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EFFECT OF THE DIFFERENT SPEED COMPRESSION ON THE MECHANICAL BEHAVIOUR OF ALUMINIUM FOAM

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Abstract

The research is focusing on the improvement of vehicle impact safety considering the mass optimization problem. The application of aluminium foam in the vehicle industry is not a novelty. The crumple parts integrated with metal foam can be one of the better solutions to improve the impact energy-absorbing capacity of the vehicles. However, it is very important that the absorber can hold the mechanical behaviour under low and high-speed impact loads. The present study represents the mechanical behaviour and energy-absorbing efficiency of closed-cell aluminium foam investigated by different compression speeds. The investigation reveals the nexus of the impact speed and the amount of absorbed energy by the foam.

Keywords: *aluminium foam, impact energy, speed-dependent test, absorbing efficiency*

Introduction

In the last decade, metallic and particularly aluminium foams have become an interesting material group, especially in the aerospace and automotive industries [1-4]. The mechanical, electrical, acoustic, and chemical features of the foam strongly influence the application field. Furthermore, nowadays owing to the trend of mass optimization in the vehicle construction field, foams have been a more important role in the vehicle body. Their formation by compression, impression, and impact is special, it differs significantly from the usual for solid metals. They can be also rigid and have good forming and thermal conductivity properties. Good impact energy absorbers, high temperature and high-pressure filters due to their strength and perforated structure; good sound absorbers and sound insulators due to their acoustic properties [5]. The enhanced energy absorbing capacity and lightweight make this alternative material attractive related to the traditional ones alloyed steels [6-7]. Due to the many positive features of aluminium foam, tons of recent studies examine its mechanical behaviour and cellular structure of it. The most frequently applied investigation method to reveal the mechanical properties of foam is the compression test results of a typical stress-strain diagram. The diagram has three main indicated sections; therefore, it divides the aim of each investigation. Some study of them is about the analysis of the first linear-elastic region [8]. There are many publications about the examination of the plateau region, which is the second range of the stress-strain diagram [9-10]. The researchers revealed the nexus between the foam density and the hardening effect of the foam, that's why they analyze the third or densification named region of the chart [11]. Furthermore, the foam behaviour can be influenced by the application of the radial constraint. The

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manufacturers frequently use foam as a filler material in shell typed parts to improve the mechanical properties of the construction. With this material, integration of the positive features of the foam can be more over improved next to the completion of the requirements of the mass optimization [12-13]. In this work, a study is undertaken of investigating the mechanical behaviour of aluminium closed-cell foams with different compression speeds. The study focuses on the impact of energy-absorbing since the result and the conclusion of the test will be used for the latter crush box structure optimization. In order to reach exact results, one must be taken into consideration the standards related to this field. The foam was examined with 1 mm/s 10mm/s and 100mm/s compression speed until 80% strain. One of the main application areas of the investigated metal foam is the integration of mechanical energy absorption into one of the most important properties of motor vehicles, for which the compaction test detailed above is the most suitable method. Due to the importance of energy absorption, the most commonly used test method is the pressure test, which is detailed in the international standard ISO: 13314: 2011 [14], if the compaction does not reach the speed limit of 100 mm / s. Above this speed, the test should be based on the ISO17340: 2020 [15-16] standard detailing the conditions for the dynamic compaction test. The standard requires that the specimen size be at least ten times the average pore size and that the height/diameter or height/width ratio may vary from 1 to 2. For comparison, the measurement results were compared using the following characteristics: The yield strength - σ_{ys} (MPa) - denotes the conventional yield strength or the first stress peak for the 1% residual deformation. The plateau stress - σ_{plt} (MPa) - is the average of the stress values calculated for the nearly horizontal section of the curve. The absorbed energy during the compression - W_{ε} (J / cm3) - is equal to the area under the stress-strain curve. In addition, the energy absorption efficiency is determined as a percentage. From this, conclusions can be drawn and we get information about what reserves the metal foam has, and suggestions can be made for developers to make more efficient use of it.

