Study of the influence of the padding in the helmet's impact response

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Abstract. Upon a ballistic impact on a helmet, the shell deforms to absorb the kinetic energy from the projectile. This deformation plays a crucial role in reducing the direct penetration of the projectile, but it can also transfer some energy to the wearer's head, which may lead to injuries. These injuries, commonly referred to as Behind Helmet Blunt Trauma (BHBT), occur when the force of the impact is transmitted to the skull without penetration, causing damage to the brain or surrounding tissues. To mitigate this risk, helmets are designed with a gap between the skull and the helmet. This gap not only serves as a protective buffer against blunt trauma but also enhances comfort and ergonomics for the user. The gap between the skull and the helmet can be filled with various materials, typically liners or padding. These inner components are critical in distributing the impact energy more evenly, reducing the risk of localized injuries. Different materials and configurations can have significant effects on the helmet's performance in a ballistic impact scenario.

This study explores different types of cellular polymers, designed in the CellMat Laboratory at the University of Valladolid, used as the inner padding of the helmet and evaluates their effectiveness in reducing blunt trauma compared to commercial solutions. The focus is on assessing how these materials respond when subjected to a ballistic impact from a 9 x 19 mm Full Metal Jacket (FMJ) projectile. In terms of forces transmitted to the user, a cellular material made of thermoplastic polyurethane (TPU) was able to produce similar results than a commercial solution, showing the path to enhance current solutions.

1. INTRODUCTION

Generally, the helmet has to protect from high-mass, low-velocity impacts, such as in sports or automotive fields. The literature has already shown solutions that are able to reduce the load for the user [1], [2], [3]. In order to avoid injury from ballistic impacts, to the head, it is required to stop the threat typically using the shell of the helmet, and reduce the associated load for the user, known as Behind Helmet Blunt Trauma. Some studies have addressed this issue. The main threat studied is the 9 x 19 mm Full Metal Jacket (FMJ) [4], [5], or steel projectiles at low velocities [6], [7]. Nowadays higher levels of ballistic protection are considered for ballistic helmets. More powerful threats, such as rifle rounds have been studied, despite the increasing difficulty of defeating them within the constraints of a personal protection system [8]. The helmet has to dissipate the energy to defeat the ballistic threat and keep the user safe. The liner plays an important role as it has to accommodate the load of the impact transmitted to the skull.

Cellular polymers are biphasic materials presenting a solid phase and a porous phase, when the pore size is reduced up to the micrometric or nanometric scale, these materials are known as micro and nanocellular polymers. The reduction of the pore size to these scales allows these materials to present an innovative combination of properties such as a reduction in weight together with excellent mechanical performance [9].

The goal is to study for the first time the response of these micro and nanocellular polymers as liners for protecting the head from the deforming cone of the composite armour in comparison to commercial liners. As there are no clear biomechanical limits, a standard military helmet was mounted on a headform, and was fired at with pistol ammunition in order to estimate the values of the current loads. After this, different liner configurations were tested and compared with the previously determined loads for the helmet.

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2. EXPERIMENTAL SET-UP

2.1 Ballistic test set-up

In order to perform the ballistics tests, a universal receiver with interchangeable barrel was used to fire the projectiles. The projectile velocity was measured with a double optical base, DRELLO LS19, mounted on a frame. The target was positioned 5 m ahead. The optical bases were positioned 2.5 m in front of the target (Figure 1). The measurement of the velocity was corrected to take into account the deceleration of the projectile from the centre of the bases to the impact point [10].

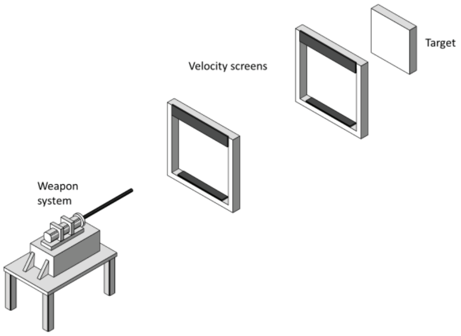

Figure 1.- Ballistic test setup.

