Evaluation of Ultra High Molecular Weight Polyethylene (UHMWPE) anisotropic configuration sample of Tensylon™, Dupont™ at medium velocity impact test

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Abstract. In this paper the impact behavior of a laminated Ultra High Molecular Weight Polyethylene (UHMWPE), was analyzed at medium velocity impacts. The aim of this study focused on the influence on the ballistic limit of four layered laminate with three fiber configurations: [0°/0°/0°/0°], [0°/90°/0°/90°], and [+45°/-45°/0°/90°]. These three configurations were tested under multiple impacts intended to maximize the information obtained per sample tested at impact. The results show a discrete increase in the ballistic limit in the configuration [0°/90°/0°/90°], compared to [0°/0°/0°/0°] configuration, whilst on the other hand, the quasi-isotropic configuration showed significant reduction of energy absorption.

Keywords: *Tensylon™, Ultra High Molecular Weight Polyethylene, Ballistic Limit, Impact Test.*

Introduction

During World War II the first fiber with ballistic applications, Nylon was unveiled. From this point the research in this area was always looking to increase penetration resistance with the use of this material. Currently textile fibers used are aramid and Ultra-high-molecular-weight polyethylene (UHMWPE), where the latter is notable for its excellent mechanical properties, with a tensile strength of 2.6 GPa and an elastic modulus of 87 GPa, being 4 times lighter and 20 times stiffer than Nylon 6,6 [1].

There are many studies related to impact analysis of engineering textiles [2-5]; among which may be mentioned B.L. Lee, *et al.*, who compared the effect of energy absorption in a woven Spectra® (UHMWPE) with and without polymeric matrix; demonstrating the influence that the matrix has to restrict movement of the fibers during an impact [6]. On the other hand, Ming Cheng *et al.*, dispute the efficiency of dissipation mechanisms along UHMWPE fibers, where they addressed that the arrangement without weaving was the best energy dissipation system, highlighting interesting topics on the rate of energy dissipation and wave reflection through a fiber [7]. Finally, the work carried out by M.J.N. Jacobs and J.L.J. Van Dingenen, analyzed the behavior of armor based Dyneema (UHMWPE), where the study consisted on impacting on each sample, 4 times in the 4 sample quadrants, analyzing the parameters that influence the most the material, demonstrating that when using non-deformable projectiles, significantly reduces the variables involved, simplifying the analysis [8].

Studies involving analyzing the ballistic limit with respect to the anisotropy of the material are relatively scarce, as is the case of Jennifer Rhymer, Hyonny Kim and Dennis

Roach; who demonstrated the influence of a composite multidirectional arrangement of fiberglass with a matrix of epoxy resin. Here they showed how the energy absorption varies in certain configurations being possible to observe variations in the failure mode in each layer of the composite laminate [9].

Methodology or experimental section

Ultra-high-molecular-weight polyethylene, Tensylon™, in unidirectional fiber presentation, was post-processed by the company Grupo Carolina S.A., to create four layer laminate with three arrangements types; $[0°]_4$, $[0°/90°]_2$, and [+45°/-45°/0°/90°]. This multilayer material was elaborated by specific thermoforming technique for its consolidation, where the fiber layers (0.25 mm thick) were partially melted with the purpose of self-bonding, no requiring extra adhesive. These samples were tested at medium impact velocity (50m/s≥V≥500m/s), in order to find the ballistic limit. This parameter is determined by testing samples against normal impacts at different speeds, with the aim of finding a velocity range in which the projectile may or may not penetrate the material (50% of the time). Here, a minimum of 6 tests are required with a maximum velocity interval of 60 m/s between impact tests, to obtain the average value. With this value, it is identified the speed at which it is 50% the chance that the projectile may or may not penetrate the sample. For impact testing, a high speed nitrogen gas gun was used (Figure 1a), which uses a non-deformable projectile of high vanadium steel with a mass of 1.11 g to impact the sample [10]. UHMWPE laminates were clamped in a vice which imprisons the sample between two metal plates by 8 screws, which distribute pressure evenly across the sample. This vice has the ability to locate the impact on 5 sample positions in order to get as much information as possible on each test (Figure 1b). The impact speed was recorded using one Shooting Chrony® Chronograph which has an accuracy of 99% in their readings.

