INVESTIGACIÓN E INNOVACIÓN EN INGENIERÍAS

Effect of the sharp profile geometry ong the cutting forces of tire recycling tools

Efecto de la geometría del perfil afilado en las fuerzas de corte de las herramientas de reciclado de neumáticos

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Abstract

Objetive: Study the impact of blade profile geometry on cutting forces during tire recycling, focusing on how variations in the shape and design of tools affect the efficiency and quality of the cut, as well as the tools' lifespan. **Methodology:** Through the construction and testing of three blade geometries, based on a prior numerical study and made from DF2 and 1.2363 steel, experiments were conducted on a Universal Testing Machine with samples of used tire rubber. **Results:** It was demonstrated that the hollow profile blade significantly reduces energy consumption and improves cutting performance compared to the 30° straight V profile blade, for both rubber-only samples and those with reinforcing textile fibers. Additionally, the study presented the evaluation of shear stresses using a 90° blade, indicating an average shear stress value of 8.67 MPa.. **Conclusions:** This finding suggests that the appropriate selection of blade geometry can significantly contribute to the efficiency of the tire recycling process, offering important economic and environmental implications.

Keywords: Blade profile, shear cutting force, tire rubber, cutting test, cutting simulation.

Resumen

Objectivo: Estudiar el impacto de la geometría del perfil de la cuchilla en las fuerzas de corte durante el reciclaje de neumáticos, enfocándose en cómo las variaciones en la forma y diseño de las herramientas afectan la eficiencia y calidad del corte, así como la vida útil de las herramientas. **Metodología:** Mediante la construcción y prueba de tres geometrías de cuchillas, basadas en un estudio numérico previo y fabricadas en acero DF2 y 1.2363, se realizaron experimentos en una máquina Universal de ensayos con muestras de caucho de neumáticos usados. **Resultados:** Se demostró que la cuchilla de perfil hueco reduce significativamente el consumo de energía y mejora el rendimiento del corte comparado con la cuchilla de perfil recto V de 30°, tanto en muestras de solo caucho como en aquellas con fibras textiles de refuerzo. Además, el estudio presentó la evaluación de esfuerzos cortantes mediante una cuchilla de 90°, indicando un valor promedio de esfuerzo cortante de 8.67 MPa. **Conclusiones:** Este hallazgo sugiere que la selección adecuada de la geometría de la cuchilla puede contribuir significativamente a la eficiencia del proceso de reciclaje de neumáticos, ofreciendo importantes implicaciones económicas y ambientales.

Palabras Claves: Perfil de afilado, fuerza de corte, caucho de neumático, ensayo de corte, simulación de corte.

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Introduction

The growing concern for sustainability and environmental preservation leads to addressing issues associated with waste and its impact on the global ecology. In this context, the proper management of resources such as end-of-life tires (ELT) becomes a necessity to ensure a cleaner and more sustainable future [1]. Waste vehicle tires are composed of natural rubber, butadiene rubber, and styrene-butadiene rubber; these components have the potential to serve as alternative raw materials for the manufacture of new products [2]. The disposal methods that are currently employed in the management of such wastes include recycling, composting, mechanical separation, and other techniques that are more environmentally damaging, such as landfills and incinerators [3]. Mechanical separation that includes techniques such as vibration, fine grinding, and magnetic separation is employed to split steel, side wires, and tire fabrics [4] and create recycled raw materials that can be reused in the manufacture of new products from steel, oil, carbon products, promoting the circular economy [5] and reducing dependence on non-renewable natural resources. Other more advanced processes including surface modification, cryogenics, and repeated processing [6] have opened up new possibilities by transforming these materials in specific ways for use in a variety of applications ranging from civil engineering applications to applications in the footwear industry, roads and railways [7].

In developed economies such as the European Union and the United States, ELT shredding operations are carried out for specific applications, including energy and material recovery [8]. However, in Latin America, the management and recycling of end-of-life tires are not as well established and ELTs represent environmental, health, social, and economic problems, as well as a challenge to curb energy demands and greenhouse gas emissions [9]. Colombia has been one of the first countries in Latin America to adopt Extended Producer Responsibility (EPR) policies, which involve manufacturers in the proper management of end-of-life tire products [10]. However, continuous improvement in the legal framework and collaboration of key actors in the product chain is necessary for an effective implementation of the EPR system [11].

