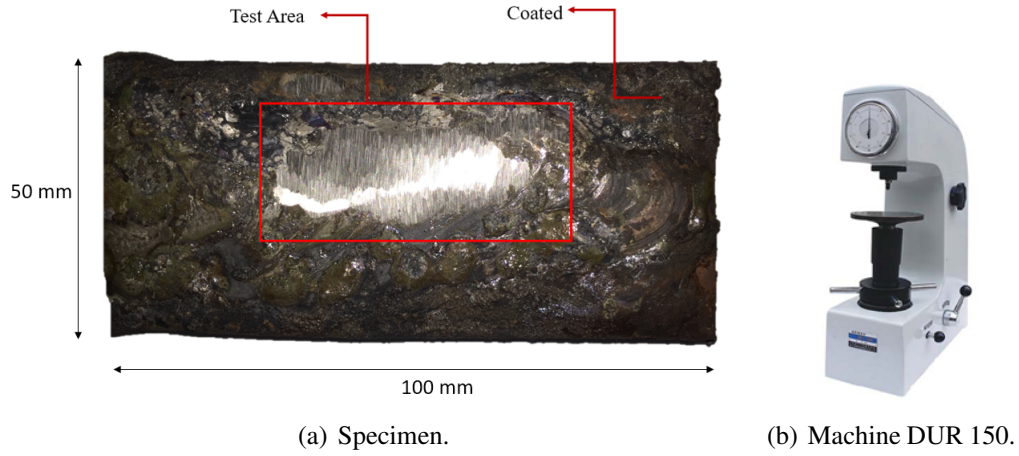


Figure 3.1: Hardness test.

3.1.2 Impact Test

The Charpy test consists of determining the resistance of a certain material when subjected to a certain impact load. One of the objectives is to measure the amount of energy absorbed by the material during the fracture. The energy absorbed by the specimen when it receives the impact of the hammer is equal to the difference between the potential energy of the hammer before and after the impact according to eq.(3.1): [64], where, m is the mass of the hammer and g is the gravity.

$$E_f = mg(h_0 - h_1) \quad (3.1)$$

The specimen was prepared with SAE 1045 steel material, Figure 3.2, with and without WI DUR 33 electrode coating on its surface. The size of these specimen was 10 X 10 X 55 (unit in millimeters). The impacting energy was up to 150 Joules, the impact speed was 5 meters / second, the elevation angle was 150° , the hammer's weight was 10 kg and the distance between the pendulum axis and the impact point was 0.8 meters. The machine used is from the manufacturer Pantec, Figure 3.3. It is used manually or in conjunction with a set of sensors connected to the computer.

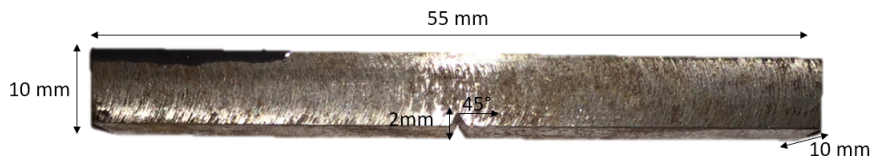


Figure 3.2: Specimen used for the impact test.



Figure 3.3: Impact test machine.
[65]

3.1.3 Tensile Test

The specimen was prepared with SAE 1045 steel material, with and without WI DUR 33 electrode coating, as shown in Figure 3.4. The tensile test was carried out on the MTS 809 machine. The load used was 85 kN. The dimension of the section area was 100 mm². The specimen had a total length of 300mm.

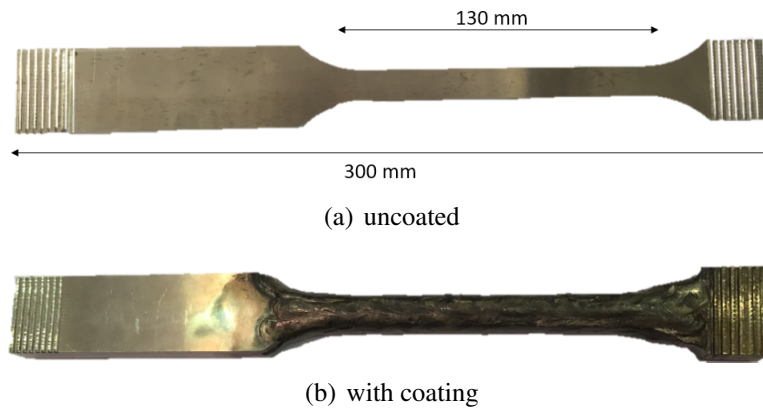


Figure 3.4: Specimens used for the tensile test.

3.1.4 Results: steel and hard electrode

To one comparison between a type of coating and the uncoated surface, the WI DUR 33 hard electrode, from the manufacturer WELD-INOX, was selected because it is more commercially used and has a low application cost, thus making the test viable. With that, characterization tests were carried out, such as: tensile, hardness and impact, in order to analyze the effect of the use of coating in this type of situation. The result of the hardness test is shown in Table 3.1.

Table 3.1: Hardness Test

Test	Rockwell Hardness	Value
Uncoated	HRC	14,3
With Coated	HRC	54

Comparing the results, the use of the coating on the surface of the specimen, brought an increase of more than 250 % of hardness on its surface.

When analyzing the results obtained in the impact test, it was observed that, even with the coating increasing the hardness on the surface, the material continued to behave like a ductile material, breaking at 45 ° as illustrated in Figure 3.5. The energy absorbed in the uncoated specimen was approximately 12 Joules, while in the coated specimen it was in the range of 15 Joules, with more than a 20% increase in the ability to absorb energy from the impact. This test was carried out at a temperature of 24 ° C.

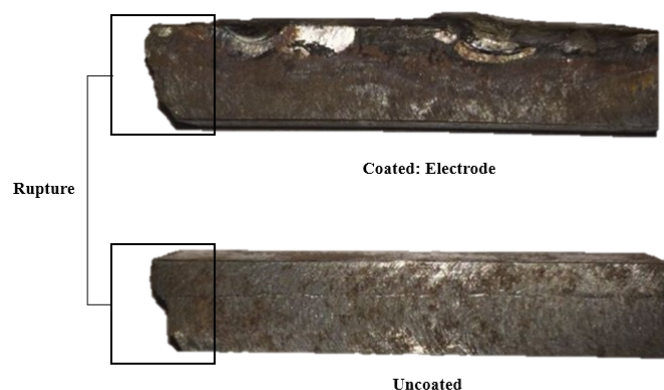


Figure 3.5: Fractured specimens after the impact test.

The tensile test in this work had to obtain information about the influence of the use of electrode coating on metallic surfaces. The results of the tensile test are presented in Figure 3.6 and it was possible to infer that the slope of the line of the tensile test with coating increased and with that, it can be concluded that the modulus of elasticity increased, leaving the stiffer material with less ductility. The values observed in this test are used in the numerical model presented in section 3.2.