Application of the metal foam in passive safety system

Rear-end collision is presently among the most common type of car accidents and collisions. According to the level of the impact energy, this type of accident can be divided into different groups. In the case of low-impact energy, only optical parts of the occupant vehicles are damaged frequently and do not result in personal injury or it is healed within 8 days. When the occupant's vehicles have higher mass or velocity at the moment of the impact, the primary safety crumple parts will be damaged in the interest of absorbing most of the kinetic energy. The bumper and the crush box of it are taken into consideration as the primary crumple zone. The research is focusing on these components' optimization. These components' energy-absorbing capacity can be enhanced with the integration of metal foam. The typical happening location of the collision is the crowded downtown and suburban roads. Therefore, the impact speed can be shown wide range, and naturally, the higher speed can result in more serious personal injury. The use of metal foams in the creasing zone shall be tested to ensure that the energy absorber responds at any rate to impact loads at different speeds. After all, we expect the ability to absorb energy in the widest possible load range. Fig. 1. shows the typical application instance of the foam related to the passive safety system.

Specimen preparation and testing

For the test, the cylindrical specimens of the closed-cell foam had 30 mm in diameter and 30 mm in length. In order to make a better conclusion, we repeat the test three times for more data. The foam was available in 200mm x 50mmx 30 mm blocked form, so with CNC technology we make the specimens according to the predefined program for the proper size. This manufacturing process is introduced in Fig. 1. After the manufacturing we measure the geometry parameters of the foam. We record their diameter, length and mass of them. According to this result, we can determine the average density of the specimens (ρ). In this study, the effect of the foam density on the absorbing behaviour is not detailed.

Fig. 1. Foam-filled crush box [14]

However, in later sections to determine the energy efficiency and the amount of absorbed energy the relative density must be defined. The relative density is the ratio of the density of the foam structure(ρ) and the density of the material of the foam (ρ_s):

$$\rho_{rel.} = \frac{\rho}{\rho_s} \tag{1}$$

For the designation, we used the SPX as the abbreviation of the specimen word. The parameters of the specimens are collected in Table 1.

Table 1. Parameters of the specimens

No.	D[mm]	L [mm]	m [g]	ρ [g/cm³]
SP1	29.93	29.58	6.95	0.33
SP2	29.90	29.43	7.04	0.34
SP3	29.81	29.66	6.91	0.33
SP4	29.88	29.42	6.47	0.31
SP5	29.93	29.31	7.08	0.34
SP6	29.89	29.84	6.95	0.33
SP7	29.93	30.03	6.82	0.32
SP8	29.99	30.01	7.32	0.35
SP9	29.81	29.53	6.15	0.30

As can be seen. the average density of the foam is 0.3 g/cm^3. We will use these results in the case of defining the absorbing density. In order to avoid the non-perpendicular positioning during the compression. we have taken fine surface machining related to the upper and lower plate of the specimen. Fig. 2. represents the machining of the specimens.

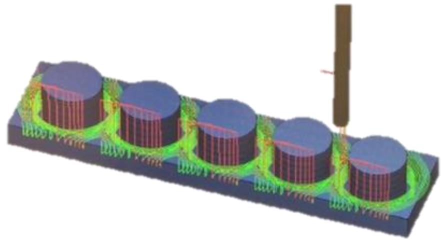

Fig. 2. Specimen machining

For the compression test. we used the Instron 8801 machine which is working on the principle of the servo-hydraulics method. The tester provides the option for the quasi-static and the dynamics compression test also. The Instron is working with the WaveMatrix software. and it is able to record the stress-strain diagram of the compression test. The Stress value is calculated by the data of the 100 kN load cell. and for strain. the displacement is recorded during the test. In favour of analyzing all segments of the stress-strain curve. the specimen will be compressed by 80 %. In the phase of the test machine preparation. we realize that the wished high speed (100mm/s) compression speed can be achieved during free running before it reaches the specimen. We detected that this acceleration range must be a minimum of 100 mm before the specimen impact. The scheme of the test is reported in Fig. 3.

