Experimental and numerical assessment of impact wear resistant coatings: mechanical characterization and surface optimization

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Abstract. The failure process of the protective structures, such as the frame of a flail mower, is mainly caused by the impact of particles with varied geometries and weights. Moreover, the continuous and cyclic nature of the loading conditions affecting protective systems often responsible for the development of erosive wear. This work presents impact wear resistance assessment of the SAE 1045 steel in two surface conditions: uncoated and with an electrode surface treatment. The goal is to evaluate the influence of coating's mechanical properties, such as resilience, elastic modulus, hardness and roughness, on the failure mechanics of the substrate. Sphere-to-flat compression tests are performed on samples of each surface configuration. Both monotonic and cyclic tests are carried-out. Results are used for the calibration of a finite element model of the problem. Simulation of various surface configurations and loading conditions are presented and a solution for the life enhancement of a specific protective system is proposed.

Keywords: Surface Testing; Impact Mechanics; Coatings; Finite Element

1 Introduction

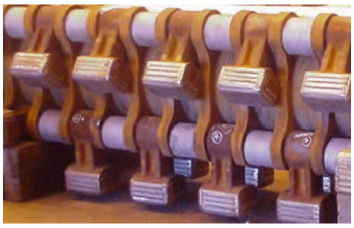
Due to the constant need for higher efficiency and lower costs, the machinery employed by the modern industry are often subjected to severe loading conditions and continuous operation. In this setting, premature failure of mechanical components are frequent and a common solution to prolong their service life is the use of surface treatments or coatings. According to Hogmark, Jacobson and Larsson [2], the use of coatings to improve the tribological properties of components such as cutting tools gears and bearings is constantly increasing. Coating composites are being designed to improve mechanical properties such as stiffness, hardness and fatigue resistance.

According to Lima [3], in the sugar and alcohol industry, several mechanisms, such as chopping knives, suffer material loss due to wear which leads to a significant increase of operational costs. The application of coatings are being used to mitigate this problem. The increase in wear resistance leads to lower maintenance costs, increase of the service life of mechanical components and improvement of the efficiency of the process. Types of coating such as coated electrode, tubular wire and even composites are used to protect surfaces that are subject to some type of wear. For Burakowiski and Wierzchón [4], coating is a line 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. According to Holmberg and Matthews [5], currently hard coatings such as titanium nitride, titanium carbide and aluminum oxide are used in cutting tools, in order to increase their durability. 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.

One of the surface coatings adopted in this study is the hard coating, applied by welding. For Hutchings [6], 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. 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 [7]. 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.

Buchanan [1], affirm 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. The application of this hard coating has increased in recent years in the industry and in equipment that suffer excessive wear, as we can see in Figure 1.

(a) Crusher discs.



(b) Hammers.

(c) Shredders.

Figure 1. Hard coating application at industry. [9]

The use of coatings provides a significant increase in the hardness of the applied surface and an increase in wear resistance. For Conde [8] the properties that the coatings provide can be summarized as: hardness, wear resistance and impact resistance, resistance to high temperatures and friction. Kotecki and Ogborn [10] state that the increase in hardness improves wear resistance. In this work, the hard coating that will be used is WI DUR 33 - WELD-INOX, which is a coated electrode.

According to ASTM [11], wear is defined as ”the deterioration or damage of a solid surface, usually with loss of material, due to the relative movement of this surface in contact with another or other substances”. In this work, just some types that wear will be abordad how: erosive wear, abrasive wear and impact wear. Erosion is a process of abrasive wear so that the repeated impact of small particles moving the fluid against a surface results in the removal of material from that surface [12]. According to Bitter [13], erosion is defined as: ”Material damage caused by the attack of particles entrained in a fluid system, impacting the surface at high speed”. Erosive wear modeling has a common problem in the study of different types of wear, which corresponds to a large number of variables related to the tribe-system, which can influence the rate of material loss.Some of the variables that affect erosion can be classified into three Topics [14] and [15]: Impact angle; Particle speed; Particle concentration; Rotation of particles on impact. Impact time Particle shape; Particle density; Particle size. Young’s modulus; Poisson’s ratio; Plastic behavior; fluid nature and temperature; Failure behavior; Hardness of materials.

