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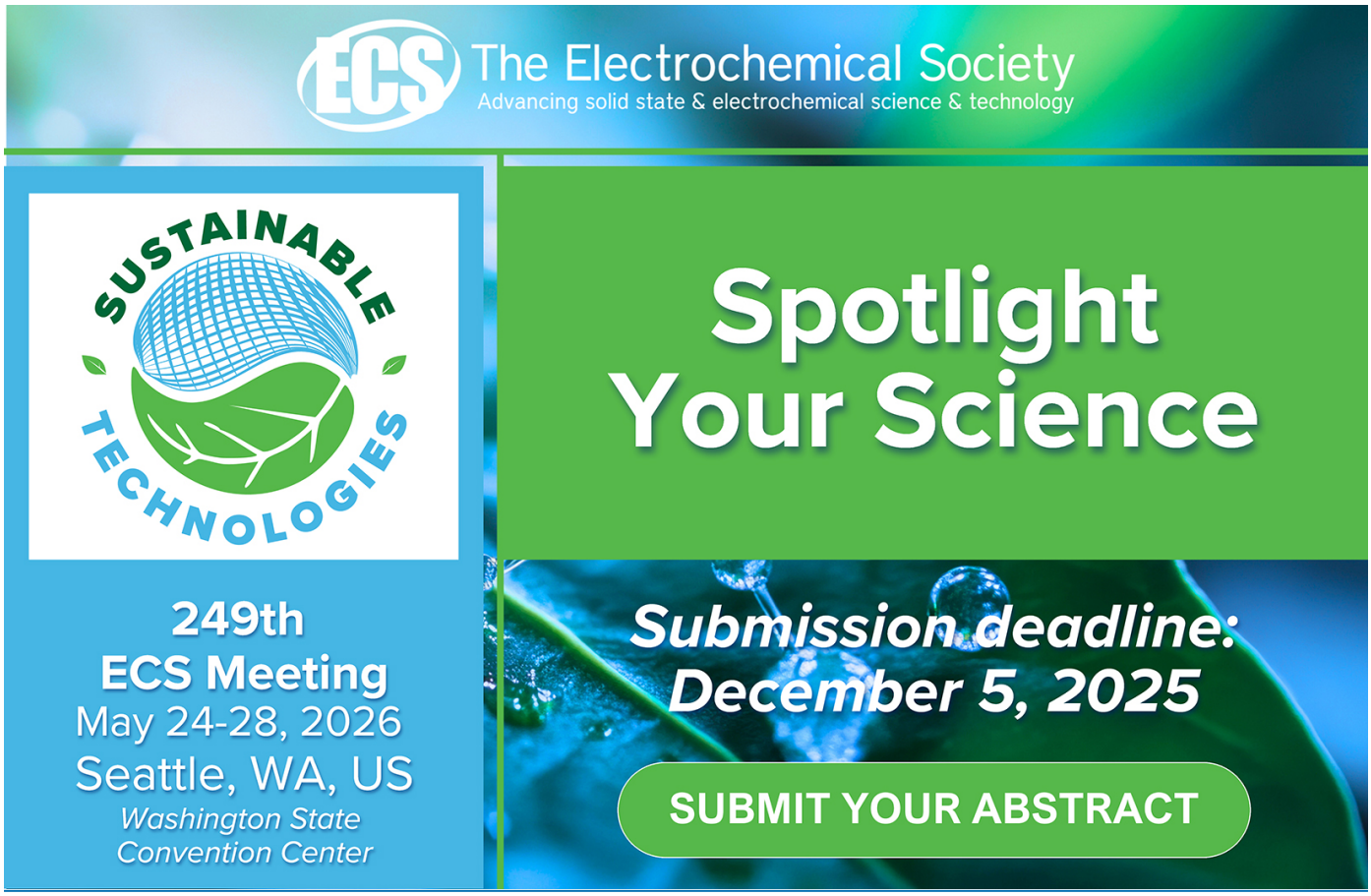
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Numerical analysis of a tire shredder machine to produce rubber particulate material