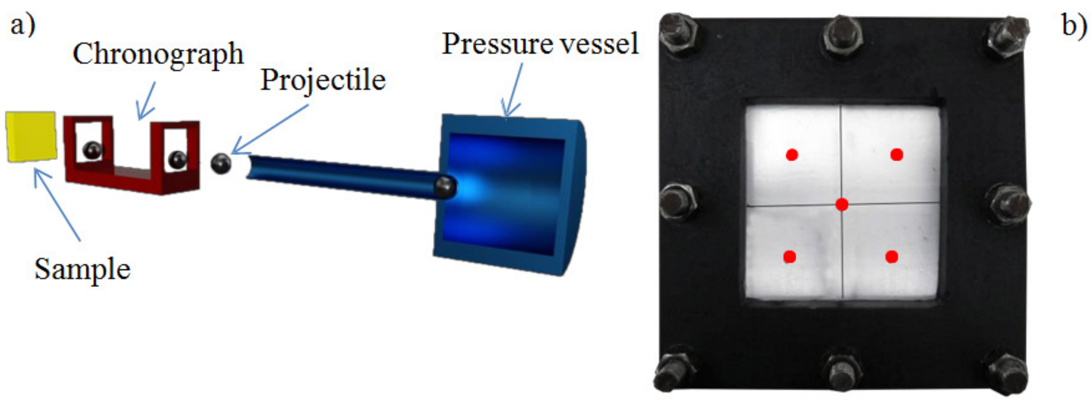


Figure 1. Impact test, a) High speed gas gun, b) Vice clamping sample.

Three laminates per each configuration were tested, with the mentioned arrangements set forth in Figure 2; in total 9 samples were tested, with five impacts each. The speed was recorded in each test to identify the ballistic limit (Eq 1) and the impact energy (Eq 2). It was observed that the ballistic limit represents the speed at which there is a 50% probability of penetration; hence the energy identified of ballistic limit represents the value of energy that the sample is able to absorb in a normal impact.

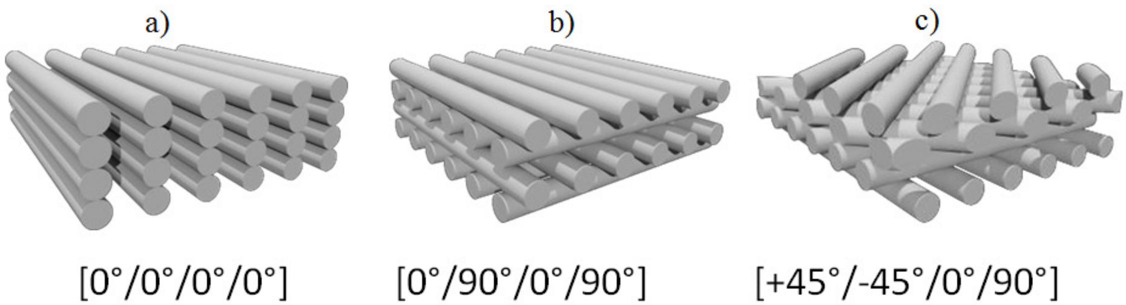


Figure 2. Materials's anisotropy representation, a) Unidirectional arrangement, b) Orthotropic arrangement, c) Quasi-isotropic arrangement.

The three configurations proposal follows: a unidirectional array [0°/0°/0°/0°], passing to an orthotropic array [0°/90°/0°/90°] and ending with a quasi-isotropic array [+45°/-45°/0°/90°]; where in some cases (depending of the type of fiber and arrangement), the use of multi-direction fiber arrays, like the quasi-isotropic one, allows greater energy absorption. So, the experiment setup intended to evaluate whether there was or not an increase in energy absorption by rotating fiber direction.

$$V_{50} = \frac{\sum_{i=1}^{6} V_i}{6} \quad (1)$$

$$E_{abs} = \frac{mV_o^2 - mV_f^2}{2} \quad (2)$$

Results and Discussion

In total 45 impacts to the samples studied here were evaluated, where it was possible to see that there was no significant variation between the values obtained from the same sample tested at the same impact velocity; 5 hits made on each sample showed similar values, which supports the reliability of this methodology established to characterize this material.