According to ASTM G40 [11], abrasive wear is defined as the loss of mass resulting from the interaction of hard particles that are forced against a surface. Therefore, abrasive wear is characterized by material loss due to the passage of hard particles on the surface. Abrasive wear occurs due to pressure parallel to the movement of hard particles on other solid surfaces. As a result, it is natural to “pull out” material, and this fact is related to the hardness of the particle and the hardness of the surface. Other properties have an influence on this wear mechanism, such as: ductility, elasticity module, crystal orientation and material microstructure [6,11].The following are other parameters that influence abrasive wear according to Hutching [6]: particle hardness; particle shape; particle size; angle and penetration. According to Conde [8], impact wear is characterized by the shock between two or more bodies, which produces a deformation in the contact area, whose magnitude is associated with the energy consumed in the impact. Two mechanisms act in this type of wear and it depends and depends on the hardness and toughness of the materials. The first mechanism involves surface deformation and the second is the fracture of the material due to repetitive impacts [3].

For the evaluation of the characteristics of the base material on a surface, the indentation test is generally used, in the relationship between load and displacement. With this, it is possible to measure or have a value very close to the hardness, the modulus of elasticity, the stiffness, the toughness information, among other mechanical properties. More information on the subject can be further detailed at: Lee [19]; Ogasawara [20]; Chen [21].

The goal of this work is to evaluate the influence of the mechanical properties of the coating, such as resilience, modulus of elasticity, hardness and roughness, on the failure mechanics of the substrate. The coatings studied in this work are coated electrode (hard coating). Characterization tests, simulation of various surface configurations and loading conditions are carried out. Finally, a solution to improve the life of a specific protection system is proposed. Computational simulations are performed using with Abaqus CAE v6.14® commercial package.

2 Methodology

Characterization tests were prepared, such as hardness, impact, traction and compression with sphere - plane configuration, for the evaluation of the hard coating: WI DUR 33 coated electrode. Subsequently, the commercial software ABAQUS was used for the numerical simulations of the test with sphere-flat configuration and comparing Hertz analytical results. With this, the influence of the use of the coating on the surface protection and properties such as elastic modulus, hardness, rupture mechanics will be analyzed. It is expected that the use of a coating will increase the hardness of the surface to which it was applied, decrease the wear, does not affect the original properties of the base material, absorb more impact energy and, with this, can be used as protection of surfaces of materials that suffer excessive wear.

2.1 Characterization Tests

One specimen for the hardness test was prepared with SAE 1045 steel material. Its surface was properly sanded, polished and cleaned to receive the surface coating, the WI DUR 33 coated electrode. The Rockwell C hardness test was carried out on the DUR 150 machine. The load used was 150 kgf, 10 kgf preload and a 120 ° tapered diamond penetrator. For the impact test was prepared other specimen with SAE 1045 steel material, with and without WI DUR 33 electrode coating on its surface. The size of these samples are 10 X 10 X 55 (unit in millimeters). The impacting energy was up to 150 Joules, the impact speed was 5 m/s, 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 m. For the tensile test was prepared other specimen with SAE 1045 steel material, with and without WI DUR 33 electrode coating. The tensile test was carried out on the MTS 809 machine and consisted of breaking the specimen. The load used was 85 kN. The properties of the materials used in the specimens are: Young modulus: 210 GPa; Yield Stress: 350 MPa; Poisson's ratio: 0.33; Specific mass: 7870 kg/m³.

The Rockwell C Hardness tests revealed a significant difference between the coated and uncoated surfaces: Uncoated - 14.3 HRC; Coated - 54 HRC. Comparing these results, the use of the coating on the surface of the specimen, brought an increase of more than 250 % of hardness on its surface. The results of the tensile test are shown in Figure 2 and it was possible to infer that the inclination of the straight line of the tensile test with coating decreased, which reflects in the decrease in the elasticity modulus. For the analysis contained in the simulation, elastic behavior up to 0.4 % and perfectly plastic up to 1 % was considered, this was necessary because the machine that the test did not break the material due to its limitation.