2.2 Ammunition

The 9 x 19 mm FMJ projectile (Figure 2) weighs 7.9 g. It has a brass jacket and a lead alloy core. This pistol round is very popular and is specified in several standards as a testing round from organisations such as the Association of Testing Bodies for Attack Resistant Materials and Constructions - best known by its acronym VPAM (Vereinigung der Prüfstellen für angriffshemmende Materialien) and the National Institute of Justice (NIJ), and the Home Office Scientific Development Branch (HOSDB) ([11], [12], [13]).

Figure 2.- 9 x 19 mm FMJ projectile.

2.3 Ballistic Load Sensing Headform

The surrogate used for testing was the Ballistic Load - Sensing Headform (BLSH) [14]. This system consists of a metallic headform equipped with different force and acceleration sensors to assess the ballistic impact protection performance of helmets (Figure 3). The headform enables a direct measurement of the dynamic loads imparted to the head by the deformation of a ballistic helmet caused by non-penetrating projectiles, and the global acceleration of the head.

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Figure 3.- Ballistic load sensing headform.

The BLSH is used to evaluate the instantaneous force produced during the impact of a projectile on a ballistic helmet. For this purpose, it is equipped with an array of seven load sensors in the impact zone. There are two different headforms, the first one has one array in the front and another in the back, and the second one has one array on each side. A skin-simulating pad covers the sensors to better simulate the actual head response [14], [15], [16]. The headform is mounted on a flexible neck, the Hybrid III anthropomorphic test device (ATD). This ATD is the most widely used in the world. It accurately simulates the human dynamic response during a crash event. As explained in [17], the head was designed to simulate a real human head. The mechanical properties of the human skull are known and described in the literature [18], and could be related to the force measurement obtained from the BLSH. However, there is no suggested correlation between the BLSH force data and brain injury data [19]. Therefore, the direct force measurement is more closely related to skull damage. To assess brain injury, the Head Injury Criterion (HIC) was used.

3 MATERIALS AND METHODS

3.1 Test procedure

First, four helmets from the Belgian Army were tested in order to determine the actual limits and response of the system. The first type of liner tested is a net system. Secondly, different liner configurations were tested to see the load transmitted to the headform from the projectile impact. Ten different configurations were tested: two commercial solutions (Skydex and Koroyd) and eight cellular materials produced for this work.

The 9 x 19 mm projectile was fired at the helmet with a velocity ranging from 328 to 361 m/s in the four positions of the helmet (front (F), right (R), left (L) and back (B)). The impact velocity does not relate to any ballistic resistance standard but to the resistance of the helmet, as when it was designed this threat was not included. The large variation of the impact velocity during the tests was attributed to the manual loading of the quantity of powder in the cartridge. The target was aligned and placed on the surrogate as explained in [28], and they were tested at least three times in different positions of the helmet (Table 1). Names given to the samples correspond to the used polymer and its density. No complete perforations of the shell were observed for this range of velocities.

Table 1.- Number of tests for each configuration.

Tested sample	Number of fair impacts
Actual liner	16
Skydex	4
Koroyd	4
PMMA 390	4
PMMA 191	4
PEI	3
TPU 265	4
TPU 329	4
TPU 367	3
TPU 414	3

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TPU 492	4

3.2 Liner

Their main function is to hold the helmet in the correct position in an ergonomically acceptable way. Ballistic helmets typically employ one out of two types of liners, foam padded and strap-netting liners. The two liner systems (net systems and pads) have different performances with regards to thermal comfort and reducing the pressure field around the head when a blast or impact event occurs. Pads allow for the distribution the impact forces over larger areas, reducing the loads on the head of the user [24], [25]. The key to the foam's energy-absorbing properties is the cellular structure and its crushable structure. During compression, the cells compress and fracture which prevents the impulse from being transferred to the body directly. Low density foam with a small cell size is more effective at reducing the transfer rate of this impulse [26], [27].

Micro- and nanocellular polymers are biphasic materials with a solid phase and a gaseous phase in the micro and nanometric range respectively. These materials have already been proven to present excellent mechanical performance under conventional laboratory loads and speeds [9]. However, as far as the authors know, these materials have not been investigated as liners.