The first configuration analyzed was $[0°]_4$, which represents 4 layers of Tensylon™ consolidated with the same fiber orientation. This laminate showed an intermediate level of strength with respect to other configurations, with a ballistic limit of 200 m/s and impact energy of 22.5 J. This is illustrated graphically in Figure 3, where it can be seen how impacts are distributed, necessary to determine the ballistic limit (BL). This graph was divided into 3 sections; in section I, impacts did not penetrate the sample (1), while in Section II is the segment where the sample (2) may or may not fail, up to the Section III which represents the segment of impacts that fully penetrate the sample (3) at all times. The six values found in zone II were used to determine the ballistic limit with Eq 1.

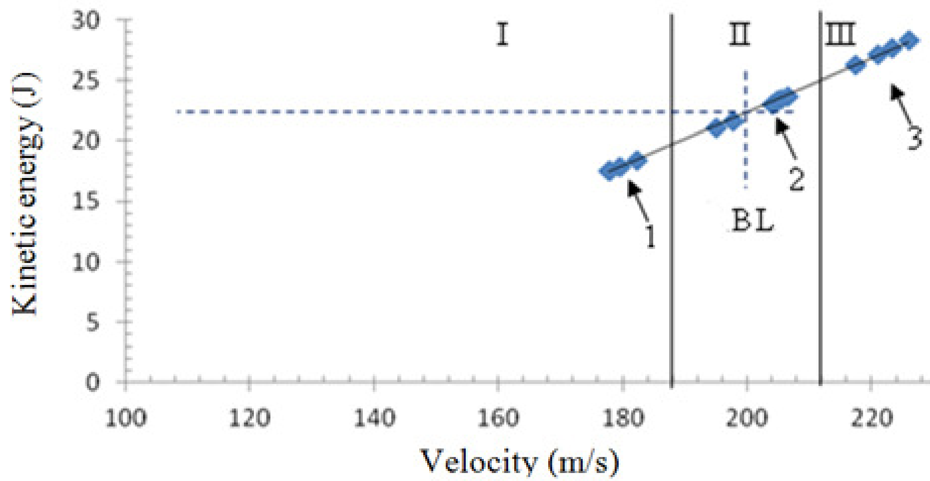
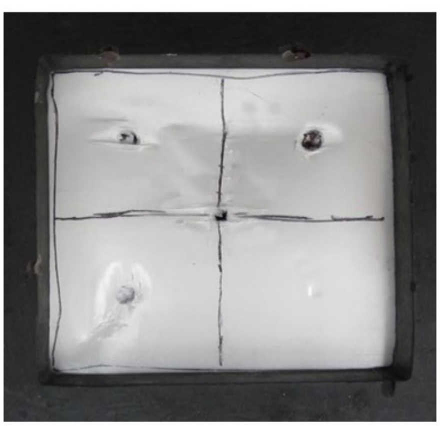


Figure 3. Result of impact tests for the [0°]4 arrangement.

Figure 4 shows the sample 1 after five impact tests. Figure 4a shows the front of the sample, observing four impacts on the four quadrants, and one more impact at the center, where only the central impact is appreciated to pass through the sample, at a speed of 180 m/s (17.5 J). On the rear side of sample (Figure 4b), it is confirmed that only the central impact was passed through, observing important deformation marks from the other impacts, highlighting the presence of this important dissipation mechanism in this sample (deformation).

a)



b)

Figure 4. Unidirectional arrangement [0°]4, a) Front, b) Rear.

Figure 5 shows the graph with three samples (4,5, and 6) tested with the configuration [0°/90°]2, where each layer orientation alternates between 0° and 90°. This configuration reported the highest level of energy absorption compared to the three configurations studied here. The ballistic limit obtained for this arrangement was 214 m/s, which gave an impact energy of 26 J.