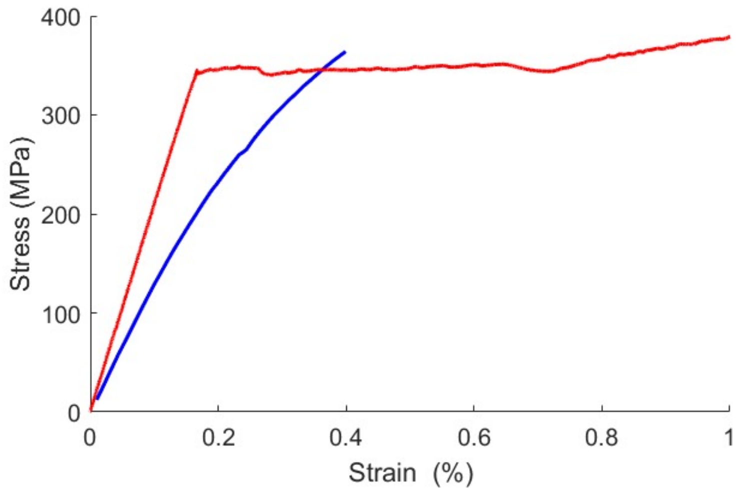


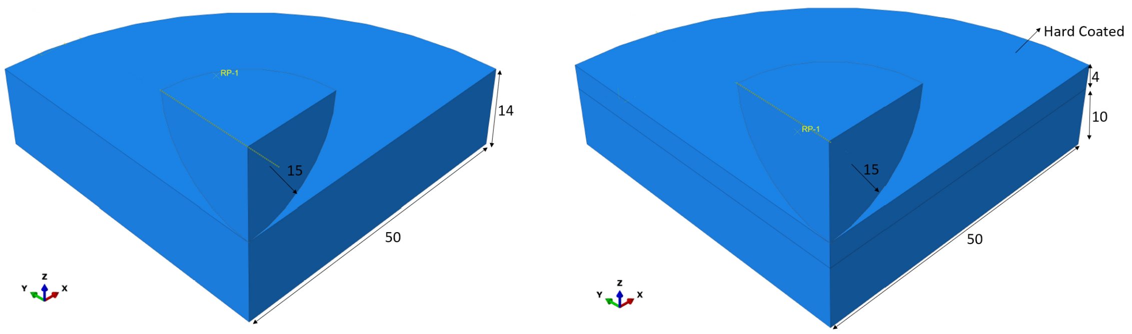
Figure 2. Tensile test results for the Uncoated specimen (red curve) and Coated specimen (blue curve).

In analyzing the results obtained in the impact test, it was observed that despite the fact that the coated configuration has a harder surface, the material continued to behave as a ductile material, breaking at 45° angle. The energy absorbed in the uncoated specimen was approximately 12 Joules, while in the coated specimen it was in the range of 15 Joules, having over 20 % increase in the ability to absorb impact energy.

2.2 Modeling

The computer simulation was performed using the simulation package ABAQUS CAE version 14.6. First, a simulation of the sphere-flat configuration was performed, with a load of 100, 200 and 300 N with the coated and uncoated surface. The geometry used in the numerical simulation is defined through quadrants observed in the contact regions, as shown in Figure 3, with dimensions in millimeters. The material applied in the simulation uncoated was SAE 1045 steel, for both the disc and the hemispherical pad.

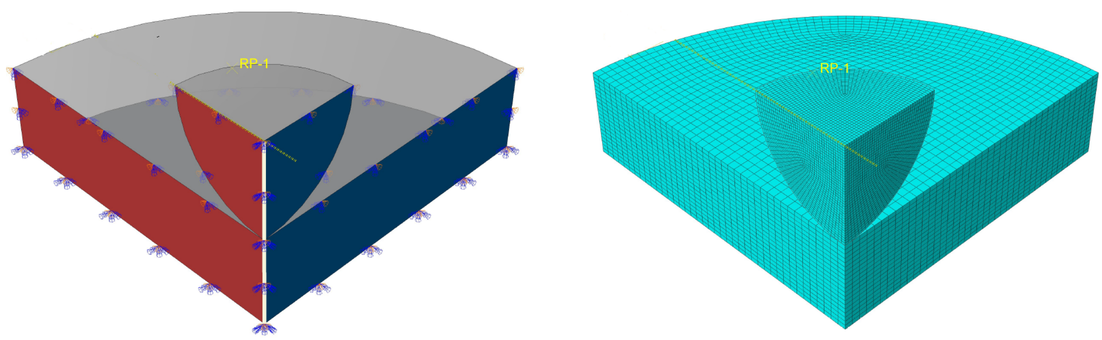
The Young's modulus of the coating was obtained from the tensile test extracted from the traction test with the stress x strain graph, being used: Young modulus: 140 GPa, Specific mass was considered cast steel: 7400 kg/m³ and the plasticity was considered perfectly plastic. In the coated simulation, was considered the application of 4 mm that hard coated.