Several authors have highlighted the importance of understanding how the shape of the tools and methods used in the tire demounting process impacts the forces applied during cutting, this influence, in turn, impacts the efficiency and quality of recycling. Key process factors such as temperature, the strength of the mechanical action and the conditions of the reaction environment affect the waste tire recycling process. Additionally, the importance of separating the steel wire from the rubber during the shredding process has been highlighted to prolong tool life and reduce mechanical maintenance [12]. For example, abrasive milling is a process that employs special tools to grind materials such as rubber, and the quality of the product depends on the tool speed and material feed [13]. On the other hand, by impact milling, the material can be destroyed by mechanical impact, converting kinetic energy into deformation energy. In impact mills, rubber residues are processed at different temperatures to obtain fragments or fine powders [14].

Rehman and Awuah-Offei [15] experimented with blades of different cutting profiles that have different longitudinal penetrations, where blades with a semi-skewed nose profile offered the highest penetration, followed by the sword type. The authors used a scale model of a rubber tire loader to study the factors affecting the resistive forces during initial penetration, finding that the angle of inclination and height above the ground does not have a significant impact, while speed and the tensile stress, as well as their combination, are relevant factors. On the other hand, Ali Gillani et al. [16] explored the use of rubber particles from discarded tires as aggregate in concrete to reduce the environmental load. Although with the introduction of rubber particles, the mechanical properties were reduced, a significant increase in fracture energy was obtained. Moreover, if metallic fibers are added, the loss in strength and durability issues can be recovered. However, the authors used commercially available fibers to improve the recycling process. These materials can be obtained from ELTs.

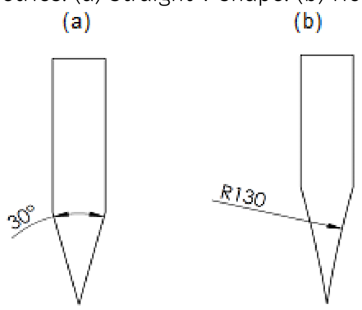
The objective of this paper is to investigate and analyze the effect of the geometry of the blade profile on the cutting forces of tools used in tire recycling. Specifically, it seeks to understand how variations in the shape and design of the tools used to process used tires can influence the forces exerted during the cutting process. This study focuses on evaluating how the sharp geometry of the tools can affect the efficiency and quality of tire cutting, as well as the lifetime of the tools themselves. The results of this research may contribute to the development of more effective and efficient tools for tire recycling, which could have important economic and environmental implications in the recycling processes.

Methodology

Blade geometries

Three-blade geometries were built to perform experimental tests of cutting force. Two of them (Figure 1) are the result of a previous numerical study where several blade profiles based on ancient sword geometries were evaluated [17].

Figure 1. Tested blade geometries. (a) Straight V shape. (b) Hollow profile.



Source: Own elaboration

To perform the numerical study, explicit simulations of the cutting process of several blade types were performed. Of nine geometries, one of them performed very well in terms of the required maximum force to cut and work done. Figure 2 shows simulated results of force vs. displacement for the two selected geometries, moreover, Figure 3 shows Von Mises elastic strain during the cutting process of the tire rubber in three moments. It can be observed that the hollow blade profile, requires less force and work done (area under the curve) than the straight V profile of 30°. Also, it is evident in the second instant that most of the cut material is retained by the 30° blade, while the hollow profile repels it.

Figure 2. Numerical results of force vs. displacement of tested blades.