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Abstract. The main objective of this work is to develop a numerical analysis of a shredder machine to generate rubber particulate material for its implementation in different sectors such as construction, artisanal, and road as aggregates in the raw material. As part of the methodology, modern design theories were considered to select the materials for the different elements of the crushing machine; for this purpose, the SolidWorks design software was used to obtain a conceptual design model of the prototype. The mathematical and numerical results indicate that the prototype of the crushing machine will work in good conditions, always guaranteeing high levels of safety and performance based on the mechanical and physical properties of the materials selected through the design theories. Likewise, this machine will be low-cost to promote growth and competitive capacity for studies of different products with rubber aggregates to solve global environmental problems. Finally, the physical behavior of the new materials can be obtained with rubber particles aggregate will allow evaluating and optimizing a different kind of products that can be used in different sectors aiding sustainability sources.

1. Introduction

End-of-life tires (ELTs) have become a pollution problem worldwide due to the high demand in the automotive sector. Rubber, the primary material with which tires are made, is not biodegradable, which generates a great long-term environmental impact [1]. Tires reached a worldwide production of around 1.53 billion units, a number that continues increasing due to the demand that arises with the manufacture of more Tires to replace those that have already reached their useful life. Once their cycle has been completed in automobiles of different types (trucks and cars, mainly), the tires should preferably be eliminated employing effective recycling on a large scale that achieves the reconversion of this material and can be reused [2]. Currently, industry transport is considered one of the main areas in the economy worldwide because food, products, and services such as land and air passenger transport are traded.

For the final tire disposal, a percentage of the tires are stored in sanitary warehouses, and another relatively low percentage is used for retreading and mechanical crushing processes. Thus, acceptable use of this type of material can be established, thus minimizing the impact by recycling tires and subsequent use as an additive in different products with improved products properties (sustainability) [3]. Discarded tires in deposits are the ideal habitat for the proliferation of pests, such as rats and mosquitoes, which transmit different diseases to humans. Due to the large number of tires discarded annually, the collection and recycling process in the post-consumer stage becomes a difficult task to perform [4,5]. Considering the case of Colombia, approximately 10 million tires were sold in the last year, which a large part after their useful life, which was stored in clandestine deposits of waste of all kinds such as garbage dumps, housing yards, public spaces, tributaries, water, streets, and parks

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generate serious consequences in environmental, economic, and health terms [6]; so far in Colombia, there is no good way to recycle tires, and therefore, the most viable way out without measuring the environmental consequences is the burning of this product. On the other hand, although the rubber of the tires is tough to generate its conflagration, once they ignite, their calorific value is very high, making them a cheap and ideal fuel for some industrial furnaces that depend on being lit 24 hours per day and 365 days of the year in cement industry considering that is the primary use of energy and raw material for its furnaces. Coal is an alternative fuel, and the thermoelectric industries where the boilers are fed mainly with particulate material from tires and generate electric power [7,8]. As an alternative to recycling tires and their particulate material, have been used as raw material for the production of asphalt pavement, which was a success with its application in countries such as Canada, the United States, and Spain, because this material Particulate provides the pavement with mechanical and physical properties such as flexibility and elasticity, which increase its useful life up to 50% in the cost of asphalt production [9].

In this research work, the prototype design of a tire crusher is proposed to obtain rubber particulate material and thus manufacture products using aggregates of this particulate material with different granulometry (synthetic court grass, decoration, pavements, and others). For this purpose, concepts and theories of mechanical design were applied. On the other hand, this machine will divide the components of the rims, taking advantage of the qualities of vulcanized rubber without generating any contamination and exploiting to the maximum its practically indestructible potential to reuse it (not destroy it, nor burn it), which can be a great opportunity to allow adequate disposal of this type of waste that by law importing and producing companies of tires must collect. Finally, the physical behavior of the new materials obtained with rubber particle aggregate will evaluate and optimize different kinds of new products based on recycled rubber material.