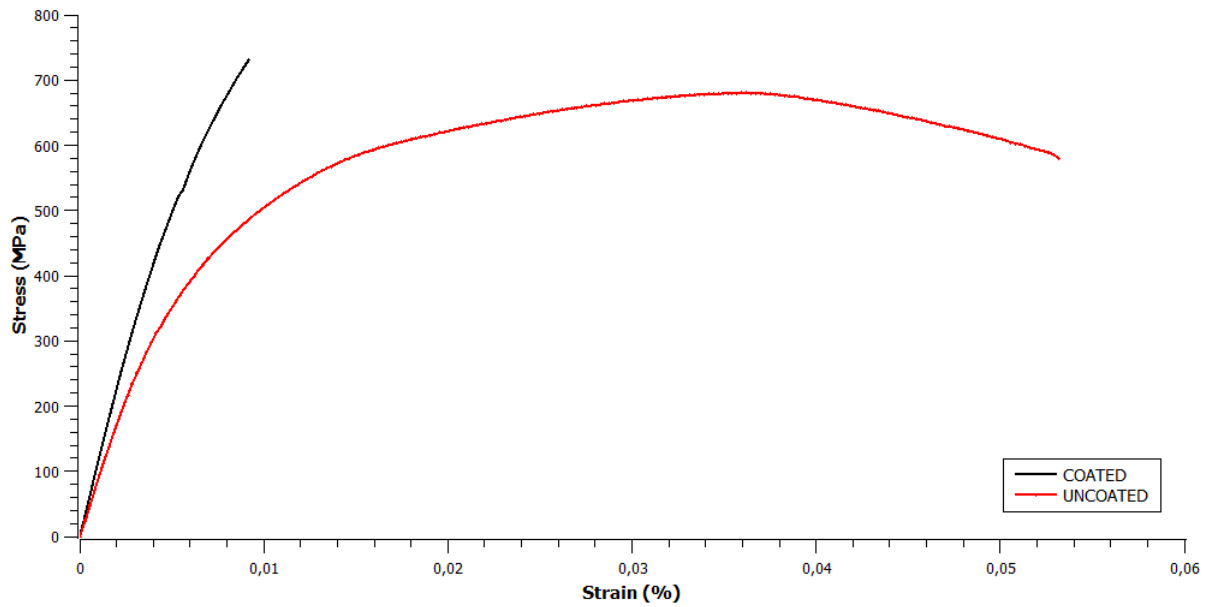
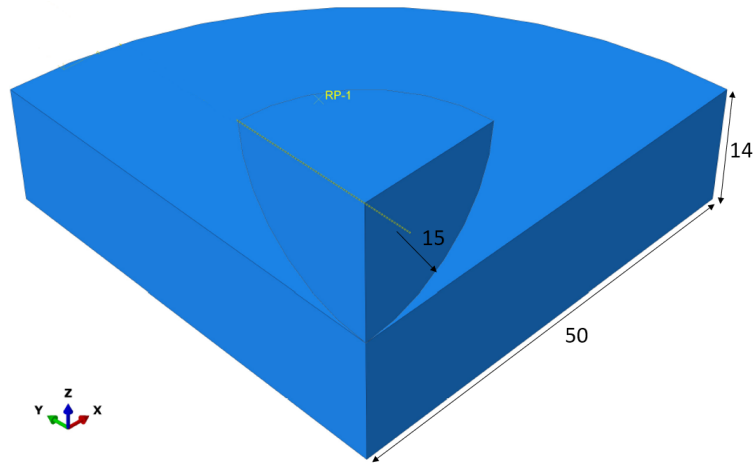


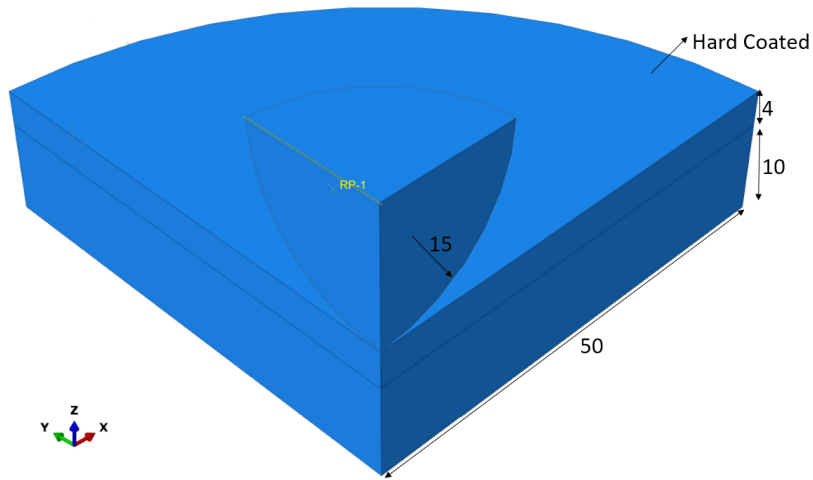
Figure 3.6: Tensile test results for the Uncoated specimen (red curve) and Coated specimen (black curve).

3.2 Numerical modeling of the sphere-to-flat configuration

A numerical model has been implemented using the simulation package ABAQUS CAE version 14.6. The model features a three-dimensional sphere-on-plane configuration. To reduce the computational cost only one-eighth of the particle and one-fourth of the flat surface are modeled, as shown in Figure 3.7. Dynamical effects are disregarded. In the coated simulation, a section with 4 mm (thickness commonly used in protection coatings) has been defined.



(a) Uncoated model.



(b) Coated model.

Figure 3.7: Assembly and geometry used in the simulation, dimensions in millimeters.

The numerical model has been implemented in a implicit quasi-static condition (step type: "static general"). No geometric non-linearity correction and load stabilization method has been used. The step size is divided into 200 identical increments, so that each increment is equal to 0.5% of the maximum 2kN load. Inertial effects are neglected due to the low mass of the particle.

The contact pairing chosen is the “surface-to-surface” method. The enforcement of normal contact constraints is carried-out via the Lagrange method and a frictionless condition is set for the tangential contact constraints. The particle is considered as a deformable “master” surface while the plane is setr as a deformable “slave” surface. The compressive load is applied into a reference point kinematically coupled to the top surface of the particle. Figure 3.8 shows the reference point used for the load application.