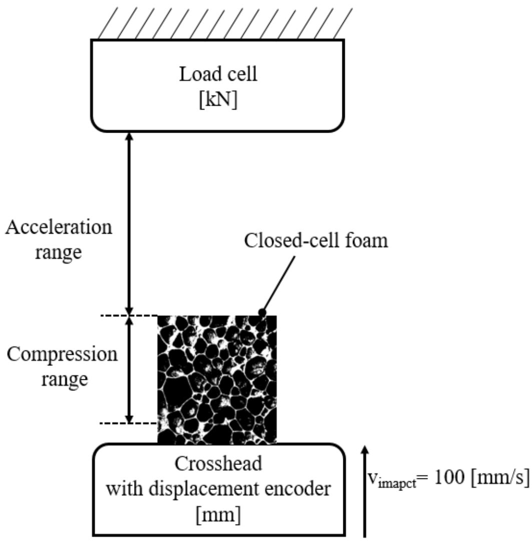

Fig. 3. Scheme of the measurement

The 1 mm/s and the 10 mm/speed compression don’t require an acceleration range. In these cases. In the starting position 30 mm was between the load cell and the crosshead. After the compression, we measured the geometries of the specimens focusing on the diameter changes of all specimens.

Interpretation of the foam characteristic

Ideal energy absorbers have a long, flat stress-strain curve. When the absorber collapses plastically at constant stress called plateau stress. Impact energy absorbers are chosen so that the plateau stress is just below that which would cause damage. So, the best way is then the foam has the longest plateau. Therefore, absorbing more energy. In crashworthiness. the foam as the absorber has to absorb the kinetic energy of the moving object without reaching the densification strain [17]. Fig. 4 indicates a stress-strain curve for an energy absorber. The area under the curves is the useful energy (W) or energy per unit volume (W_v) which can be absorbed. Here F is the force. ε the displacement recorded by the displacement meter. According to the related standards. plateau stress is the arithmetical mean of the stress between the 20 and 40% strain. The end of the plateau can be considered with the 1.3 times the previously calculated plateau stress [18]. The first maximum point of the curve is the first maximum strength and the study uses this stress value for the comparison. Fig. 4. shows the typical stress-strain curve of the compression test of cellular material.

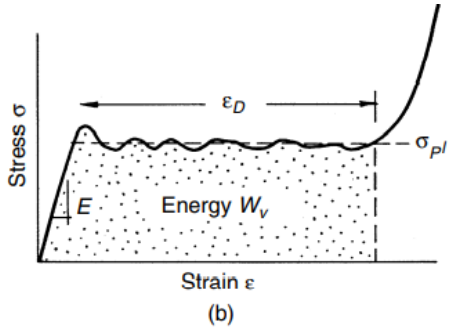

Fig. 4. Typical stress-strain curve of metal foam [14]

During the compression. the foam absorbed the impact energy of the cross-head accompanied by cell deformation and densification. The Gibson-Ashby Model systematically describe the nexus between the mechanical properties of porous or cellular structure and the relative density. like the plateau stress. Young's modulus and the densification strain. The relationship according to the Gibson-Ashby model [17]:

$$\frac{E_L}{E_S} = C_1 \left(\frac{\rho_L}{\rho_S}\right)^n \tag{2}$$

$$\frac{\sigma_L}{\sigma_S} = C_2 (\frac{\rho_L}{\rho_S})^m \tag{3}$$

where the E_L. ρ_L. and σ_L are the elastic modulus. density and yield strength of the cellular material. ε_D is the value of onset densification strain of the cellular structure where the densification region starts that is why the study records its value of it. Furthermore, the ε_D has an important role. since it can be considered a practical limit for energy absorption applications using cellular structures. Since after the curve achieves the strain limit. the cellular structure will continue to absorb energy. However, the expense of transferring stress throughout the cellular structure [19]. So, this problem is due to the densification of the foam since it begins to become a solid structure. which is able to conduct the impact energy. and this can result in damage to the object or injury to the human body- integrity. In this study. numerical integration is used to determine the absorbed energy of the cellular structure. giving the area under the compressive stress-strain curves.

Compression with 1 mm/s

The compression measurement was started with a compaction speed of 1 mm/s. Compression was performed to 80% deformation and the measurement was repeated 3 times and use the SP4-5-6 labelled foam. Owing to the low speed and the maximum recording frequency during the compression we could record more than twenty-thousand values. Due to the tons of data exact stress-strain curve can be drawn. Table 2 collects the results of the tests. but the conclusion is formulated by considering the average of them. The curves are presented in two sections. Firstly, the 0-60% strain stage and after the 0-80% strain range is presented to be able to analyze the plateau stage and the whole compression curve.