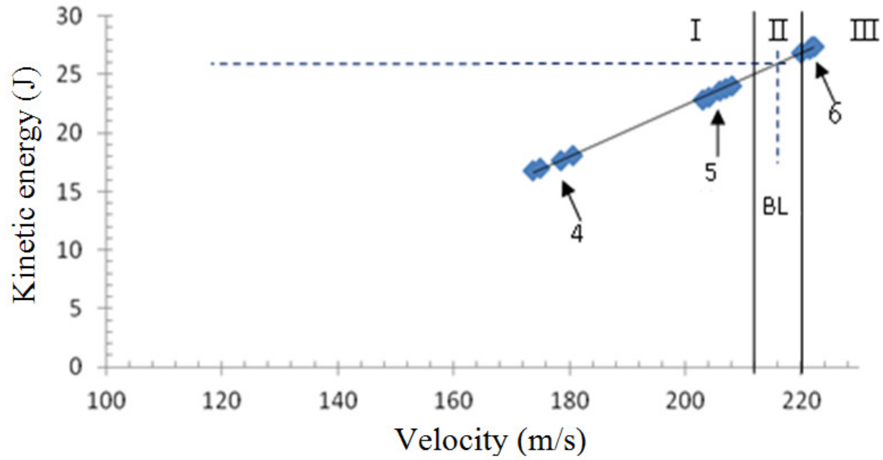


Figure 5. Result of impact tests for the $[0°/90°]_2$ arrangement.

Figure 6a shows the image of the sample 5 following impact tests, where it can be seen 5 impacts marks, being only one hit which penetrated completely (the one at the center); one partially penetrated and three did not penetrate. For the case of partial perforation, where the projectile is retained by the sample, observed more clearly at the rear side (figure 6b); being a particular case, since the projectile partially penetrated the material, unable to leave the sample, which can be considered the ballistic limit. In order to obtain the average value, it needs repetitions to ensure that at these conditions, the sample will be always at the perforation threshold [11].

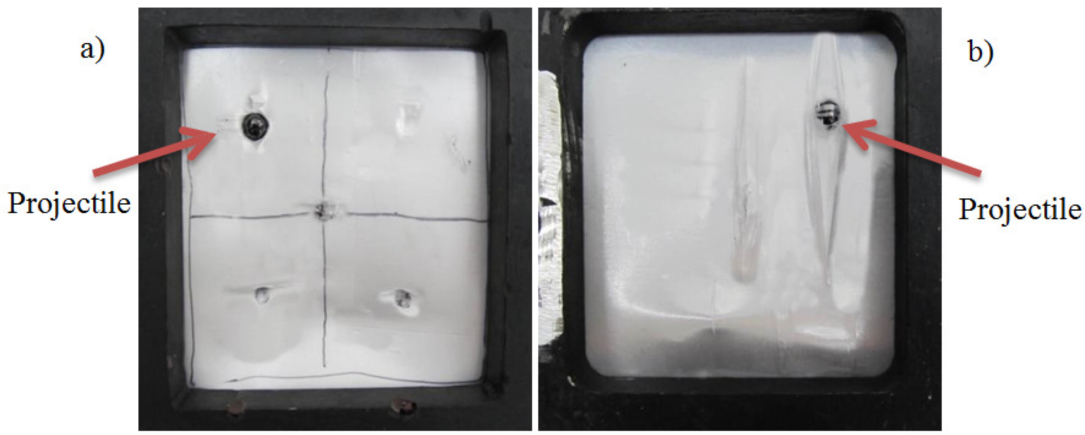


Figure 6. Orthotropic arrangement $[0°/90°]_2$, a) Front, b) Rear.

Finally the quasi-isotropic arrangement [+45°/-45°/0°/90°], is tested at normal impacts. This configuration had the lowest ballistic limit with a value of 115 m/s and impact energy of 7 J. Figure 7 presents the experimental results of samples (7, 8, and 9), where a wide dispersion of data following impact tests can be observed. This sudden reduction in energy absorption it may be related to the fiber rotation to off-axis directions (+/-45°), classified as secondary fibers, where the principal directions (0°/90°) are reported to be more efficient to absorb and dissipate energy [12, 13].