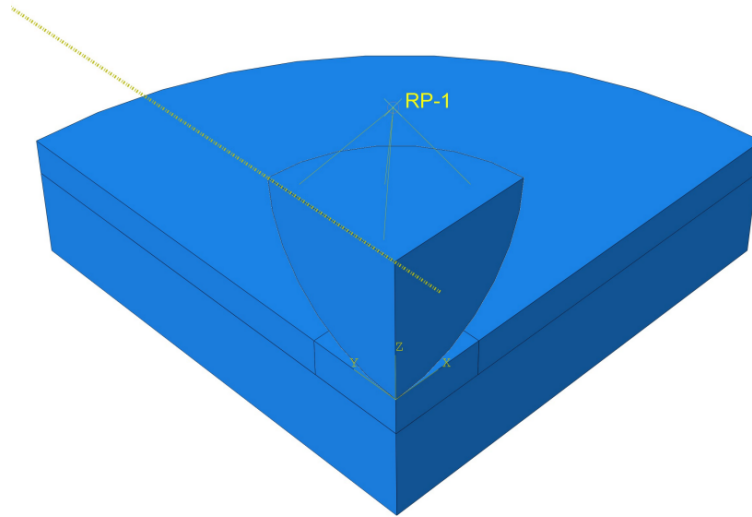
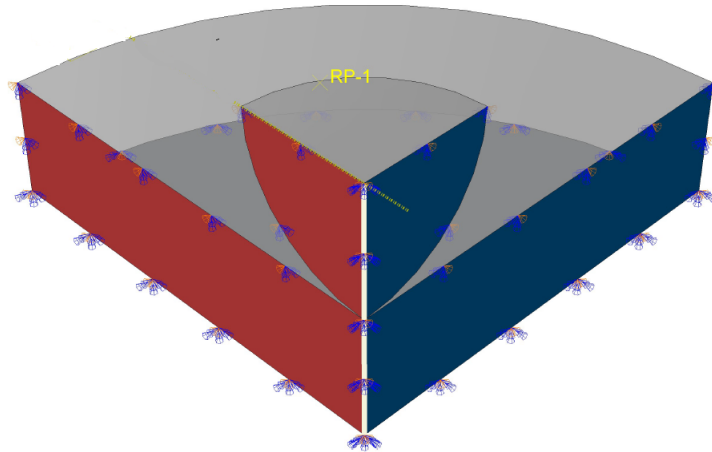
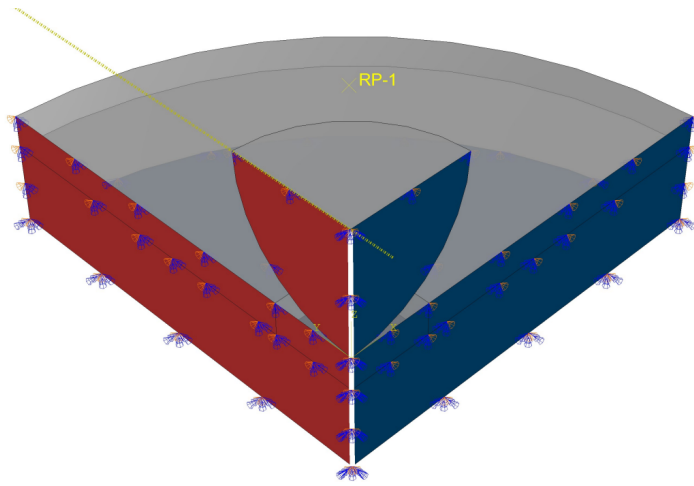


Figure 3.8: Reference point with compressive load of 2000N.

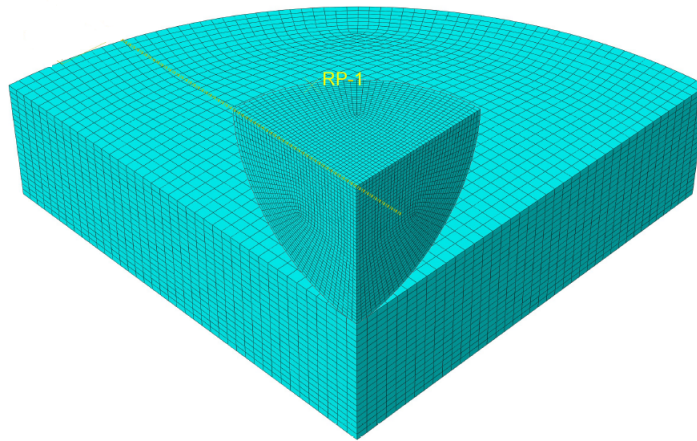
The boundary conditions applied to the plane ensures only vertical and radial displacements. Its bottom is fully restricted and the planes yz and yx have symmetry constraints. The spherical indenter has a similar restriction, as illustrated in in Figure 3.9-a and 3.9-b. The finite element employed is a linear 8-node hexahedron with reduced integration. Figure 3.9-c and 3.9-d shows the numerical models with the selected mesh (average element size equal to 1). Table 3.2 presents the summary of the properties of the contact formulation:



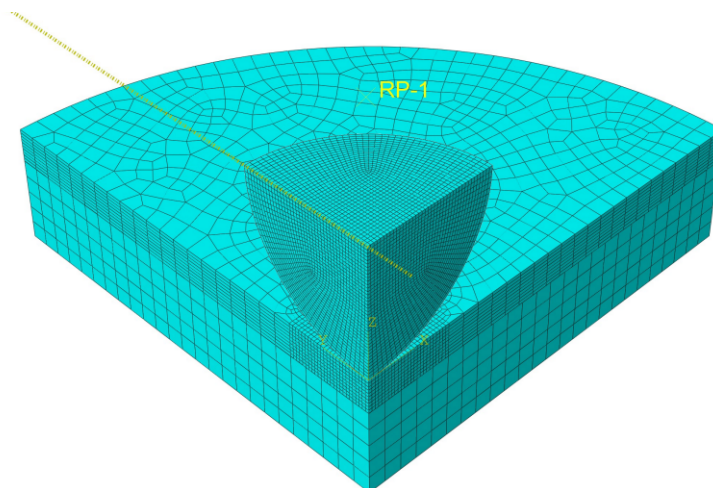
(a) Boundary conditions uncoated.



(b) Boundary conditions coated.



(c) Finite element discretization uncoated.



(d) Finite element discretization coated.

Figure 3.9: Numerical model: sphere-plane configuration.

Table 3.2: Contact formulation properties.

Type Contact	<i>"Surface-to-Surface"</i>
Tangential Behavior	No Friction
Normal behavior	<i>"Hard contact"</i> <i>"Default"</i>
Slip formulation	<i>"Finite Sliding"</i>
plane surface	30720 elements
Spherical indenter	32000 elements

The indenter is defined as a linear elastic material (Young's modulus 550000 MPa and Poisson coefficient of 0.20) while the plane is defined as a inelastic material. The elastic properties considered for the coatings (hard electrode, PC-ABS, polyurethane and Nylon and steel base materials (SAE 1045 and SAE 1020) were taken from [58, 66] and are detailed in Tables 3.3 and Table 3.4 while the inelastic properties are given in Table 3.5 and 3.6.

Table 3.3: Material properties: Steel 1045, Steel 1020 and Electrode.

	1045 Steel	1020 Steel	Electrode
Young modulus, E (MPa)	206000	185000	55800
Poisson's ratio	0.29	0.29	0.29
Specific mass, (kg/m ³)	7850	7850	7850
Yield strengths, (MPa)	490	300	390

Table 3.4: Material properties: PC-ABS, Polyurethane and Nylon.

	PC-ABS	Polyurethane	Nylon
Young modulus, E (MPa)	2200	768	2350
Poisson's ratio	0.44	0.40	0.39
Specific mass, (kg/m ³)	1150	1200	1140
Yield strengths, (MPa)	50	12	105

Table 3.5: Plastic properties used in simulation: Steel 1045, 1020 and electrode.

Steel 1020		Steel 1045		Electrode	
Yield Stress	Plastic Strain	Yield Stress	Plastic Strain	Yield Stress	Plastic Strain
300	0.0000	490	0.000	390.00	0.000
312	0.0234	496	0.014	406.74	0.001
313	0.0484	536	0.021	417.98	0.005
313	0.0734	573	0.033	431.46	0.006
386	0.0864	594	0.044	458.43	0.010
418	0.1234	615	0.057	480.90	0.014
439	0.1484	631	0.072	510.11	0.018
454	0.1734	636	0.084	530.34	0.022
459	0.1984	640	0.101	550.56	0.026
461	0.2234	640	0.120	577.53	0.032
463	0.2484	634	0.141	595.51	0.037
440	0.2734	608	0.155	622.47	0.045
420	0.2984	566	0.165	642.70	0.054
		517	0.171	671.91	0.065
				687.64	0.079
				701.12	0.088
				705.62	0.099
				705.62	0.111
				710.11	0.123
				712.36	0.135
				698.88	0.144
				683.15	0.153
				665.17	0.159

Table 3.6: Plastic properties used in simulation: Nylon, PC-ABS and Polyurethane.