Table 2. Main results of the 1 mm/s compression test

	SP4	SP5	SP6	Average	Unit
σ_{pl}	2.69	2.75	2.88	2.77	MPa
$\sigma_{pl\ end}$	3.38	3.44	3.42	3.41	MPa
$\varepsilon_{pl\ end}$	50.01	46.63	47.11	47.91	%
$\sigma_{first\ max}$	2.62	2.74	2.69	2.68	MPa

The arithmetical means of the 20-40% strain range was 2.61 MPa. It can be considered as the plateau stress of the foam. The plateau range reached its end at 47.91% strain, so from here considering the starting of the densification stage. The compression test occurred curves are represented in Fig. 5. and Fig. 6.

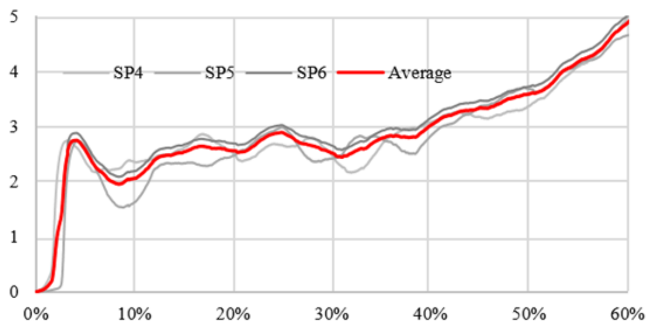

Fig. 5. Stress-strain curve with 1 mm/s up to 60% strain

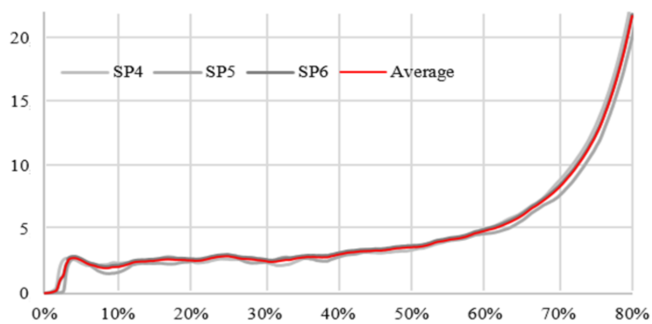

Fig. 6. Stress-strain curve with 1 mm/s up to 80% strain

Compression with 10 mm/s

In the second section of the comparison test. the impact speed was increased up to 10 mm/s. For this section. the SP1-2-3 labels have used the designation. The same temperature and test circumstances are supported. Despite the 10 times higher speed owing to the high data record frequency there are tons of values to edit the stress-strain curves. There was no significant difference. and the foam was able to hold the typical characteristic and values. To the measuring same recording. the frequency was used. The compression results in a typical stress-strain curve (Fig. 7. and Fig. 8.). in which the three segments can be well distinguished. Table 3 summarizes the results of the 10mm/s speed compression.

Table 3. Main results of the 10 mm/s compression test

	SP1	SP2	SP3	Average	Unit
σ_{pl}	2.53	2.15	3.13	2.60	MPa
$\sigma_{pl\ end}$	3.28	2.79	4.07	3.38	MPa
$\varepsilon_{pl\ end}$	48.91	48.66	48.57	48.71	%
$\sigma_{first\ max}$	2.29	2.01	2.73	2.34	MPa

According to Table 3. results. there was a wide fluctuation in the specimen's curve. As Fig. 6. confirms the SP2 and the SP3 specimens show a relatively large plateau stress difference. The average of it was 2.6 MPa. Remarkable notice that the running of the curve is not smooth. the stress fluctuation along the curve's line is wide focusing on the range up to 60% strain. especially in the first section. The densification stage is starting from 48.71% strain.