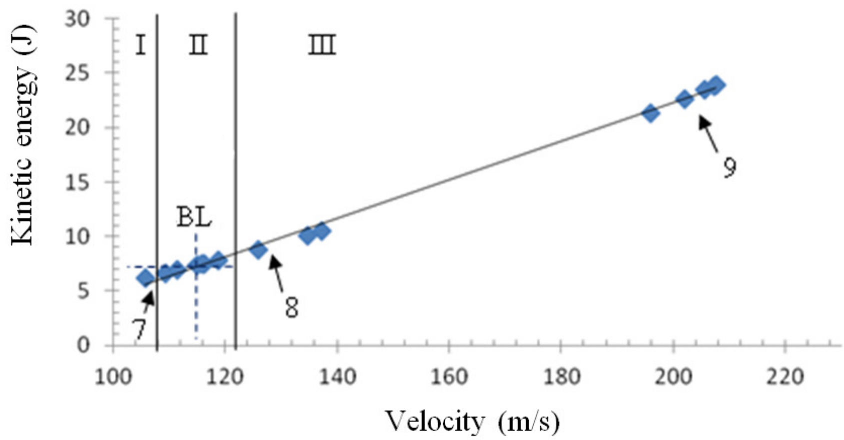


Figure 7. Result of impact tests for the [+45°/-45°/0°/90°] arrangement.

Figure 8 shows photos of the sample 7 with multiple impacts, where 4 shots penetrated and one did not. Something that is interesting to note here, is the low deformation at the back side of the sample in comparison to previous arrangements, attributed in this case, to the multidirectional fiber orientation that increase in-plane rigidity.

Ballistic limit behavior of quasi-isotropic arrangements [+45°/-45°/0°/90°], with respect to the other configurations is somehow controversial since, ideally the more pathways for energy distribution present in a composite material subjected to stress, the better dissipation energy ability it should have. However, when there is only one dissipation direction (0°), this presents a substantial energy absorption; moreover, when the two main directions are used (0°/90°), appears to be the most energy absorption format; but when 4 directions are presented (+45°/-45°/0°/90°) there is a significant reduction in energy absorption. This behavior needs to be explained in a deeper analysis, since complex phenomena interactions occurred simultaneously during an impact event.

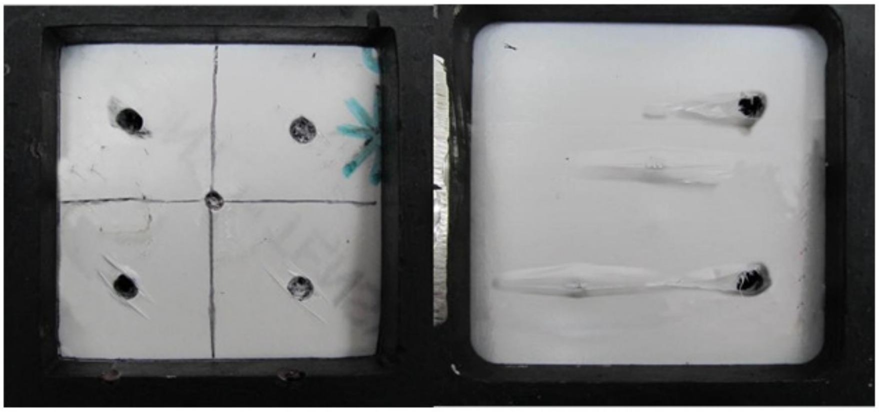


Figure 8. Quasi-isotropic arrangement [+45°/-45°/0°/90°], a) Front, b) Back.

The total energy absorption of a material could be divided by the contribution of several mechanisms where, each work independently, achieving certain energy dissipation due to the projectile impact. It is reported that the principal mechanisms of energy dissipation are the load on primary fibers (fibers in direct contact with the projectile at 0° and 90°), load in secondary fibers (surrounding to primary directions fibers), fiber-matrix debonding (intralaminar delamination), debonding between the material layers (interlaminar delamination), and matrix debonding among other mechanisms [2]. These mechanisms working together may increase absorption of energy, or otherwise, may decrease it.