(a) Assembly - 1 quadrant : uncoated model. (b) Assembly - 1 quadrant: coated model.

Figure 3. Assembly and geometry used in the simulation.

The contact used is of the "surface-to-surface" type Explicit, which the external surfaces of the rigid geometries are the "master" surfaces and the geometry nodes related to the target material which are the "slave" surfaces. The boundary conditions of the flat disk were restricted in all directions, leaving it fixed, and the Eighth was restricted from lateral displacement and a force of 100, 200 and 300 N was applied. Such boundary conditions can be seen in Figure 4-a. The mesh used is of the C3D8R type (3D stress family, linear order, hexahedron with 8 knots, with reduced integration, first order and with maximum degradation). Figure 4-b shows the numerical model with the mesh applied.



(a) Boundary conditions. (b) Finite element discretization.

Figure 4. Numerical model: sphere-plane configuration.

The contact formulation was - Type Contact: "Surface-to-Surface"; Tangential Behavior: No Friction; Normal behavior: "Hard contact" "Default"; Slip formulation: "Finite Sliding"; Mesh: Family C3D8R; Disc - flat: 30720 elements; hemispherical pad: 32000 elements; hard coated: 30720 elements.

The choices the formulation contact were due to the "Surface-to-Suface" method offering more consistent results, considering the no - friction because it is a problem that seeks Hertzian solutions, using "Default" (penalty method) and " Finite Sliding "to calculate the contact area and pressure distribution on the contact. For validation of the computational model, the classical Hertz's formulae [17,18] were used and applying the linear elastic material. The variables analyzed were the indentation and the normal contact pressure. The next, in Table 1, are presented the analytical results of: indentation distance and maximum contact pressure.