Nylon		PC-ABS		Polyurethane	
Yield Stress	Plastic Strain	Yield Stress	Plastic Strain	Yield Stress	Plastic Strain
105.00	0.000	50.00	0.000	12.00	0.000
118.34	0.045	51.41	0.007	13.11	0.002
124.53	0.079	52.69	0.012	14.42	0.005
129.95	0.106	54.19	0.019	15.39	0.008
131.49	0.125	54.83	0.026	16.37	0.011
133.04	0.151	55.89	0.067	16.86	0.014
135.36	0.179	55.47	0.107	17.35	0.017
136.13	0.204	55.04	0.164	17.35	0.020
136.13	0.235	56.11	0.216	17.35	0.023
		57.39	0.258	17.35	0.026
				17.10	0.028

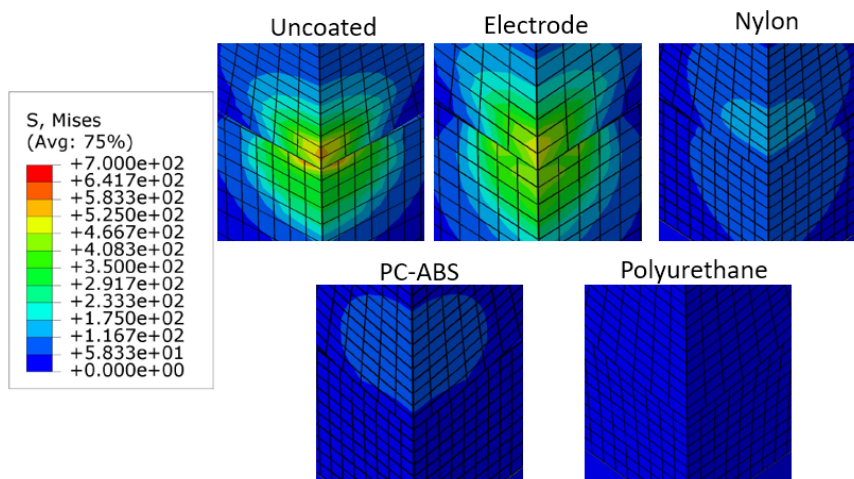
Chapter 4

Results and Discussion

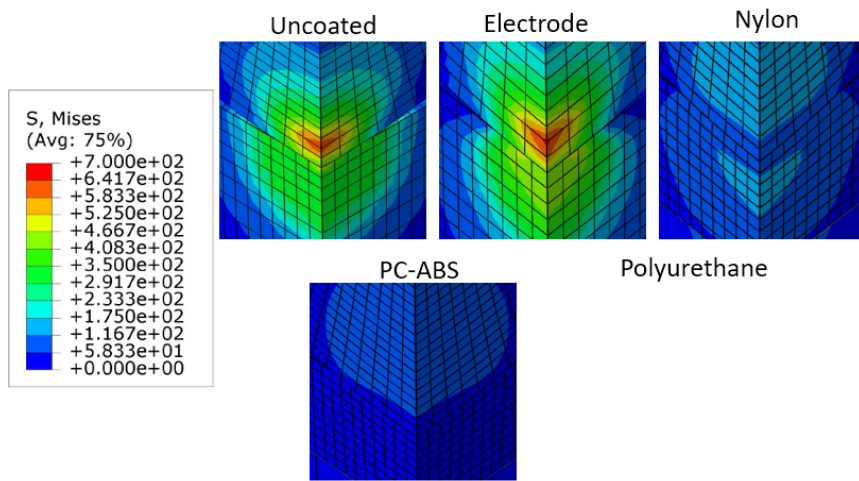
This chapter shows the effect of the Electrode, PC-ABS, Polyurethane and Nylon in the protection of surfaces when comparing to an uncoated surface. Its content is divided in results for: equivalent von Mises stress, equivalent plastic deformation, indentation depth and discussion.

4.1 von Mises equivalent stress

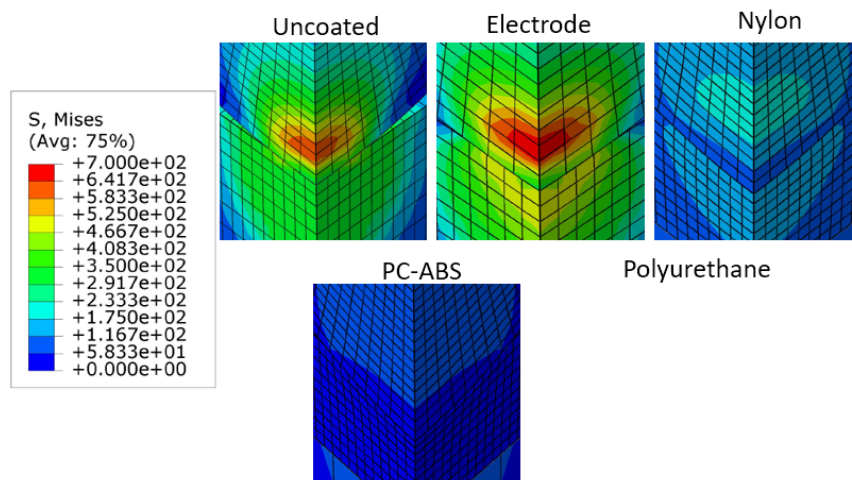
The results of von Mises equivalent stress are detailed in the Figure 4.1, for the SAE 1020 steel base material, and Figure 4.2, for the SAE 1045 steel base material. Results are shown for 500N, 1000N and 2000N.



(a) 500 N compression force.

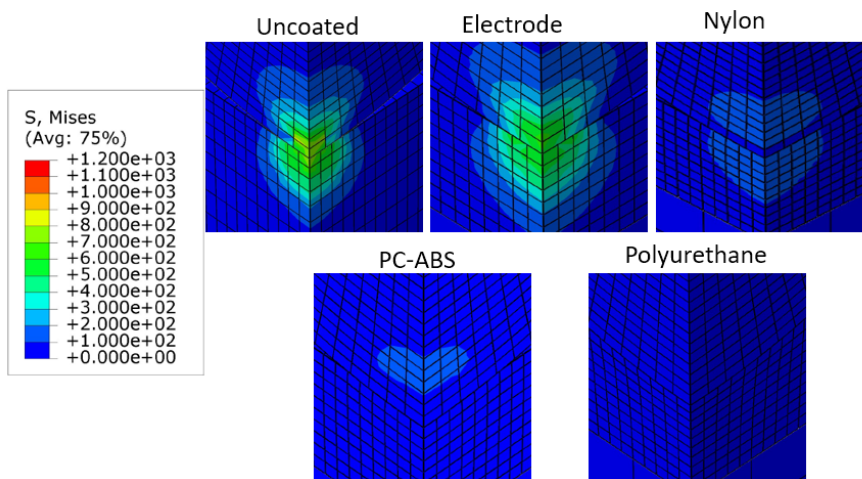


(b) 1000 N compression force.