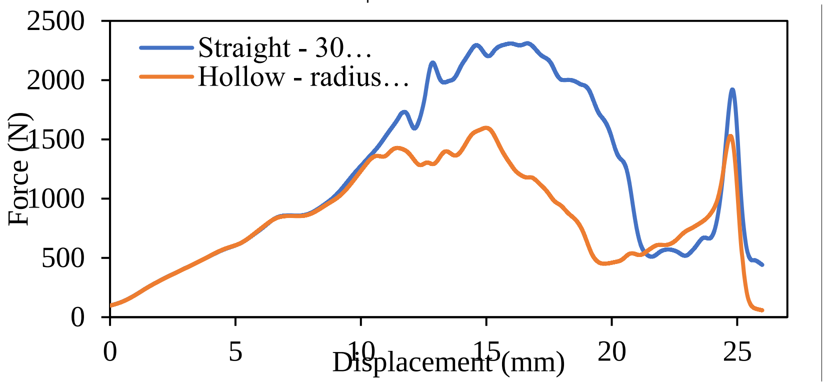


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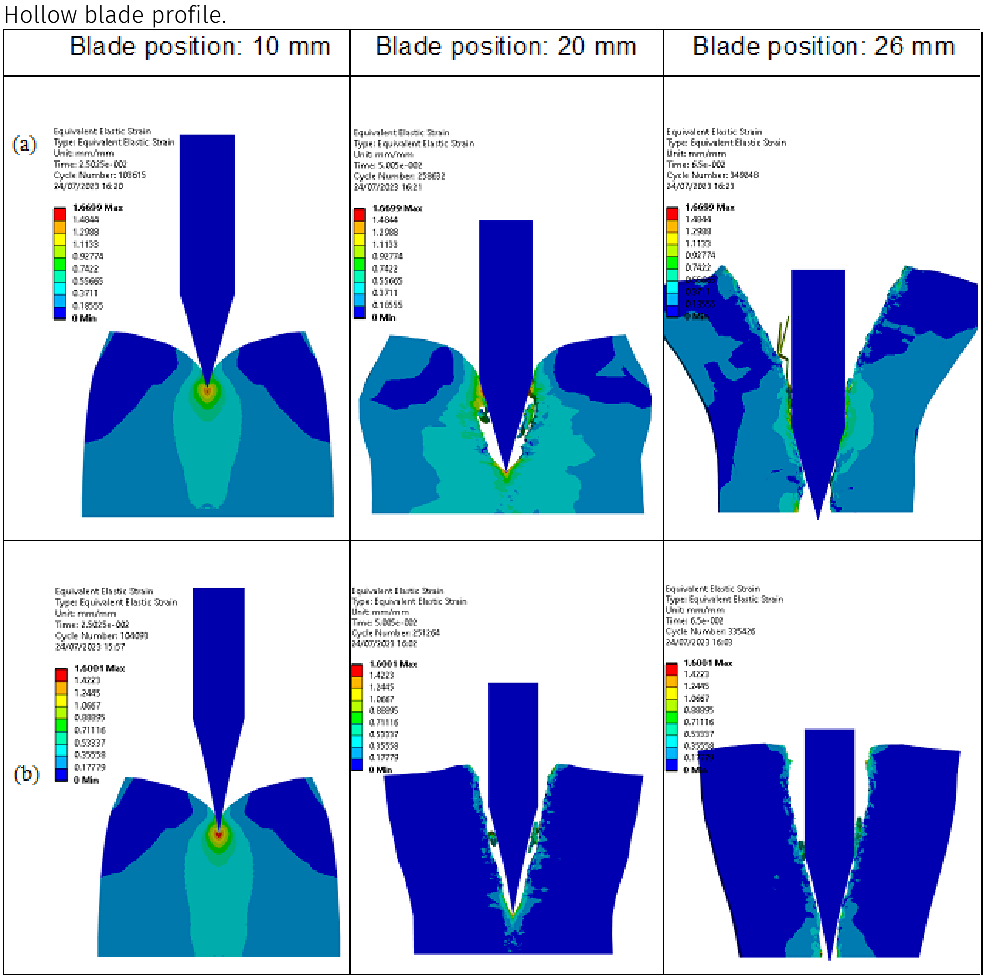
Figure 3. Evolution of the cutting process of tire rubber for (a) straight 30° blade profile, (b) Hollow blade profile.



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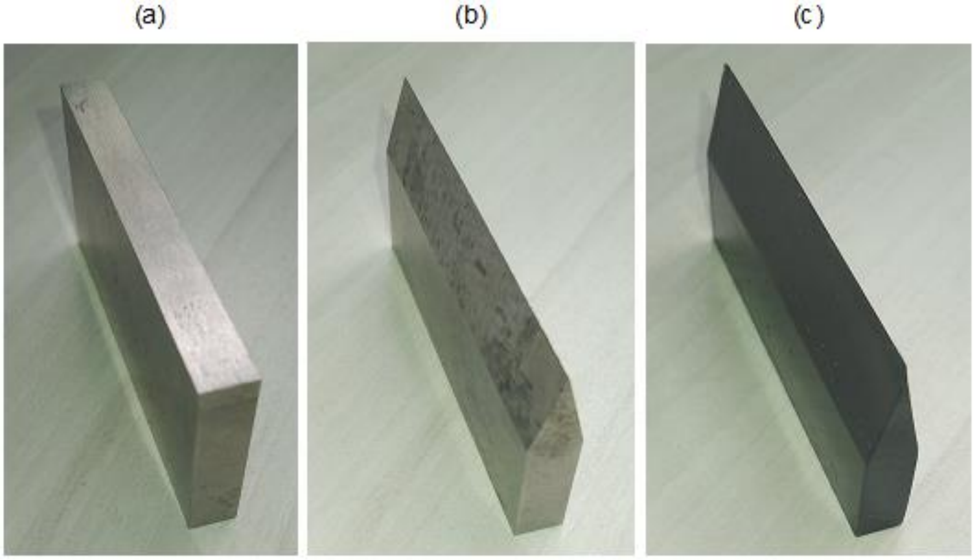
On the other hand, the third blade geometry was selected as a 90° geometry to evaluate the shear stress required to cut the material of end-of-life tires (ELTs). A 30° V shape blade and a 90° one was fabricated in DF2 tool steel hardened up to 56-58 HRC. Since the hollow blade result was selected from the numerical study, this was fabricated in 1.2363 tool steel and hardened until 59-61 HRC. Table 1 shows the chemical composition of the used materials, and Figure 4 shows the tree blades after manufacturing.