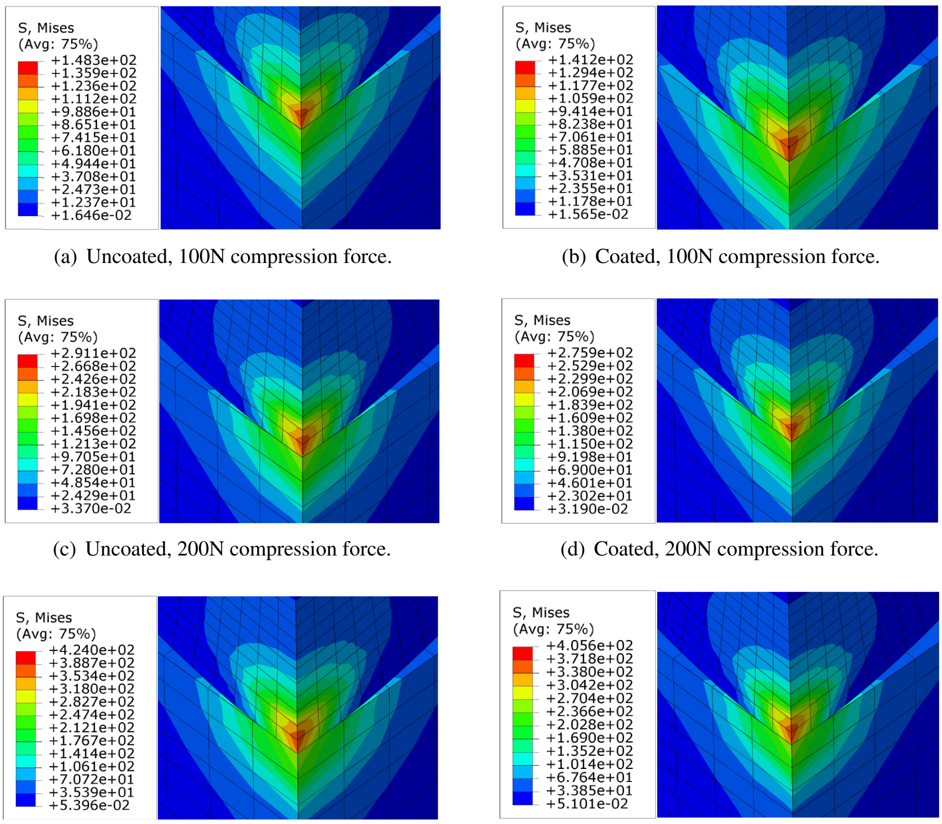
Table 1. Model validation

Force (N)	Indentation Distance (μm)			Contact Normal Pressure (MPa)		
	Analytical	Model	Error (%)	Analytical	Model	Error (%)
100	14.9	15.4	3.35	129.1	134.7	4.33
200	16.3	17.1	4.91	276.7	287.5	3.90
300	18.6	19.2	3.22	363.3	381.3	4.95

When comparing the analytical result with the numerical results without coated, such as indentation, we note that for a force of 100, 200 and 300 N the analytical result was 14.9; 16.3; 18.6 respectively, and the numeric was 15.4; 17.1; 19.2 respectively. Units in micrometer. Thus, the error was less than 5 %, which validates the model.

3 Results

Next, in Figure 5, the numerical estimations for the equivalent von Mises stress are presented. When comparing the results of the equivalent von Mises stress, the model that uses coating with the model that does not use coating, we noticed a small decrease in the von mises tension in the range of 5 %, in the coated model.



(a) Uncoated, 100N compression force.

(b) Coated, 100N compression force.

(c) Uncoated, 200N compression force.

(d) Coated, 200N compression force.

(e) Uncoated, 300N compression force.

(f) Coated, 300N compression force.

Figure 5. Equivalent von Mises stress distribution (MPa).

Even with a 5 % decrease in the Equivalent von Mises stress distribution on the coated surface, its behavior can be considered similar on both surfaces. The next, in Table 2, are presented the results of the indentation depth and the normal contact pressure observed for the Uncoated and the Coated surfaces. All values were obtained from the first contact node.

Table 2. Results of the uncoated and the coated surfaces

Force (N)	Indentation Distance (μm)		Contact Normal Pressure (MPa)	
	Coated	Uncoated	Coated	Uncoated
100	14.4	15.4	254.1	134.7
200	16.2	17.1	508.3	287.5
300	18.0	19.2	720.6	381.3

The use of the surface coating decreased the indentation by about 6 % in the 3 loads conditions: 100, 200 and 300 N. The contact normal pressure increased by 88 %, 77 % and 89 % for loads of 100, 200 and 300 N respectively. These changes may have occurred due to the increased hardness on the surface due to the coating, better energy absorption capacity than the surface coating used provided.

4 Conclusions

Analyzing the results obtained, it was possible to observe that the coated electrode provided an increase in hardness of more than 250 % and an energy absorption of more than 20 %. It is also worth mentioning that the modulus of elasticity was reduce. The analytical results and the computer simulation of the sphere-to-flat configuration have shown similar results (relative error lower than 5 %), validating the numerical model. When comparing the results of the numerical simulation with and without the use of surface coating, it is observed that the coated counterpart shows lower indentation while leading to a higher normal contact pressure. This behavior is linked to the hard coating's higher rigidity, which provides more resistance to the substrate.

The numerical results have shown that the equivalent von Mises stresses distribution on the coated surface decreased by 5.03 %, 5.5 % and 4.5 % and reduction in indentation of 6.9 %, 5.5 % and 6.6 % for loads of 100, 200 and 300 N respectively. It is concluded that the use of coating made possible an increase in the protection of the surface, allowing a gain in the useful life, when applied in equipment that suffer similar damages. At normal contact pressure, there was an increase of 88 %, 77 % and 89 % for loads of 100, 200 and 300 N respectively.

The results show that the increase in hardness lead to a positive impact in the resistance of the SAE 1045 steel. In order to confirm this effect, experimental tests (employing a spherical indenter and coated flat counterparts under severe levels of plastic strain) is planned. In addition to the electrode coating, surface protections such as polymeric layers will also be tested. This new set of experimental data will allow for a comprehensive analysis of surface protection solutions against abrasive, erosive and impact wear.

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