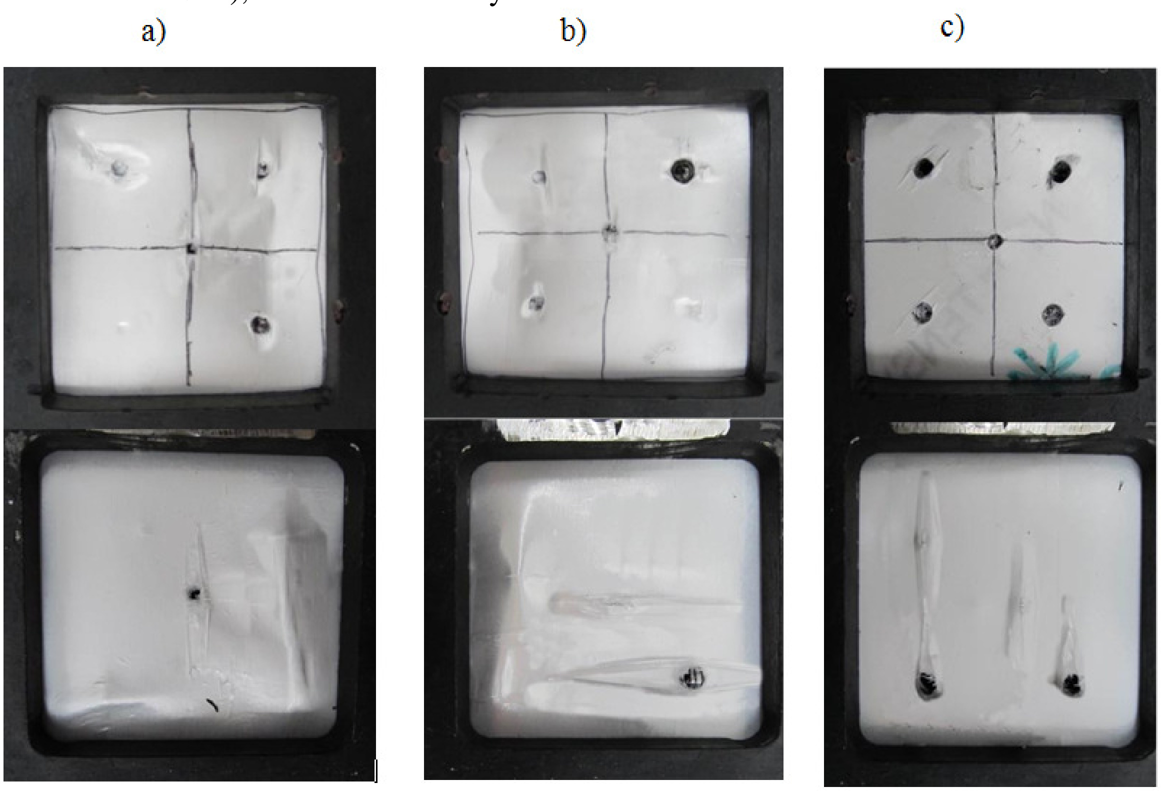


Figure 9. Samples tested, a) Unidirectional arrangement $[0°]_4$, b) Orthotropic arrangement $[0°/90°]_2$, and c) Quasi-isotropic arrangement [+45°/-45°/0°/90°].

For this study, only the orientation of the fibers in the material is varied, which limits the analysis to two main factors; the load of primary fibers and interlaminar delamination between primary and secondary fibers. Basically, when the projectile strikes the sample, a tension process started in primary fibers, which begins debonding neighboring fiber bundles. In this process a relationship between the speed of fiber debonding and the time to reach the maximum fiber length, rule the energy dissipation process. For the [0°]4 laminates, the fibers use only one of the two principal fiber direction, reflected as a slight decrease of energy absorption when is compared with the $[0°/90°]_2$ arrangement, that uses the energy dissipation more efficiently. For the case of quasi-isotropic arrangement [+45°/-45°/0°/90°], where each fiber is unique in its position, was evaluated thinking that during an impact test, debonding mechanisms will absorb more energy than those in previous configurations; however, the opposite happened here. This behavior agreed with previous experiments; where secondary fibers (in this case 50%), absorbed the impact energy indirectly, while primary fibers are directly receiving the impact load, absorbing as more energy, including sharing the load to neighboring fibers (off-axis). Apparently this fiber distribution, reduced the capacity to deform at the in-plane direction when a normal impact hits, observed in Figure 9, possibly due to a mismatch generated when simultaneous strain appears.

Summary

Three laminate arrangements of Tensylon™ were tested in order to identify differences between them, highlighting the one with better performance. It was observed that the unidirectional arrangement showed good energy absorption while the orthogonal arrangement slightly improved, assumed to be due to the better energy distribution among the primary load directions X and Y. For quasi-isotropic arrangement, secondary fibers (off-axis), were less efficient to absorb energy in comparison to the primary ones, reflected into a poorer performance in comparison to the other two previous arrangements. It was interesting to note how the deformation at the rear sample on the quasi-isotropic arrangement was significantly reduced at the bare eyes than that of the other two systems studied.

Acknowledgement

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