2. Methodology and materials

With the development of this research work, a machine was designed for the crushing of tires used in automobiles, resulting in rubber particulate material, which can be used in future research works for different applications, such as the grass of synthetic courts, additive in road paving, decorative floors, among others [10,11]. Mechanical crushing is the most viable option due to its easy use, construction, and low cost, significantly reducing the considerable amount of used tires accumulated in landfills, thus reducing the environmental impact. The main purpose is to find another life cycle to the pulverized material of rubber after its manufacture, serving as support to other investigations with which it will be given its potential use, where polluting emissions to the environment will be significantly reduced due to its possible use in furnaces. The crushing or grinding is when a reduction in the volume of material in smaller size particles or granulometry is obtained, which can be used as additives in different industrial sectors or production processes [12]. The crushing machines used to pulverize the tires use a simple principle of the shear-type employing blades located along the axes that rotate (1 axis or 2 axes). These axes have the function of catching and shredding the initial product when the crushing is going to be carried out. Generally, two-shaft shredders are used, ideal for their particular structure and obtaining particulate material of large geometries or difficult to process [13].

2.1. The rims or tires

A tire, also known as a tire or rim in different parts of the world, is a toroidal element of rubber that is used in the wheels of various vehicles and machines. The primary function of this element is to generate an adequate contact by adhesion and friction with the pavement, making it possible to start, stop and guide the vehicles during motion [14]. The mechanical, chemical, and physical properties of these materials have been improved over time, depending on different factors such as climate, storage conditions, and conditions of use (load, speed, inflation pressure, maintenance, and others), that generate wear in the life cycle for which they are used. After their use, it is not easy to establish the environmental impact these materials generate under the different forms of recycling [15]. This elastic element is made of rubber that is used mainly in the wheels of vehicles. These are intended to support vehicle loads to

facilitate movement on the surface (adherence) [16]. The tires are made up of the following important elements: The tread is a layer of rubber with grooves that facilitate traction on the surface to move and stop the vehicle. The body comprises layers of textile interspersed over the rim's structure, which provides strength and shape. Finally, the beads are the two lines of steel cords that hold the rim located along the inner edges.

2.2. Materials used in the manufacture of tires

The rim is a material made of different materials such as fabrics, rubber compounds, textile materials, steel, synthetic fibers, among others, used in its structure to form this product of the automotive industry. To obtain shape tires, it is necessary to use robust and specialized manufacturing equipment to guarantee quality and functionality during its operation. Also, the main materials used in manufacturing tires are natural rubber, synthetic rubber, carbon black, steel, filled, and new tire weight [17].

2.3. Recycling process

Recycling is a physicochemical or mechanical process, which consists of subjecting a material used to a total or partial treatment cycle to obtain raw material or a new product, which can be implemented in a new one in the life cycle [6]. The recycling process is also defined as recovering discarded solid materials and reusing them as raw materials to manufacture other products, generating economic, social, and environmental benefits. First, it is important to recycle harmful materials because the recycling sector generates sources of work in unskilled labor. Second, it allows the generation of new low-priced raw materials with similar properties. Third, notice that it can be used as additives to improve and evaluate the behavior of new products, and finally, the recycling process reduces the final disposal of wastes that contribute to the deterioration of ecosystems and the environment [18].

The tire life cycle is the set of stages that begin with producing a new tire and continue with the first use (retreading), and, later, it can be used again in second use. The ELTs culminate when the tires reach the end of their useful life, turning them into ELTs arranged for direct burning, fillings (retaining walls), landfills, recycling mechanical (particulate matter), or advanced alternatives such as pyrolysis. The materials separation of the tires is made a complex recycling process due to the separation of these elements of different nature, which, when processed, are useful as raw materials for the production of asphalt, rugs, athletic tracks, decoration, among others [18]. When tires are not recycled, they are used as fuel due to their great calorific potential or buried, which causes a tremendous long-term environmental impact since they contaminate water sources and the soil [1].