For the testing campaign, different micro and nanometric polymeric foams have been designed by the CellMat Laboratory at the University of Valladolid, to be tested as liners. The produced materials from different polymeric matrices, present a wide range of relative densities and cell sizes. The materials have been produced through the gas dissolution foaming technique which comprises three steps, saturation, desorption, and foaming. During saturation, the polymer is saturated under a CO_2 atmosphere at a certain saturation pressure and temperature (P_{sat}, T_{sat}). Once the sample is fully saturated the gas is rapidly released to atmospheric pressure creating a thermodynamical instability that produces phase separation and the creation of nucleation points. Finally, samples are submitted to a foaming temperature (T_f) above the glass transition temperature of the gas-polymer system, during the foaming time (t_f) to expand the nucleation points into the final cells.

To produce the foams, three polymeric matrices with different properties have been selected: a common thermoplastic polymethylmethacrylate (PMMA), a high-performance polymer polyetherimide (PEI) and an elastomeric thermoplastic polyurethane (TPU). An example of the obtained cellular structures is shown in Figure 5.

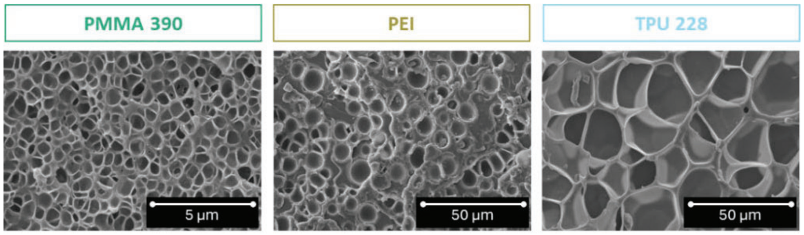

Figure 5. SEM micrographs of some of the produced cellular materials: PMMA, PEI, and TPU.

The combination of the different polymeric matrices with a wide range of production parameters allows the production of foams with very different characteristics (Table 2).

Table 2.- Production parameters and characteristics of the produced foams.

	Saturation Parameters		Foaming Parameters		Cellular Materials Characteristics	
Material	**Psat (MPa)**	**T sat (ºC)**	**T f (ºC)**	**t f (s)**	**Areal Density (AD) (g/m^2)**	**Cell size (nm)**
PMMA	31	25	60	120	7800	300-600
			100		3820	500-800
PEI	30	225	170	180	19000	1000
TPU	30	150	150		4560	2000
			140		6160	
			130		7040	
			120		7760	
			110		8880	

PMMA with relative areal densities (AD) from 3820 to 7800 g/m^2 and cell sizes from 40 to 800 nm have also been obtained. PEI presents the highest AD, 19000 g/m^2, combined with a 1-micron cell size. Finally, foams based on TPU have been produced with a wide range of AD from 4560 to 8880 g/m^2 and a fixed cell size of around 2 microns.

The produced liners have also been compared with commercially available liners: the originally mounted strap-netting system, Skydex and Koroyd. The commercial solution Skydex consists of four layers: in contact with the helmet, a hook-and-loop fabric layer; followed by the Skydex impact layer, a patented polymer-based geometry designed to absorb energy. Next is a comfort layer made from reticulated urethane, and finally a moisture-wicking fabric layer in contact with the head. The Koroyd solution consists of a collection of welded polymer tubes that deform plastically under impact. The first two commercial solutions have already been implemented in ballistic helmets available in the market. The third is present in several types of helmets, mostly motorcycle and industrial helmets, but it can be designed to withstand specific mechanical loads. The tested configuration was designed to limit the transmitted force to the skull to values below 5000 N.

3.3 Setup for sample testing

For the commercial solutions (Skydex and Koroyd), it was possible to place the material directly in its correct place (front, back, right, and left) for each type of sample in the helmet, a former helmet from the Belgian Army manufactured by Schuberth.