Table 1. Materials' chemical composition.

Material	% elements								
	C	Si	Mn	P	S	Cr	Mo	V	W
DF2 [18]	0.95	0.035	1.1	0.03	0.03	0.6	--	0.1	0.6
1.2363 [20]	1	0.3	0.5	--	--	5	0.95	0.2	--

Source: Own elaboration

Figure 4. Manufactured blades. (a) 90° profile (b) 30° straight profile (c) hollow profile.



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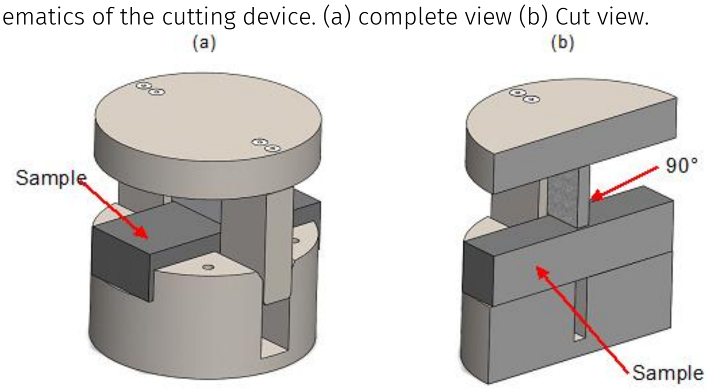
Cutting device

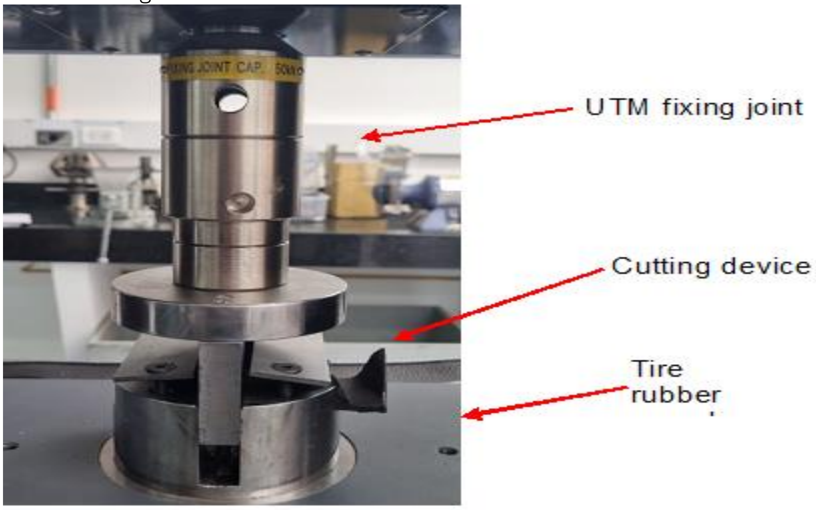
To perform the experimental tests to determine the cutting force, a device adapted to the Universal Testing Machine (UTM) was built. The device is composed of two elements: one holds the blade and the other holds the tire rubber sample. Figure 5 shows a scheme of the assembly along with a cut view that indicates internal details. The lower part of the device has a space to allow the blade to go through the entire thick of the rubber sample so that when using a rectangular blade, the shear stress required can be easily calculated. The device was planned to be used under a compression test, therefore, to make it resistant, it was built with AISI 1045 steel. Additionally, Figure 6 shows the assembly mounted on the UTM ready to be tested.

Figure 5. Schematics of the cutting device. (a) complete view (b) Cut view.



Source: Own elaboration

Figure 6. Built cutting device mounted on the UTM.