2.4. Mechanical design process

For the mathematical calculations, the Shiley design book [19] and different catalogs were taken into account to select mechanical elements (gears, blades, and the motor). For the conceptual design of the machine and elements, the SolidWorks 2017 [20] student version software was used, to obtain the conceptual design of the shredder machine. Besides, the finite element analysis (FEA) was carried out to evaluate the correct selection of the geometries and physical performance of the mechanical elements designed. Design models and concepts were generated through the methodology proposed by [21-23].

3. Results and discussions

The application of the shredded tire has been determined for: light fillings, athletic tracks, thermal insulation, insulation, acoustic, multipurpose tracks, mats, safety pavements, landfill covers, footwear, road, and railway equipment [11,15]. The use in the improvement on the mechanical, physical, and chemical of the properties of the tires, such as: marking of the sides of the roads, containment element in parks and playgrounds, breakwaters, traffic obstacles, artificial reefs for fish and shellfish farming, among other applications in the construction and structure sectors. For an adequate crushing for the potential ELTs applications, it's necessary considering the use or application required [24]. The crushing process is usually carried out through systems with more than two parallel axes of blades, rotating at different speeds. Note that the separation of the axes defines the size of the pieces obtained.

3.1. Design parameters

The parameters shown in Table 1 were established according to the different bibliographic sources consulted, to start with the design of the tire shredder machine.

Table 1. Parameters considered to the design of the shredder machine.

Parameter	Consideration	
Average of the most used tires	R22.5	
Average mass	~35.38 Kg	
Average of the revolutions during 3 min by 707.6 Kg/h	About 20 tires per hour	
Average cutting force for wire	Ø = 1.6 mm is equal to 162 KN	
Average deformation of the maximum force for the wire	Ø = 1.6 mm is equal to 7.23 mm	
Average operating speed for crushing	n = 20 rpm	
Other considerations	Blades	Spacers
Diameter	300 mm	200 mm
Thickness	35 mm	
Quantity	16 in each axis	15 in each axis

The estimated power and torque mathematical calculations were performed based on mechanical design theories considering the parameters presented in Table 1. Thus, the total mass ($W_{total} = 974.1$ N) was calculated for a needed cutting force power in each axis of 68.24 HP. For the static load axle calculations, the following maximum moments and forces were determined for cutting the tires: $M_{max(2)} = 630.89$ Nm, $F_{max} = 162$ KN and $M_{max(1)} = 25{,}717.5$ Nm; resulting in a maximum touch of $T = 24{,}300$ Nm. Likewise, a safety factor value of $sf = 1.4$ was defined according to the specifications of the Shigley design book [19] to estimate the diameter of the shaft, with the mechanical and physical properties of AISI 1050 CD steel used for the construction of the machine elements as follow: specific weight ($\gamma = 76.5\ KN/m^3$) and density ($\rho = 7798\ Kg/m^3$), yield strength ($Sy = 580$ MPa), ultimate strength ($Sut = 690$ MPa), and Brinell hardness ($HBN = 197$).

The dynamic load shaft calculations were estimated using the modified Goodman diagram that considers bending and torsional moments in shafts, and Equation 1 was used. A diameter value of $d = 93.5$ mm was obtained, but a recalculated axis diameter of $D = 0.178$ m $= 178$ mm was calculated for the correct function of the machine considering a size factor of $Kb = 0.85$. Notice that n is the operating speed (20 rpm) for low crushing speeds, Sy is the tensile strength (580 MPa), M is the maximum momentum (25,717.5 Nm), and T is the maximum touch (24,300 Nm) previously calculated.

$$d = \left[\frac{16\times n}{\pi\times Sy}(4M^2 + 3T^2)^{1/2}\right]^{1/3}. \quad (1)$$