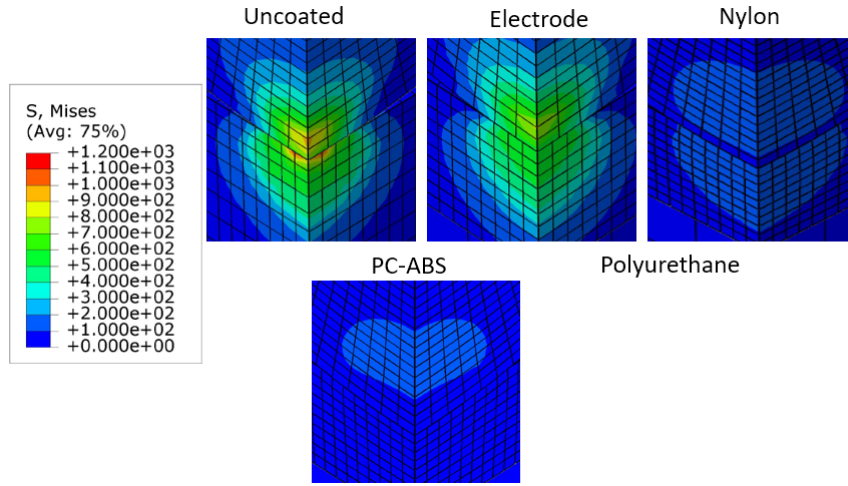


(c) 2000 N compression force.

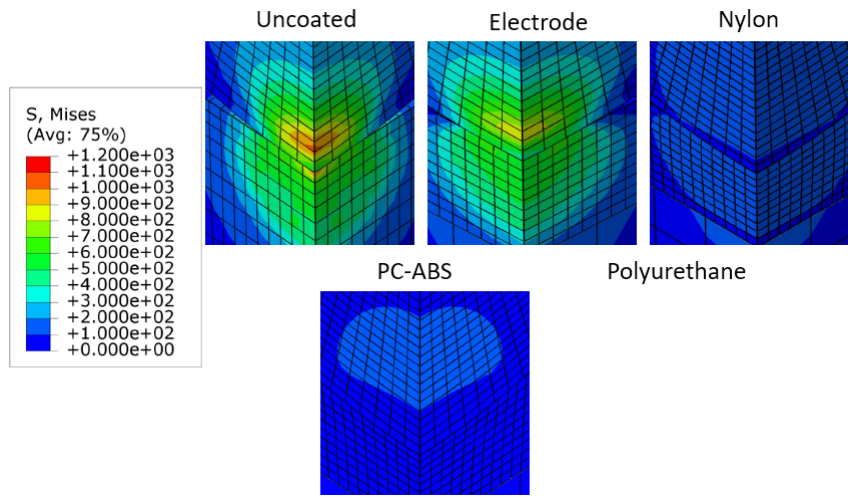
Figure 4.1: von Mises equivalent stress distribution (MPa) - base material 1020.



(a) 500 N compression force.



(b) 1000 N compression force.



(c) 2000 N compression force.

Figure 4.2: von Mises equivalent stress distribution (MPa) - base material 1045.

A qualitative analysis of these images reveals a remarkable decrease of the maximum stress whenever a polymer coating is employed. This behavior is directly linked to the stiffness of this material class. Different from the steel surface and the electrode coated configurations, the polymers yielded to the applied normal load and, as consequence, most of the external load is dissipated in the form deformation of this material. This expected behavior reiterates that soft coatings may protect surfaces at its on expense, which may reduce cost while also increasing the need for maintenance.

Also from Figures 4.1 and 4.2, it can be noted that the stress is always concentrated at the center of contact zone. As the load increases, the contact area becomes larger and stress field becomes more uniform. The stress values for the uncoated and the electrode coated surface are quite similar. The steel and the electrode shows the highest stress levels (700-1200MPa), this behavior is explained their high stiffness. The polymers are less rigid and have a much lower stress level (100-200MPa).

In order to assess the overall behavior of the critical finite element (element at top of flat surface and in at the center of the contact zone), Stress versus Force plots are provided. The stress is computed as the average value of all 8 nodes of the hexahedron finite element.

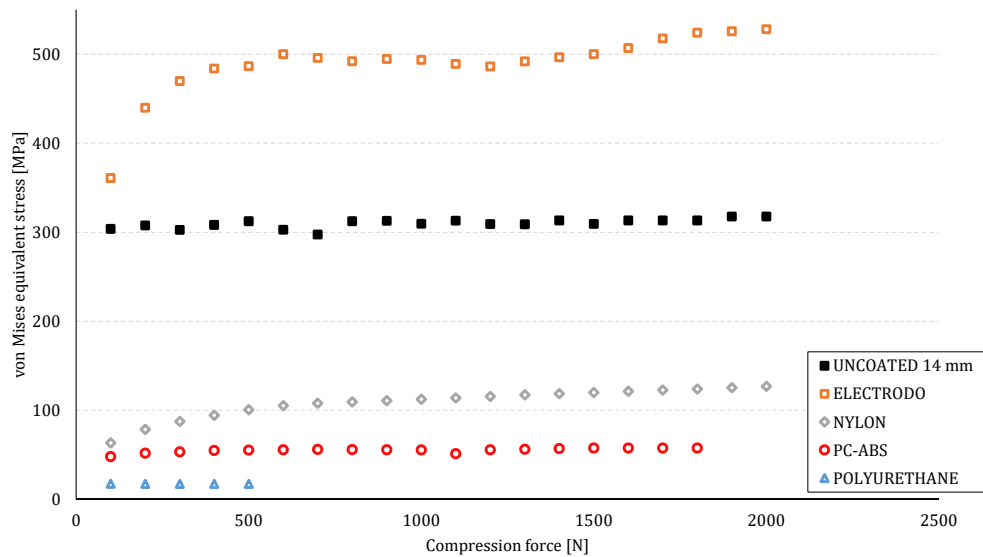


Figure 4.3: von Mises equivalent stress - base material 1020.

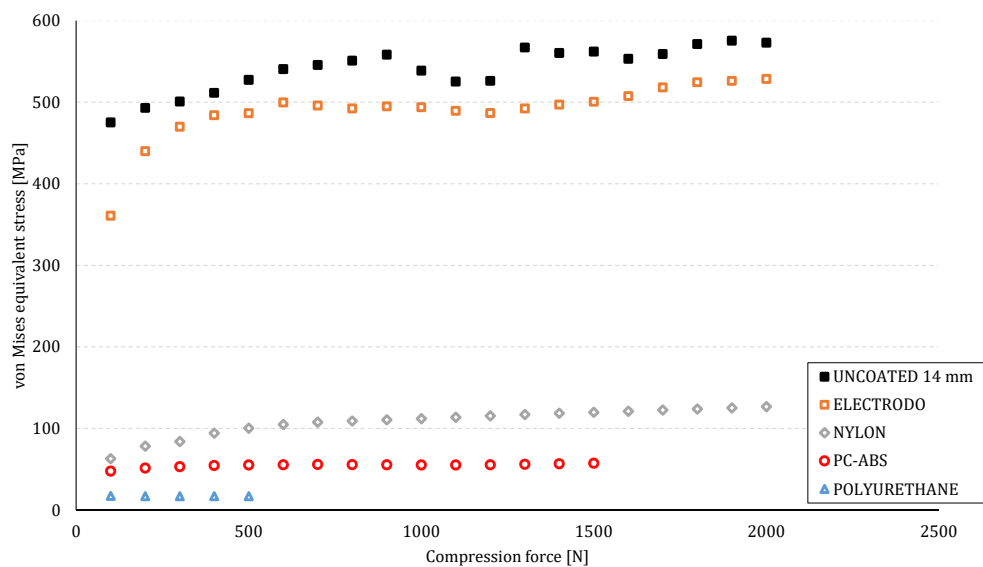


Figure 4.4: von Mises equivalent stress - base material 1045.