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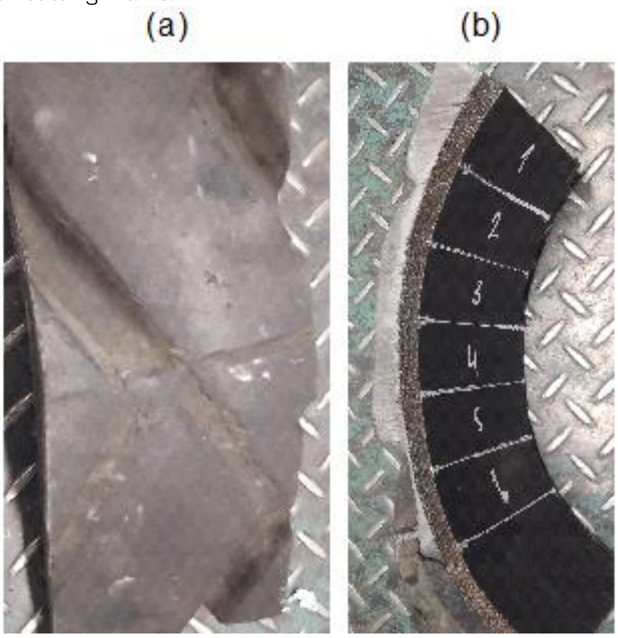
Tire rubber samples

To test the selected blade profiles, a used tire was sectioned to obtain several samples of rubber from the different parts of the tire band. Figure 7 shows a section of a used tire band with marks indicating the required cuts to obtain the samples that fit the cutting device. It is observed that at the center of sections (# 3, 4), the rubber thickness is lower than the section at the lateral ends (# 1, 6), this is because the curved profile of the tire band gets more wear when it is in contact with the ground. The dimensions of the samples are 40 ± 1 mm wide, 100 ± 1 mm long, and have a maximum thickness value of 30 mm.

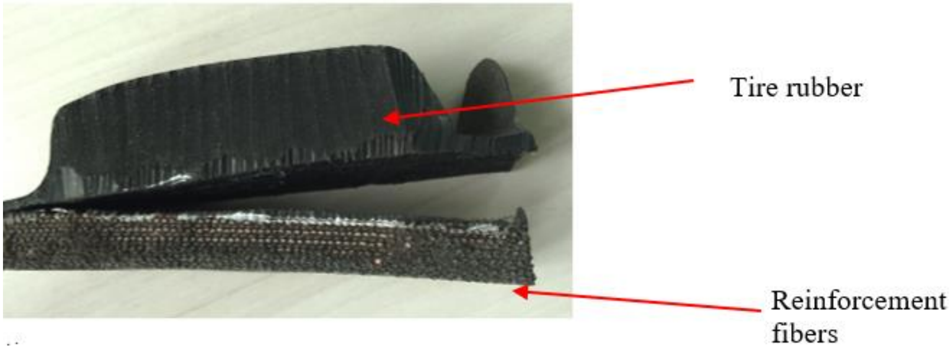
Figure 7. Section of a used tire to get samples. (a) External View (b) Side after cutting and internal view with cutting marks.



Source: Own elaboration.

On the other hand, two types of samples were extracted. One of them was obtained by extracting the section that only contains rubber from the thicker spots of the used band tire (# 1 and 6), as shown in Figure 8. The other one corresponds to the complete section that includes rubber and reinforcement textile fibers extracted from the most worn spots.

Figure 8. Separated rubber from reinforcement fibers of a section of a used tire band.



Source: Own elaboration

Experimental tests

As mentioned before, the cutting tests were performed under compression tests in a Shimadzu Universal Testing Machine model AGS-50kNX with a capacity of 50 kN. To ensure the repeatability of results, at least three tests were performed with each blade, however, in some cases more tests were performed to evaluate the behavior of the blades in different spots of the band. Two kinds of tests were performed: the first one aims to obtain the cutting forces and the energy required by the V straight and hollow blades; the second one seeks to evaluate the mean shear stress required to cut the rubber. In this case, the 90° blade is required. Table 2 resumes the performed tests.

Table 2. Tests performed at the universal testing machine.