Due to manufacturing limitations in thickness, several layers of the produced cellular materials were stacked to produce the testing samples with a thickness of around 20 mm. (Figure 4.a). This stack was located in the desired position of the helmet (Figure 4.b.). Finally, the helmet was fixed to the load-sensing headform aligning the helmet position with the desired impact point (Figure 4.c.) and ensuring the correct gap between the headform and the helmet.

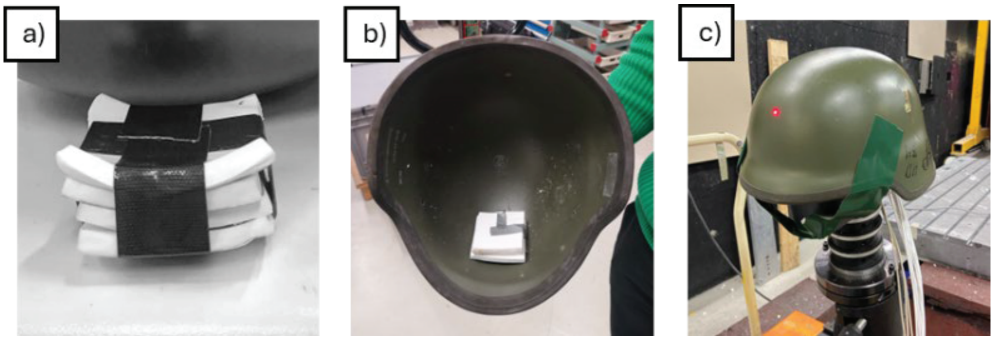

Figure 4.- a) Stacked cellular samples to obtain the desired thickness b) Cellular samples positioned in the helmet c) Helmet positioned on the load-sensing headform.

3.4 Head Injury Criterion (HIC)

Some experimental measures have been developed by the automotive and sports industries to assess injury risks for low-speed, high-mass impacts. Criteria such as HIC, viscous criterion, angular rotation thresholds, translational acceleration limits, and head impact power have been proposed. It is commonly accepted that skull fracture can be related to the maximum dynamic force; however, there is no consensus on the criterion to use to cover the full spectrum of possible blunt impact head injuries.

The Head Injury Criterion is a measure of the likelihood of head injury arising from an impact, taking into account the duration of the event and the mean value of the acceleration. The HIC can be used to assess safety related to vehicles, and sports equipment [20]. It is deemed appropriate for low-speed, non-penetrating impacts [21]. The impacts assessed here are outside of the scope of this criterion, but the goal is to check the feasibility of an armour and liner system and to compare their response with an actual helmet.

The HIC is defined as:

$$HIC = MAX\left(\frac{1}{T_2 - T_1} \int_{T_1}^{T_2} a(T)dT \right)^{2.5} (T_2 - T_1) \qquad \text{Eq 1}$$

where T is time. $T_2 - T_1$ is limited to a specific value, usually 15 ms or 36 ms (HIC-15 or HIC-36) [22] and a is the acceleration of the head measured in *G'*s.

The HIC value can be related to an injury threshold [23]. These limits are used as guidelines in the automotive field. In that field, impacts happen at relatively low velocities and a timescale of 15 ms is appropriate. For a ballistic impact, it can last a couple of ms, deviating from the initial assumptions of HIC. So, no direct link to injury should be derived from this data. But it is still relevant to be able to compare the different systems, as the only objective is to compare the outcome after the impact and not to assess the risk of injury.

4 RESULTS

From the BLSH, it is possible to extract the information on the force and acceleration applied to the head during the impact. One result of the force measurement for each tested material is represented in Figure 6.

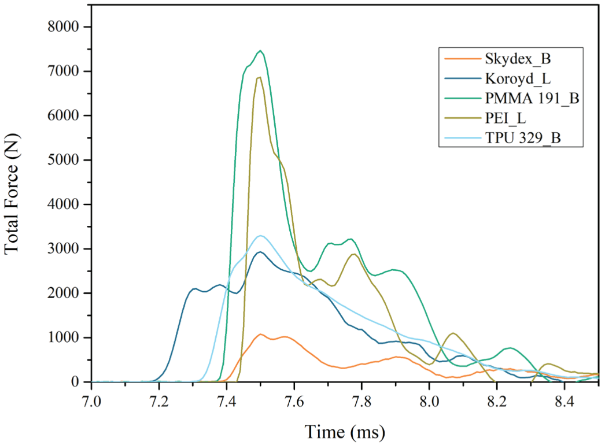

Figure 6. Force versus time.