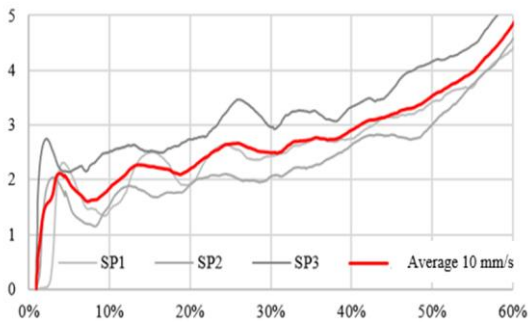

Fig. 7. Stress-strain curve with 10 mm/s up to 60% strain

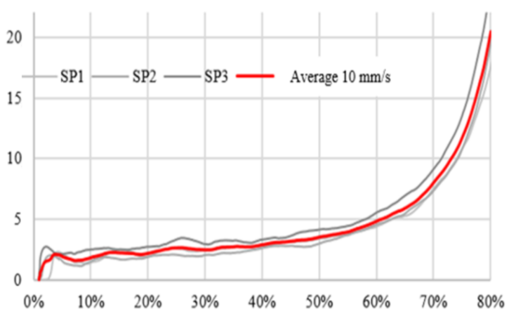

Fig. 8. Stress-strain curve with 10 mm/s up to 80% strain

Compression with 100 mm/s

In the third section of the comparison test. the impact speed was increased up to 100 mm/s reaching the dynamic compression test limit. For the 100 mm/s dynamic compressions we used the SP7-8-9 labelled specimens. The same temperature and test circumstances are supported. As the above chapter mentioned. in this test must apply acceleration range before the impact. The Instron 8801 is working on the principle of servo-hydraulics. This means the hydraulics cylinder cannot reach 100mm/s immediately after starting. So, we apply a 100 mm path to accelerate the crosshead for the proper velocity. Naturally, the compression displacement is the same, so the foam is compressed up to 80% strain. There was no significant difference. and the foam was able to hold the typical characteristic and values. To the measuring same recording. the frequency was used. Despite the dynamics load compressing the test results in a typical foam stress-strain diagram introducing them in Fig. 9. and Fig. 10. The results have been tabulated for ease of reference in Table 4.

Table 4. Main results of the 100 mm/s compression test

	SP7	SP8	SP9	Average	Unit
σ_{pl}	2.53	2.15	3.13	2.60	MPa
$\sigma_{pl\ end}$	3.28	2.79	4.07	3.38	MPa
$\varepsilon_{pl\ end}$	48.91	48.66	48.57	48.71	%
$\sigma_{first\ max}$	2.29	2.01	2.73	2.34	MPa