Type of blade	Only rubber		Complete section	
	Number of tests	Evaluated zone	Number of tests	Evaluated zone
30° straight blade	5	Center (3), ends (2)	3	Center
Hollow blade	5	Center (3), ends (2)	3	Center
90° blade (shear stress)	N/A	N/A	3	Center

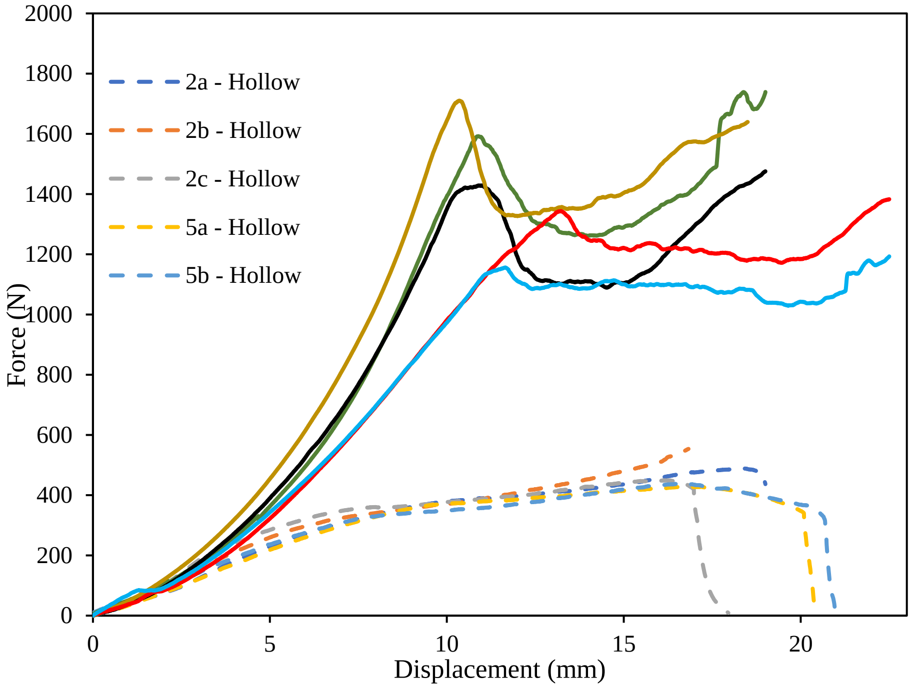
Source: Own elaboration.

Results

Behavior of the blade on only rubber samples

The samples of the tire band that only contained rubber were subjected to cutting tests with the two blades (straight 30° and hollow) according to the procedure shown in Table 2. Figure 9 indicates the results of force vs. displacement of the performed tests under a compression configuration in the UTM. The difference in magnitude between the two geometrical configurations of the tested blades is observed. Moreover, the presence of a peak force at around 10 mm of displacement in the 30° straight blade for all the tests is noticeable. According to what was observed in the simulation results presented in Figure 2 and Figure 3, it is assumed that the peak force is reached before the first breakage of the surface occurs. However, for the hollow blade, such a peak of force is not present, indicating that for this geometric configuration, the cutting process is performed smoothly, and thus more efficiently. On the other hand, the difference between the samples extracted from different spots of the band can be observed. As expected, thicker samples corresponding to the spots near the ends (# 5 in Figure 7), require a larger displacement, and therefore more work. However, the maximum force is similar for both, thinner and thicker samples, which indicates that for these tests the maximum force only depends on the geometric configuration of the blades.

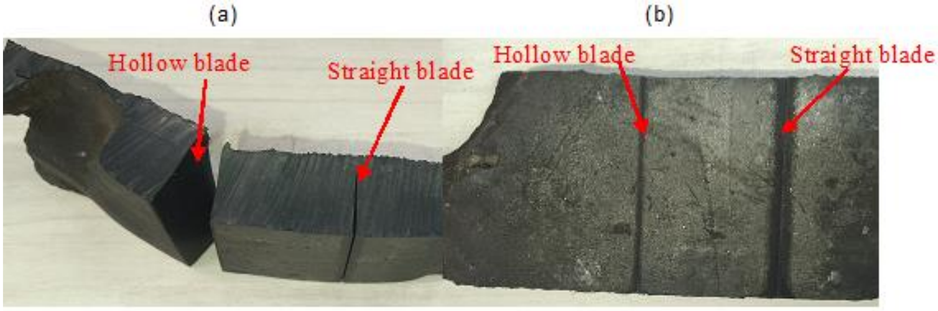
Figure 9. Experimental results of the cutting tests in only rubber samples for straight (solid line) and hollow blades (dashed lines).



Source: Own elaboration.