For the estimation of the shaft life (N), the equations for steels with $BHN \leq 500$ were used, obtaining a value of $N = 2.4163 \times 10^{25}$ for infinite life because it exceeds the 10^6 cycles, with a static beam deformation due to transverse load reaching a value of $\delta = 1.439$ mm. The blades are in the calculated resistant circular section of the axis (D), which have a section is calculated as $A = (\pi \times D^2)/4$; note that shredder manufacturers recommend hex section shafts to withstand the stresses of the rotating blades obtaining an area of $0.6495 \times D^2$. For a hexagonal section of: 20,578.76 mm^2 with diameter 178 mm, similar to [23,24]. Subsequently, considering the maximum cutting force of 162 KN, deformation at the maximum force of 7.23 mm, and the cut area of 128.68 mm^2 AISI 4140 steel was established ($Sy = 1{,}590$ MPa and $BHN = 486$, with a safety factor of $sf = 2.5$). The transmission system was designed to consider the calculations shown in Table 2.

Considering the results presented in Table 2 was selecting a Baldor reducer engine. The transmission system was designed taking into account the following characteristics of the gear motor: motor power of 200 HP including service factor at heavy load, at 1,780 rpm with 63 rpm of output, for a designation 4 and N° 240 lubrication type B per bath or disc was established, with a real distance between centers

of $C_{real} = 119.142$ in, considering these assumptions, the gears were selected. Table 3 summarizes the calculations for the gear and bearing system considering no energy loss. Also, the useful service life (L10) of this mechanical element considering 8 hours per day is $L10 = 3.51$ million revolutions.

Table 2. Calculations of the transmission system.

Design consideration	Value
Power (H)	50890 watts ≅ 68.21 HP
Total power (H_{Total}) = H × 2	136.42 HP
Design power (H_{Design}) = H_{Total} × sf	341.05 HP

Table 3. Calculations of the force in the gear and bearing systems.

Design consideration	Value
Forces in gear: $W_{Tagential}$ and V_{Radial}	509,012.132 N and 185,265.26 N
Forces in the bearing: y-axis (Ay) and 3D-axis (Az)	215,068.11 N and 504,444.18 N
Forces in the bearing: y-axis (By) and 3D-axis (Bz)	25,830.51 N and 157,401.21 N

3.2. Conceptual design and numerical analysis

From the numerical analysis developed in SolidWorks [20], Figure 1 shows the conceptual design of the tire crushing machine to obtain rubber particulate material (Figure 1(a)), and the numerical analysis FEA was developed to validate the correct operation of the elements designed and the physical behavior of the materials selected; notice that red and blue areas show the maximum and minimum efforts generated, respectively, in the numerical analysis.