The peak value is presented in the Figure 7:

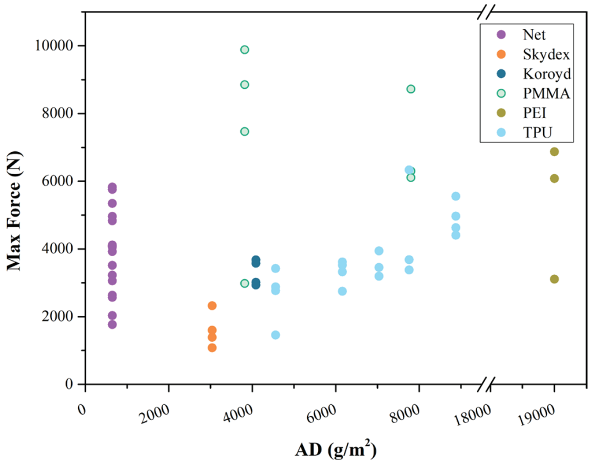

Figure 7. Maximal force versus AD.

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Comparing the obtained values of the maximum force for the different materials in Figure 7, it is possible to observe that the net solution offers a lighter solution, with a measured force between 1763 and 5756 N. The commercial Skydex is the next lightweight solution that offers reduced force levels, with a maximum of 2320 N.

From the cellular materials manufactured for these tests, a correlation is observed between the areal density with the transmitted force. On the one hand PMMA, while offering lightweight solutions reaches force values up to 9880 N. PEI material presents a medium force around 5000 N but with a very high AD. Finally, the TPU in the lighter version offers force values of 3422 N. The measured force in TPU increases with AD.

Regarding the acceleration values, Figure 8 shows the values for the HIC.

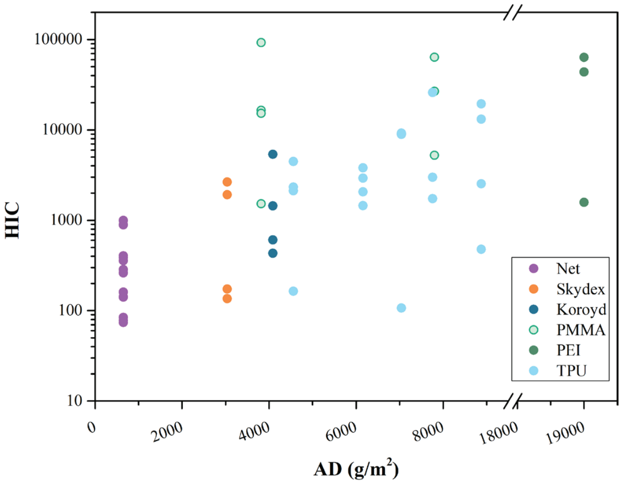

Figure 8. HIC versus AD

5 DISCUSSION

For all the tested solutions, the net liner seems to be the lighter one, but it offers a lower degree of protection, as the results for this particular case show a potential for injury, as the skull can support around 5000 N [16], [29]. Skydex and Koroyd are able to reduce to force to the user to a satisfactory level, with Skydex being lighter than Koroyd.

Regarding the produced cellular materials, the ones based on PMMA and PEI offer a very high transmitted force to the headform. As shown in Figure 6, PMMA collapsed and crumbled during the impact (Figure 9), not being able to absorb the incoming energy and transferring a significant load to the headform. Most probably the steep line is produced by the direct contact of the back face of the helmet with the headform.

Figure 9. PMMA sample after the impact.