From Figure 4.3, referring to the simulation with the base material SAE 1020 steel, it is possible to verify that polymers might not be suited for over 1kN due to possible rupture. The polyurethane supported a load up to 500N and the PC-ABS 1800N, after that, there was a total rupture of the coating. The only polymer that supported 2000N and did not break was Nylon, maintaining the initial objective of protecting the base material. With this, it can be affirmed that the change in the base material did not interfere in the performance of the coating. The results employing the 1045 steel as base material, seen in Figure 4.4, shows a similar behavior. Herein, the polyurethane supported a load up to 500N and the PC-ABS 1500N, after that, there was a total rupture of the coating. The only polymer that supported 2000N and did not break was the Nylon, maintaining the initial objective of protecting the base material.

For the two base material configurations, it is evident that for applications in which the base material will suffer high loads the recommended coating would be the electrode or nylon. In cases of lower loading applications, the other polymers could also be a viable option.

4.2 Equivalent plastic deformation

The results of the equivalent plastic deformation (PEEQ) are presented in Figures 4.5 and 4.6 . The values are extracted as the average value of the critical finite element.

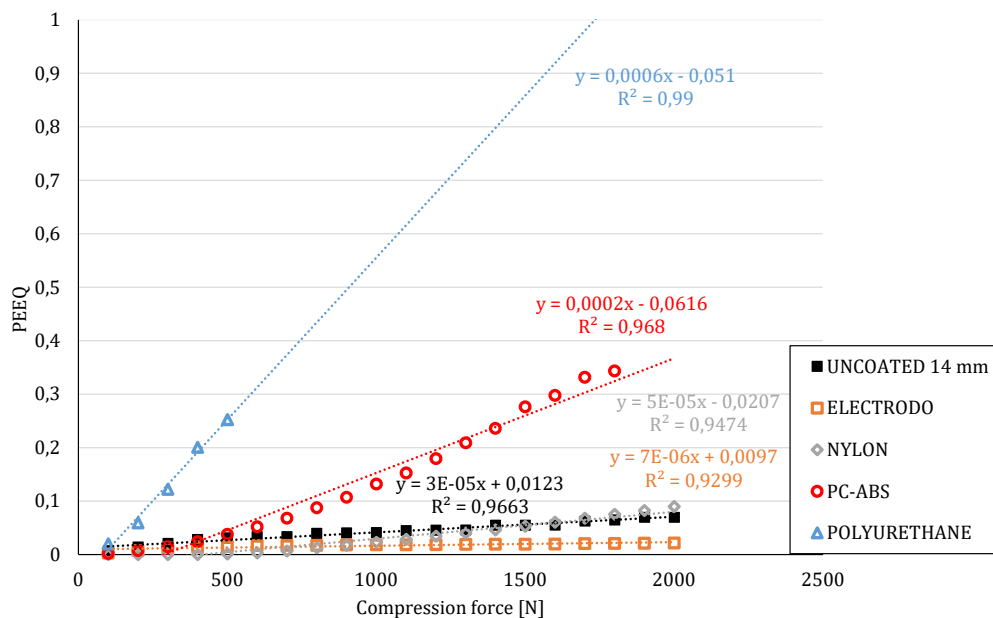


Figure 4.5: Result of equivalent plastic deformation - base material 1020.

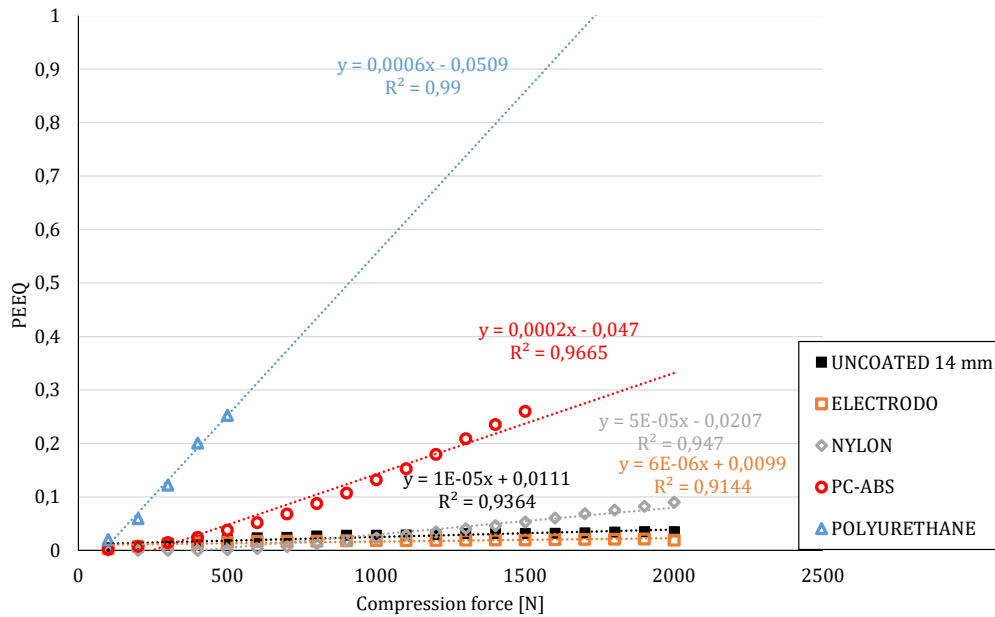


Figure 4.6: Result of Equivalent plastic deformation - base material 1045.

Referring to the simulation with the base material SAE 1020 steel, Figure 4.5 shows that among the coatings studied, the electrode had the best performance with a maximum PEEQ of 0.05, Nylon had a maximum PEEQ of 0.1, Polyurethane had a maximum PEEQ of 0.28, and PC-ABS had a maximum PEEQ of 0.35. The electrode's performance was better than that of the base material SAE 1020 steel, which had a PEEQ of 0.08. This confirms that its use can reflect on the protective increase of the surface on which it is applied. The results employing the 1045 steel as base material, seen in Figure 4.6, shows a similar behavior. Herein, the polyurethane and nylon had a PEEQ of up to 0.28, after that, there was a total rupture of the coating. The only polymer that supported 2000 N and did not break was Nylon, maintaining the initial objective of protecting the base material with a PEEQ of 0.1. The electrode performed similarly to the base material SAE 1045 steel, with a PEEQ of 0.05.

Evaluating the linear equations from Figures 4.5 and 4.6, the first term consists of the evolution of plastic deformation in relation to load. The higher this value, the lower the performance of the associated material. The second term, which is a constant, represents the initial resistance of the material to the increase in plastic deformation. The higher this value, the worse your initial resistance will be. Analyzing the results of the simulated surface coatings, we noticed that for the first term, which is the rate of evolution of the deformation as a function of the load, what has the lowest value is the electrode, followed by nylon, PC-ABS and lastly polyurethane. The electrode has a lower rate of deformation evolution with the increase in compression load in relation to the other coatings studied.