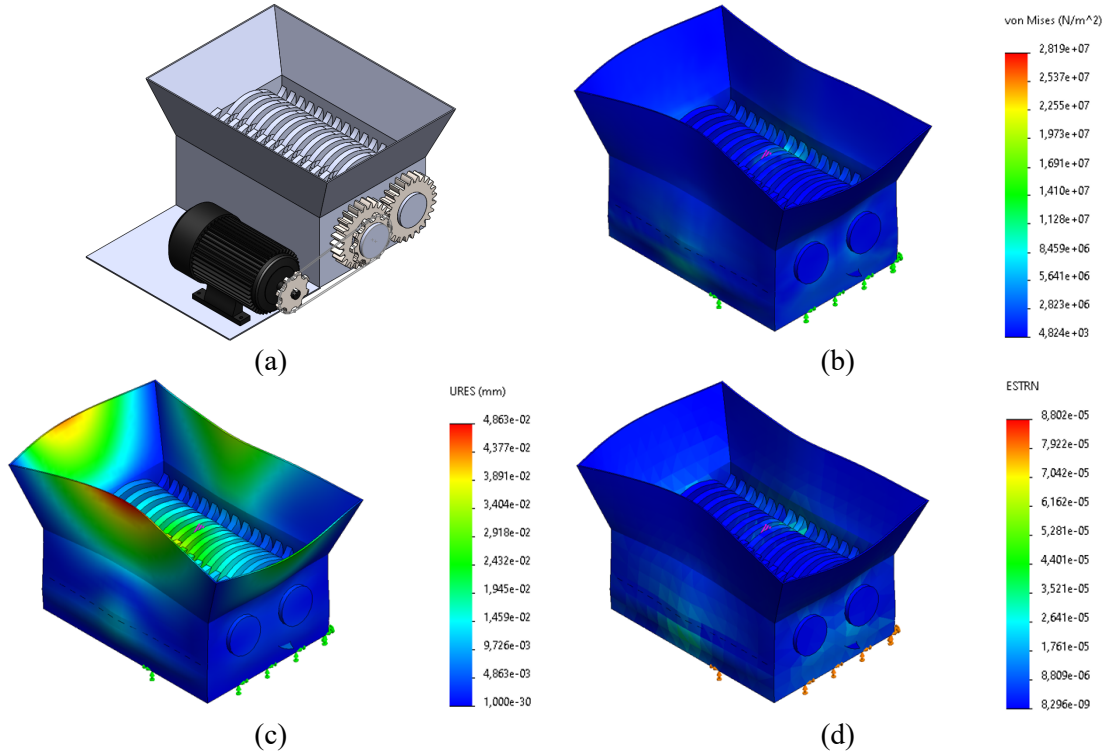


Figure 1. (a) Conceptual design of the tire shredder; (b) total elastic limit; (c) total displacement; (d) equivalent deformation.

Figure 1(b) shows exposed values between 28.1 MPa and 2.82 MPa; these values do not exceed the Young's modulus values for the material selected (AISI 1050 carbon steel, E = 200 GPa) being lower. Figure 1(c) were found maximum and minimum values of the total displacements of the machine, which

reach values until 0.048 and 0.0048 mm, which are lesser values that do not affect the machine's performance considering the mechanical and physical properties of the material. Finally, Figure 1(d) exposes values of equivalent deformation (change on the material area) between 8.802×10^{-5} mm and 8.809×10^{-6} mm; these values demonstrated the machine's excellent design and physical behavior ideal operating conditions considering the mechanical properties of the AISI 1050 carbon steel; notice that the values found do not affect the machine's integrity on the yield strain of the material, obtaining similar results with those reported by [23,24].

4. Conclusions

The implementation of this double axle shredding machine is an efficient solution to the rubber recycling problem, considering that new particulate material of the used tire is created. The machine consists of an effortless design of the mechanical components, making it more versatile in handling, manufacturing, and replication. The proposal of this shredder design is of great importance considering that with the optimization of the shredding system, it can be exposed in a market that needs to use a clean recycling system for the tires, creating at the same time employment opportunity with the production of particulate matter. Furthermore, through design parameters, considerations, and theories, it was possible to select the appropriate material for the components with the optimal operating conditions and performance. For the power transmission system, it is necessary to make a readjustment in the selection of the motor because a motor-reducer system generates high costs, and what is sought for this design in addition to efficiency is the economy for the subsequent construction of this proposal. Also, the numerical analysis results indicated that the mechanical and physical properties of the material (AISI 1050 carbon steel) were selected to provide an excellent and optimal performance of the shredder machine under ideal operating conditions aiding sustainability.

Finally, it was possible to evaluate and analyze the rubber crushing machine behavior considering the physical and mechanical properties of the materials with which the machine was designed under mechanical design theories, always guaranteeing high safety and performance during the operation. Furthermore, this machine is the starting point to evaluate the physical and structural behavior of new products that use to aggregate this type of material (with different particle granulometry) for the construction industry. Also, it is expected to reduce the pollution emitted by end-of-life Tires due to the pollution and contamination to the environment.

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