Figure 10 shows the comparison of the cutting marks for hollow and straight blades. It can be observed that the hollow blade has gone through the entire thickness, while the straight blade can't perform a complete cut of the material. This demonstrates the improved performance of the hollow blade. Contrary to this, the 30° straight blade has not performed a complete cut and, as seen in Figure 10 (b), a mark broader than the one left by the hollow blade is identified. Considering the contact pressure, the broader mark indicates a larger contact area, which means a larger force, and therefore more energy consumed. Regarding this, Table 3 collects the results of work consumed in each test, measured as the area under the curves of Figure 9. A big difference in energy consumption is noticeable between both geometries, a reduction of 66% on the average of energy consumption with the hollow blade was identified. Besides, the thicker samples (5a and 5b in Table 3) cut with the hollow blade required more work due to a larger distance covered. However, this did not happen with one of the thicker samples cut with the straight blade (5b), where it is identified that it required the minimum force between the thicker samples, which reduces the area under the curve.

Figure 10. Remaining marks on the rubber samples after the cutting tests. (a) Side view, (b) Top view.



Source: Own elaboration

Table 3. Results of work consumption for only rubber samples.

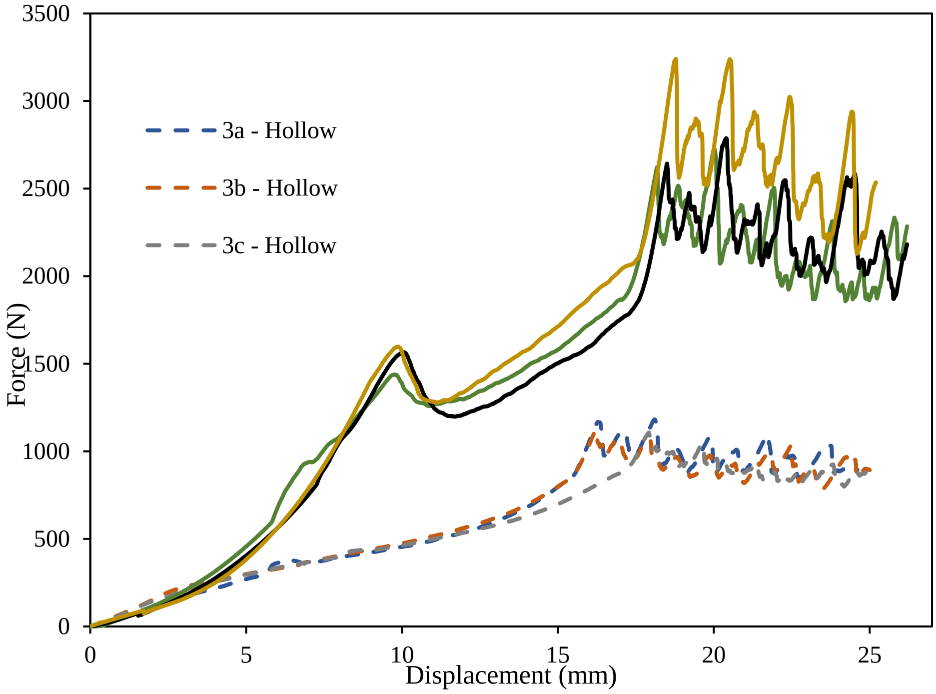
Type of blade	Test				
	Center (thin zone)			Ends (thick zone)	
	2a	2b	2c	5a	5b
30° straight	17.53 J	15.98 J	18.12 J	19.05 J	17.56 J
Hollow R 130	6.01 J	5.28 J	5.45 J	6.14 J	6.41 J

Source: own elaboration

Behavior of the blade on complete section samples

Contrary to the samples discussed above, here, samples consisting of the entire section of the tire tread including the textile fibers were tested. Figure 11 indicates the results of the tests for both V straight and hollow blades. As in the case of only rubber samples, the difference in the force employed for both blade profiles is evident. The behavior of force at the beginning of the cut is similar to the behavior in the rubber samples. This is illustrated by the similar values of force (around 1500 N) at the first peak for the 30° straight blade for both, only rubber and the complete section. Then, when the blade reaches the reinforcement fibers, the force increases significantly reaching the maximum peak of force which is around 3000 N for the 30° straight blade and 1100 N for the hollow blade. As expected, these values are higher than the ones obtained for only rubber samples. During the cutting process of the fibers, several peaks of force are reached. This is because there are several layers of fibers, as shown in Figure 8. Moreover, it can be observed that when the fibers are being cut, the average force tends to be constant, with a value of around 2365 N for the 30° straight blade, and 919 N for the hollow blade. Therefore, the reduction of the cutting force with the hollow blade is around of 61%. The effectiveness of the hollow blade in cutting the band section can also be verified by evaluating the work done during the cutting process. Table 4 shows the values of work computed as the area under the curve for the graphs of Figure 11 at a distance of 24.5 mm.