On the other hand, cellular materials based on TPU show better results being able to reduce the load to the head with a reduced mass. Due to the fact that TPU is an elastomeric polymer, it can handle this load several times without affecting its mechanical properties. This characteristic might be useful for other types of severe loads that do not affect the integrity of the shell, as the overpressure of an explosion. As can be seen in Figure 10, TPU 329 shows a similar behaviour in the second impact (B_2) as in the first impacts at different positions.

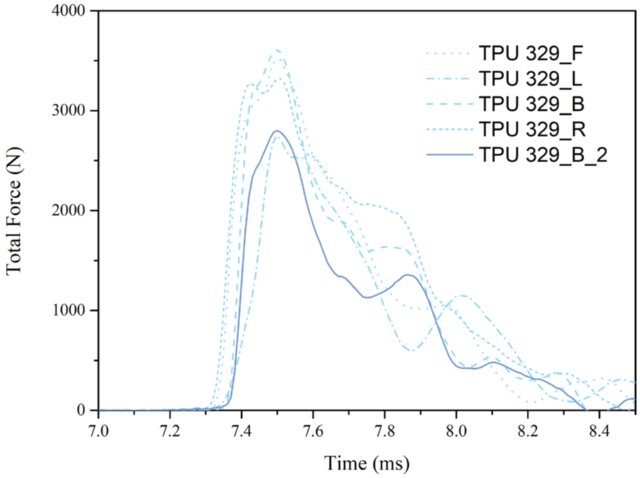

Figure 10. Force for the firsts and second impact for the TPU.

These tests show the potential of the produced cellular materials for pads for helmets, or other protective systems with high mechanical constraints as they could offer high levels of protection with a lightweight structure.

The time between the signal starting to increase and its maximum is important to understand the transfer of the force. A long time delay, such as the one observed in the commercial Skydex and the produced TPU foam means that the liner is able to transfer force to the headform for a longer period, and therefore it will allow to effectively reduce the maximum of the curve. Surprisingly, the TPU material worked in the elastic region, being able to withstand more impacts with similar characteristics. On the other hand, a short time delay means a short time to transfer the force, increasing the value of the maximum as is the case with PMMA or PEI.

For the values of the HIC, all of them are quite high as the net, with the lowest values, exceeds 900. The Skydex performs slightly better than the Koroyd. And from the manufactured samples it is possible to observe a tendency for the TPU to reduce the HIC with lower AD. More samples would determine the real shape of the curve as it seems to achieve a flat region below the 6000 g/m^2. The results of the PMMA and the PEI are very high and inconsistent, and the PMMA shows a response independent from the AD.

It can be concluded that elastomeric polymers are the ones able to reduce both the total force as well as HIC. The presence of cells of around 2 microns in this elastomeric matrix not only reduces the AD of the materials but also leads to the observed mechanical performance. When the impact is received, instead of the material deforming as a whole, each of the cells compresses within the elastic range, resulting in excellent performance. Additionally, if the cell size is small enough in comparison to the volume occupied by the polymeric chain, the mechanical properties of the cellular polymers are even better, due to 3D confinement [31].

On the other hand, the manufacturing production method is cheap and very versatile, because the control of each production parameter allows for a wide range of cell sizes and relative densities. The obtained preliminary results show that elastomeric matrices with smaller AD and cell sizes could lead to the reduction of the total force and HIC. Materials with these characteristics will be produced for further testing.

As can be seen, cellular materials with the elastomeric matrix, TPU, are again the ones performing better, with HIC values in the same range as Skydex samples. On the other hand, cellular polymers from rigid matrices show high HIC values.

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6 CONCLUSIONS

In this study, the loads transmitted to the headform from the impact of a 9 x 19 mm FMJ projectile into a helmet were analyzed. It compared the influence of several liners. The tests compared three commercial solutions (net, Koroyd and Skydex) and eight cellular samples manufactured for these tests. The output results were the force and acceleration measured by the headform.

Among the manufactured materials, the cellular polymers based on TPU seem to be the best as they offer a performance comparable to the commercial ones, showing the potential of this kind of material to handle severe loads. It offers very good results for the force as well as for the acceleration. Moreover, it is an elastic material, and therefore its mechanical properties are not diminished after an impact.

Acknoledgmements

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