For the second term, which is the constant, we note that what has the highest value is polyurethane, followed by PC-ABS, nylon and finally the electrode. Thus, it is evident that polymers, due to their higher constant value, will have a lower initial resistance to deformation, which will provide less surface protection at higher loads. It is then concluded that for low compression loads, polymers can be used, but with the increase of this compression load, the recommendation is to use the electrode because it was the one that presented the best performance in relation to deformation x load.

The results of the coatings indicate that both the electrode and polymers are suitable for practical applications with low loads. The choice should be defined on a cost-benefit analysis, adapted to the reality of the service. However, for applications where there are high loads, the recommended coating would be the hard electrode, as its high resistance will reflect in a gain in the useful life of the surface on which it is applied.

4.3 Indentation depth

The results of the indentation depth are presented in Figures 4.7 and 4.8. The values are extracted from the first contact node of the critical finite element.

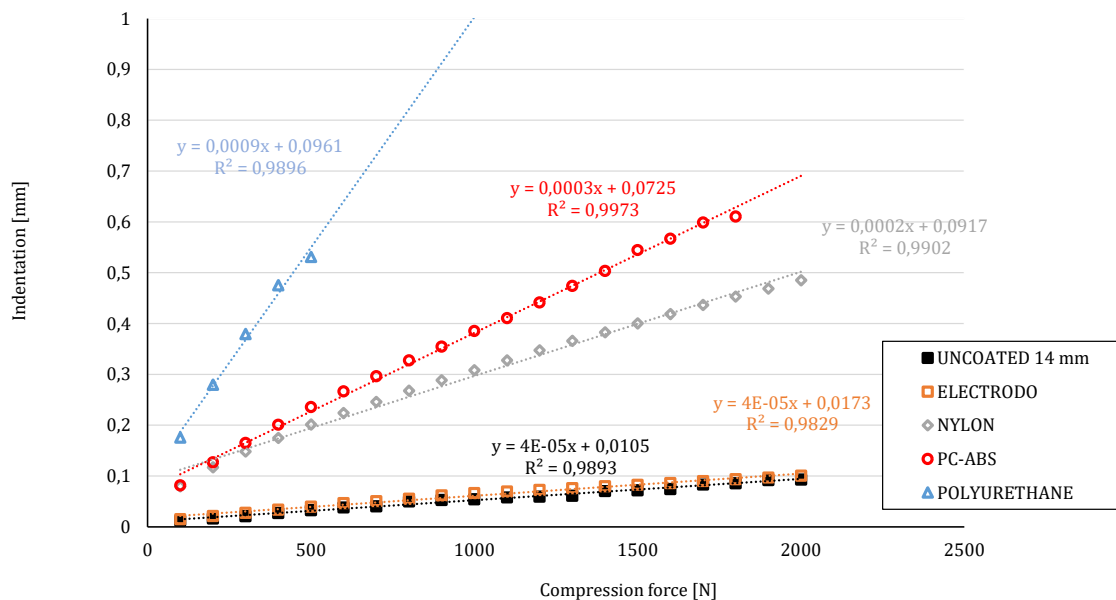


Figure 4.7: Indentation depth - base material 1020.

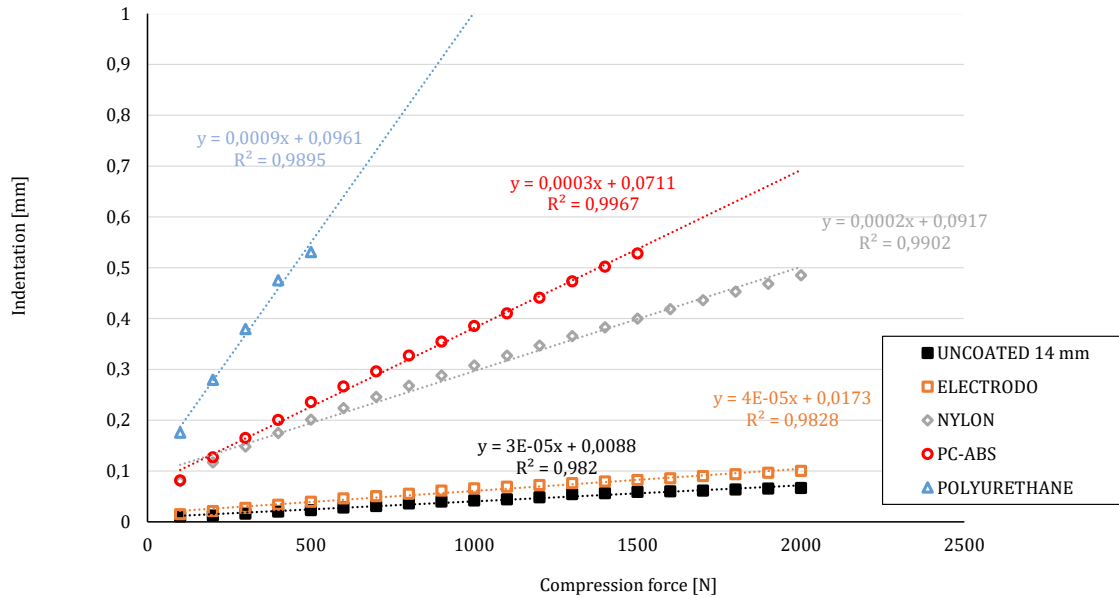


Figure 4.8: Indentation depth - base material 1045.

Referring to the simulation with the base material SAE 1020 steel, Figure 4.7 shows that the hard electrode coating has greater rigidity and obtained less indentation compared to other coatings. The electrode performed similarly to the base material SAE 1020 steel. With a load of 2000N, it reached a maximum of 0.1mm of penetration. Polyurethane had the worst performance, reaching an indentation of 0.5mm and rupture with a load of 500N. Applications with small loads could be an option, but for higher loads, it is not recommended. The PC-ABS has a maximum load capacity of 1800N and an indentation depth of 0.5mm. The Nylon performed better than other polymers. It resisted a load of 2000N and had a maximum indentation of 0.5mm. The results employing the 1045 steel as base material, seen in Figure 4.8, shows a similar behavior. Herein, the electrode performed similarly to the base material SAE 1045 steel with indentation depth of 0.1mm. Polyurethane and nylon had an indentation depth of up to 0.55mm, after that, there was a total rupture of the coating. Nylon had an indentation of 0.5mm, but, among the polymers, it had the best result.

The hard electrode coating performed best for applications with higher loads when compared to other simulated surface coatings. Considering that the purpose of the surface coating is to protect the base material, the only coatings approved for this type of test were the hard electrode and Nylon, however, Nylon had an indentation depth 5 times more than the electrode, which means that with the continued increase in load, it would soon rupture. In view of these facts, the most suitable material for this application would be the hard electrode.

The Table 4.1 shows the maximum indentation depth of coatings.