Figure 11. Experimental results of the cutting tests in samples of the complete tire tread section for straight (solid line) and hollow blades (dashed lines).



Source: Own elaboration.

As in the only rubber samples, a noticeable reduction in energy consumption is identified, corresponding to a value of 57%, being this a little lower than the reduction reached in only rubber samples. Moreover, in these tests, on the cutting surfaces the same mark profiles shown in Figure 10 were also identified.

Table 4. Results of work consumption for complete tire tread samples.

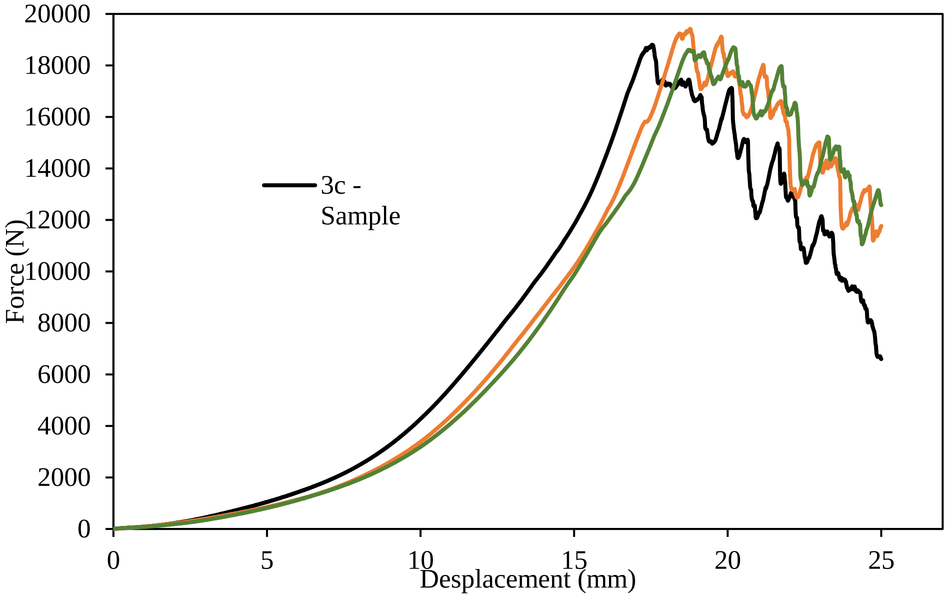
Test Type of blade	Center (thin zone)		
	3a	3b	3c
30° straight	32.6 J	32.15 J	36.23 J
Hollow R 130	14.75 J	14.64 J	13.96 J

Source: Own elaboration.

Shear stress evaluation

The 90° blade in Figure 4 was used to determine the maximum shear stress required to cut an entire section of tire tread. Figure 12 shows the results of force vs. displacement for the 90° profile blade. Here, a constant increase of the force until a peak is reached at the point where the blade finds the first layer of the reinforcement fibers is observed. Then, every time a layer of fiber is reached, a new peak appears, but with a lower value. This is because the area to cut is lower. The values of force in this case are significantly higher than the ones obtained with the sharp blades, reaching around 19 kN. This occurs because the force is distributed in a wide area that requires to be cut. Therefore, to calculate the shear stress, the maximum obtained force was divided by twice the cross-section of the sample, obtaining an average of stress for the three samples of 8.67 MPa.

Figure 12. Experimental results of the cutting tests with the 90° straight profile. Source: own elaboration.



Source: Own elaboration.

Conclusion

Experimental tests were performed on samples of end-of-life tires to obtain the cutting forces required for their process. It was required that a specially designed device be adapted to a universal testing machine that holds the cutting blades in a compression test. Numerical simulations helped obtain the best profile of the blade, and two of several profiles numerically evaluated were chosen to perform experimental tests. The tested blades have a straight 30° V profile and a hollow profile, and to ensure that the obtained geometry was well reproduced, the blades were manufactured in a CNC machine. Moreover, to avoid premature wear, both blades were hardened to 58-60 HRC. As in the simulation, the experimental tests with the hollow profile showed the best performance for both cases, when they cut only rubber samples, and when cut rubber and reinforcement fibers [19,20]. The results showed a reduction of almost 60% in energy consumption when the hollow blade is used concerning the straight profile. Also, tests with a 90° straight blade were performed to obtain the mean shear resistance of the samples, obtaining a result of 8.67 MPa.

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