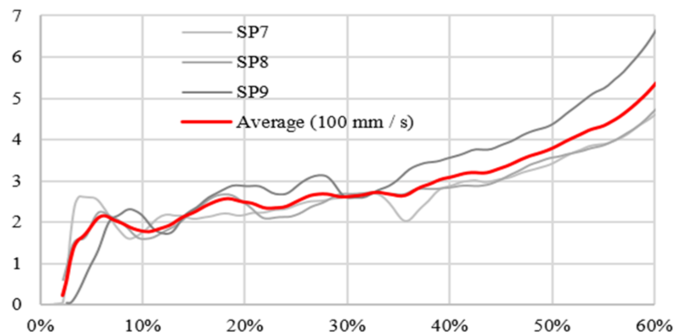

Fig. 9. Stress-strain curve with 100 mm/s up to 60% strain

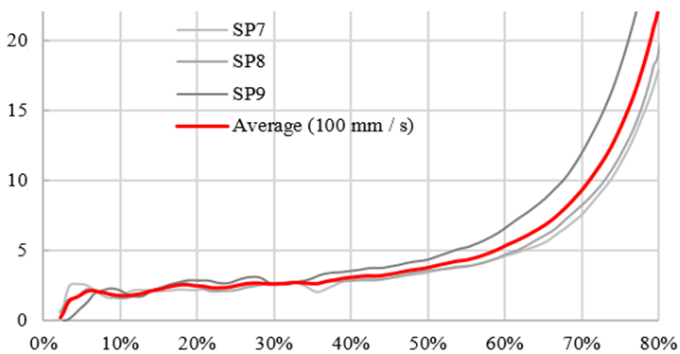

Fig. 10. Stress-strain curve with 100 mm/s up to 80% strain

Comparison

Analyzing the stress-strain curves of the investigation it can be seen that there was no significant difference between them as Fig. 9. shows. In the first linear elastic section the 1 mm/s speed compression results in higher maximum strength than the others. In the plateau section. all of the measures give similar characteristics. only the first section of the plateau shows a few fluctuations. In the second section of the plateau and the densification range. the steep curves are similar. In this 1-100 mm/s remarkable difference cannot be formulated. as it is confirmed by Fig. 11. However, in this type of investigation. some recent studies share the experience of the effect of the dynamics compression. For example. Mukai et al reported in their study that the foam was able to absorb more impact energy when the speed of the compression was higher. According to this source the closed cell foam which was analyzed by quasi-static and dynamic compression test results in different values related to the absorbed energy. The average values of absorption energy per unit volume of ALPORAS at the strain of 55% for the quasi-static and dynamic strain rates are calculated to be 1.00 and 1.51 MJ/$m^{3.}$ respectively. The value of W at the dynamic strain rate is about 50% higher than that at the quasi-static strain rate. The experimental results obtained in this study suggest that there is a large difference in mechanical strength and absorption energy between tested at a quasi-static and dynamic strain rate. It is therefore important to know the actual strain rate sensitivity for a special application in order to properly select materials [19].

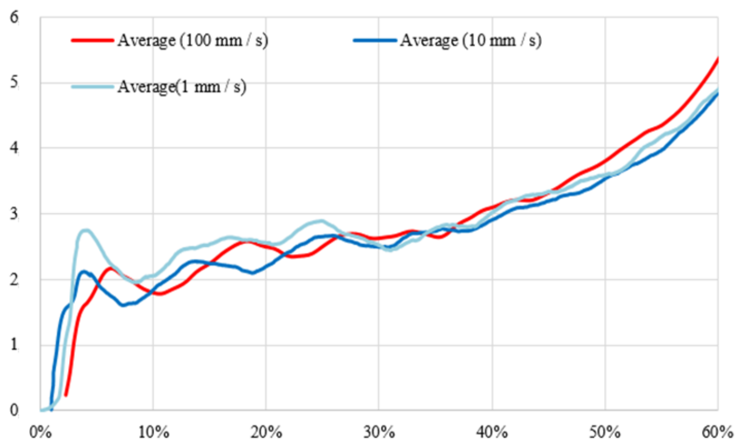

Fig. 11. Comparison of the stress- strain curves

Absorbed energy

When the foam is loaded by compression. the walls of the cell bend and buckle at almost constant stress (plateau stress) until the cells begin to impinge with each other. The compression results in the above-detailed type stress-strain curve. There are more ways to determine the theoretical absorbed energy taking into consideration of the mechanical properties of the foam. One of them is the next formula considering the yield strength of the foam and its relative density of it [18]:

$$W_{absorbed} = C_1(\frac{\rho}{\rho_s})^{3/2}\sigma_{ys}\varepsilon_D \quad (4)$$

In the crashworthiness. the densification range must be avoided. since the impinged cells would be able to conduct the impact energy toward the driver and/or passengers. Therefore, the useful period of the diagram is running up to the densification strain (ε_D). The members of the formula to the theoretical energy amount can be determined from the diagram and with the approximate nexus. or with the (4) and (5) The plateau is up to the densification strain. beyond which the characteristic of the diagram rises strongly steeply. Taking into consideration of the foam density the plateau stress and the densification strain can be calculated with the next formulas [16]:

$$\sigma_{plateau} \approx (0.25 \dots 0.35)\sigma_{ys}(\frac{\rho}{\rho_s})^m \quad (5)$$

$$\varepsilon_D \approx (1 - \alpha_1 \frac{\rho}{\rho_s}) \quad (6)$$

For currently available metal foams m lies between 1.5 and 2.0 and $\alpha_1$between 1.4 and 2.
Using the real stress-strain curve with the next integration formula the absorbed energy can be determined by calculating the amount of area under the curve. The rule is a numerical integration method to be used to integrate the area under the curve. With the integration. we can get real information about the amount of absorbed energy.

$$W_{abs} = \int_0^{\varepsilon_D} \sigma(\varepsilon) d\varepsilon \quad (7)$$

The study is focusing on the useful absorbing period. so the upper limit of the integration is the densification strain. The next table compares the theoretical and the real absorbed energy values.