Table 4.1: Result of maximum indentation (mm)

	Base Material	Electrode	PC-ABS	Polyurethane	Nylon
SAE 1045	0.08	0.1	0.55	0.55	0.5
SAE 1020	0.1	0.1	0.6	0.55	0.5

Evaluating the linear equations from Figure 4.7 and 4.8, the first term consists of the evolution of the indentation depth in relation to the load. The higher this value, the lower the performance of the associated material. The second term represents the initial resistance of the material to the increase of the indentation depth. Therefore, the higher the value, the worse its initial resistance will be.

It is observed that for the lowest value for first term, representing the rate of evolution of the indentation as a function of the load, is the one of the electrode, followed by nylon, PC-ABS and polyurethane. This lower rate of indentation evolution in terms of an increasing compression load, defines the result the electrode coated configuration as the most resistant to compression.

For the second term, which is the constant, it is noted that polymers have a higher value than the electrode. This means that they will have a lower initial resistance to indentation, resulting in less protection of the surface they are applied to.

The hard electrode coating is ideal for practical applications with high loads applied to a surface. It has the greatest resistance to indentation among all simulated surface coatings. This may reflect in an increase in the useful life of the components in which it is applied. It is also important to highlight that the performance of the hard electrode was similar to that of the base material, which is steel.

4.4 Discussion

The results presented in the previous topics show that surface coatings increase the useful life of surfaces they are applied to. The ideal coating is chosen based on the service conditions it will be subjected to, such as absorbed load, type of wear, objective of gaining useful life, and reducing maintenance costs. Each coating has its own unique characteristics and possibilities of use, depending on the objective in question.

The hard electrode coating performed similarly to the base material, from stress distribution to linear equation analysis, with satisfactory results. The hard electrode coating had

the lowest indentation value, reaching a maximum of 0.1 mm at a load of 2000N, which was at least 5 times better than the studied polymers. This indicates that even under high loads, the electrode will perform well and maintain its objective of protecting the base material. The results showed that the hard electrode coating had a low rate of indentation evolution with increasing compression load compared to other coatings studied. It also had high initial resistance to the increase of indentation depth, characterizing a material with higher hardness. The results of equivalent plastic deformation indicate that the material has a low rate of deformation evolution with increasing load, ensuring excellent performance in applications with different types of loads on a surface.

The hard electrode coating had the best performance among all simulated surface coatings. It is ideal for practical applications with high loads applied to a surface and may increase the useful life of the components in which it is applied. However, its high cost of application often makes it unfeasible to use as it requires modern equipment for its application. Therefore, this type of solution is preferred in industrial applications such as excavators, buckets, turbines, fans, hammers, screws, crushing discs and other surfaces that are subject to high wear during field service. Therefore, when making your choice, it is important to consider the relationship between financial impact and gain in useful life associated with the reduction of corrective maintenance.

The polymers had different performances. Nylon supported up to 2000N, while PC-ABS ruptured between 1500N to 1800N and polyurethane ruptured at 500N. Evaluating the results of von Mises and indentation, all had similar results, but when we evaluated the equivalent plastic deformation, we noticed that, among the polymers, nylon was the one that had a smaller evolution of plastic deformation in relation to load, which resulted in a good performance, peaking at a PEEQ of 0.1, while PC-ABS and polyurethane reached a PEEQ of 0.3, approximately. The polymers are not suitable for practical situations with high loads. However, they have a positive point of being applicable at a lower cost. This makes their use possible in practical situations with low compressive loads and with low cost.

For practical applications with load compressive to 500N, the use of polymers is recommended, in this case Nylon, due to low cost. Now, for applications with loads greater than 1000N, the ideal use would be the hard electrode.

Tests were conducted to determine whether the base material would affect the performance of the coatings. The thickness of the base material was varied between 10 and 14mm using both steel 1045 and 1020. In both cases, there was no significant difference in coating behavior. Therefore, the performance of the coating used in practice is independent of the surface characteristics on which it is applied.

The next is the Table 4.2 with variables for choosing the coating.

Table 4.2: Variables for choosing the coating

Coating	Compressive load level	coating price	aplication price
Electrode	over 1000 N	medium	high
Nylon	until 500 N	low	low
PC-ABS	until 500 N	low	low
Polyurethane	until 500 N	low	low

Finally, the use of surface coatings today is a technique for surface protection in various field applications, often used in the reconstruction of lost dimensions in a part due to wear, load absorption and wear prevention. The purpose of applying wear-resistant coatings is to increase the useful life of equipment or surfaces and reduce the cost of early corrective maintenance. Any of the coatings used in this study can be applied depending on the load requirements and the ease of application versus cost of application trade-off.

Chapter 5

Conclusion

This work presented the surface coating behaviors when subjected to severe compressive loads. Computational modeling were carried-out in the following five configurations:

1. 14 mm of base material (reference condition);
2. 10 mm of base material + 4 mm of hard electrode;
3. 10 mm of base material + 4 mm of Nylon;
4. 10 mm of base material + 4 mm PC/ABS;
5. 10 mm of base material + 4 mm of Polyurethane.

In each simulated configuration, load of 2000N were applied. The results of von Mises equivalent stress and equivalent plastic deformation studied in this work were extracted from the averages of the 8 contact nodes of the first finite element and the results of indentation depth were extracted from the central contact node (i.e. critical region) and compared to each other. This evaluation was carried-out using the linear regression equation obtained for configuration of indentation depth and equivalent plastic deformation . The goal was to determine the critical load that each material supported, the evolution of their stress distribution, indentation depth and total equivalent strain.

The main conclusions drawn from this study are:

- The use of surface coating does provide protection against compressive loads, preventing premature wear of the base material. In this work, all the coatings had benefits to the surface on which it was applied;
- Simulation was carried-out with base material SAE 1045 and SAE 1020, and the results obtained related to the behavior of the coating (electrode and polymer) were similar. This was expected, since the electrode material is also steel;

- The hard electrode behaved similarly to the base material, from the stress distribution to the analysis of the linear regression equations. It was the coating that stood out among all those studied in this work because it presented a low rate of stress evolution in relation to the load subjected, high initial resistance to indentation and a low rate of deformation. This coating is ideal for applications where there are high loads, in industry it is common to be used in crushers, truck buckets, excavators, press hammers, among others, making clear its importance in protecting surfaces, resulting in reduced maintenance corrective costs;
- Polymers had a lower improvement than the hard electrode. However, for moderate loads they can be a good option due to their lower application cost, which makes their use more viable in relation to the electrode. Among the polymers, the one that had the best performance was the Nylon which supported up to 2000N and had a better resistance to plastic deformation indentation. PC/ABS and Polyurethane exhibit fracture at 1500N and 500N, respectively. Thus, for loads below 2000N, Nylon would be the option to use with the possibility of using a gain in the useful life of the surface on which it is applied.

Finally, it is evident that protective surface coatings generate improvements against premature wear of the base surface, which reflects in the gain of useful life, reduction of costs with corrective maintenance, generating a productive gain. For applications with more severe loads, the use of hard electrode coating is recommended, in which its base material is steel. As for applications in which there are small loads, the use of polymer is recommended, and among the 3 studied in this work, it would be Nylon, as it was the one that had a satisfactory performance up to a load of 2000N.

Although the results of this work are satisfactory for identifying the influence of the use of coatings for surface protection, more research is needed and for future studies it is necessary to carry-out experimental tests in the sphere-plane configuration to confirm the numerical results presented in this work. It is also important to study more loading conditions and to include more commercially available coatings.

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