Table 5. The foam absorbed energy

Type of compression	**Absorbed energy considering the mechanical properties of the foam**	**Absorbed energy based on the real stress-strain curve**
	$W_{abs.} = C_1(\frac{\rho}{\rho_s})^{3/2}\sigma_{ys}\varepsilon_D$	$W_{abs.} = \int_0^{\varepsilon_D} \sigma(\varepsilon) d\varepsilon$
1mm/s	1.419 MJ/ m^3	1.49 MJ/m^3
10mm/s	1.281 MJ/m^3	1.301 MJ/m^3
100mm/s	1.449 MJ/ m^3	1.391 MJ/m^3

Energy efficiency

The energy efficiency can contain more useful information about the applied and measured metal foam. With this method. we can be informed about the capacity utilization of the foam during energy absorption. In crashworthiness the aim is that use the maximum absorbing capacity of the foam. to reduce the loading effect of the crashes. Taking these results into consideration we can make suggestions on development and optimization. The long-term plan of our research is to develop a vehicle crush box using foam as an energy absorbing. With these efficiencies. we can formulate the way of the development and investigation of the crumple box. Furthermore. it is a good measure value to compare the crash absorbing efficiency of each construction. To determine the impact energy absorbing efficiency of the foam the next formula is used [20]:

$$W_{eff} = \frac{W_{absorbed}}{\sigma_o \varepsilon_0} 10^4 \quad (8)$$

where the σ_o and the $\varepsilon_0$is the actual stress and strain value of the stress-strain curve range where we would like to define the efficiency of the foam. In case of vehicle crashworthiness. it is recommended to avoid the densification range of the absorber foam. since from this status the cells can conduct the impact energy to the driver or passengers. Owing to this the efficiency is analyzed up to 50% strain.

Table 6. The foam absorbing efficiency

Type of compression	W_{eff}
1 mm/s	79.08 %
10 mm/s	75.58%
100 mm/s	82.69%

As the table indicates the capacity utilization of the foam was about 80%. There was no significant difference between each type of compression. However, it can be stated based on the values that there is reserve capacity in the foam since it would be best if the efficiency proximities the maximum. 100% value.

Conclusions

In this study. a comparison test has occurred about the compression speed dependency related to the foam mechanical behaviour. The long-term aim of the research is to develop a vehicle crumple zone part. which is able to absorb more impact energy. The research is focusing on the bumper crush box of the vehicle. Therefore, it must be designed to be able to perform its task over a wide range of speeds. The component is expected to be able to retain its energy-absorbing properties over a wide range of speeds. The crush box energy absorbing capacity will be improved with aluminium-foam filler. Therefore, before the construction. it must be checked that an aluminium foam could able to hold its mechanical behaviour under different speed compression. Despite the different performance compression. the foam was able to hold its mechanical properties. All of the measurements were repeated 3 times. However, a significant difference was not detected. Focusing on the plateau range. the fluctuation between the measurements was under 5%. Another important experience is stated. according to which the starting of the densification part of the compression stays around 48% strain. In crashworthiness. the foam has to absorb the most impact energy. but the densification must be avoided. since after it the compressed cells are behaving as a rigid body. and it can conduct the impact force toward the driver or passengers. Therefore, it was important that analyze the speed effect for the starting point of the densification zone. The results of the test confirm that aluminium foam is one of the better absorber materials in the case of vehicle passive safety development since independence from the speed of the impact it can hold its energy efficiency. Furthermore, according to other recent studies the absorber foams are able to absorb more energy in a higher (over 10^3 s^{-1}) speed range. Referring to present and recent studies it can be stated that the optimization of a passive safety system of vehicles with foam-type energy absorbers is one of the best ways. Since it is not just able to hold its positive mechanical behaviour in large-scale investigation speed. it can be more efficient.

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