

6-2023

Thermoplastics Foams: An Automotive Perspective

Sai Aditya Pradeep
Clemson University, spradee@clemson.edu

Srishti Shukla
Indian Institute of Technology

Nathaniel Brown
Clemson University

Srikanth Pilla
Clemson University, spilla@clemson.edu

Follow this and additional works at: https://tigerprints.clemson.edu/auto_eng_pub



Part of the [Automotive Engineering Commons](#)

Recommended Citation

Pradeep, Sai Aditya; Shukla, Srishti; Brown, Nathaniel; and Pilla, Srikanth, "Thermoplastics Foams: An Automotive Perspective" (2023). *Publications*. 104.
https://tigerprints.clemson.edu/auto_eng_pub/104

This Article is brought to you for free and open access by the Automotive Engineering at TigerPrints. It has been accepted for inclusion in Publications by an authorized administrator of TigerPrints. For more information, please contact kokeefe@clemson.edu.

Thermoplastics Foams: An Automotive Perspective

Sai Aditya Pradeep^{1,2}, Srishti Shukla³, Nathaniel Brown¹, and Srikanth Pilla^{1,2}.*

¹Department of Automotive Engineering, Clemson University, Greenville, SC-29607

²Department of Materials Science and Engineering, Clemson University, Clemson, SC-29634

³Department of Mechanical Engineering, Indian Institute of Technology (BHU), Varanasi, IN

*Corresponding author: spilla@clemson.edu; Ph: 864-283-7216.

1. Introduction

The automotive industry has witnessed a massive shift in terms of materials used, ranging from being a metallic heavyweight in the 1950s to employing a hybrid sandwich of multiple material systems. This apparent shift can be attributed to achieving improvements in performance, safety and fuel efficiency, along with responding to the various environmental regulations imposed by different governments. The recent advocacy of Corporate Average Fuel Economy (CAFE) standard of 54.5 MPG by 2025 by the US Environmental Protection Agency (EPA) to reduce greenhouse gas (GHG) emissions [1] has spurred the sector at large towards the use of lightweight materials.

Thermoplastic foams possess enhanced strength-to-weight ratio, impact resistance and acoustic properties, reduced permeability to water vapor/air compared to their solid counterparts, and have increasingly become an indispensable commodity in today's industrialized, mechanized world. Foamed thermoplastics from polyolefins to polycarbonates can be best utilized in the automotive sector to fulfill the demand for lightweight materials, given that 75% of fuel consumption is directly related to vehicular weight [2], and that a 6–8% increase in fuel economy can be realized for every 10% reduction in vehicular weight [3].

A thermoplastic foam typically consists of two phases (solid and gas), wherein the solid phase is the polymer matrix and the gaseous phase is air trapped in inter-connected or isolated cell-like structures within the matrix. Furthermore, foams can also be classified on the basis of cell size, structure, rigidity, structure of strut and blowing agents employed as exemplified in Figure 1. Typically, during foam processing, gas is either blown into the molten polymer (physical foaming) or chemical compounds that evolve gases under different processing conditions either due to chemical reactions or thermal decomposition (chemical foaming). However, obtaining thermoplastic foams is challenging as it encompasses the effective utilization of knowledge base of various scientific fields, including polymer chemistry, physics, engineering – chemical, mechanical and process, and equipment design and operation.

The automotive industry is currently experimenting with and has successfully commercialized some biodegradable thermoplastic foams in an effort to combat large-scale pollution. Few automotive OEM's have also begun the use of bio-sourced polymeric foams in premium segments in order to promote sustainable bioplastics. Examples of such foams include the compounding of non-degradable polymers such as polyolefins with degradable materials like starch, wood flour, jute and hemp, and/or the use of inherently degradable materials such as partially substituted cellulose, starch, aliphatic/aromatic polyesters, polylactic acid, plasticized polyvinyl alcohol,

polyesteramide and polycaprolactone. This chapter delves into the physical and mechanical properties, processing and applications of thermoplastic foams in the automotive industry.

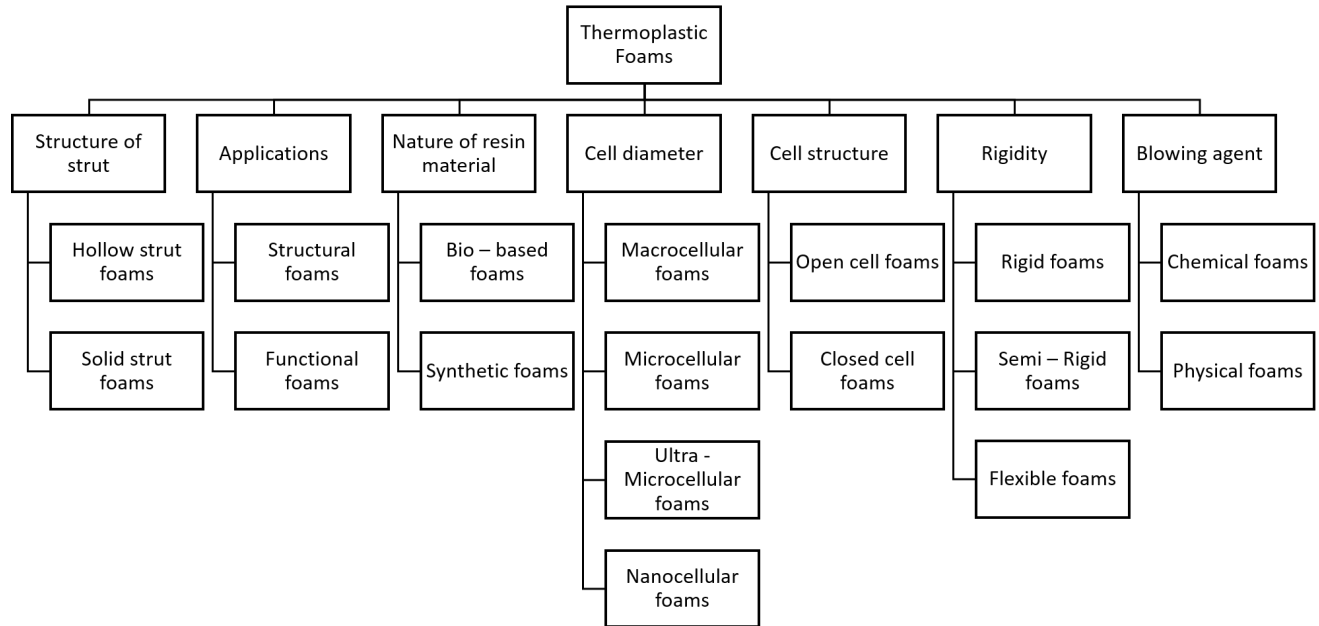


Figure 1: Classification of Thermoplastic foams on the basis of various criterion

2. Structure-Property Correlation

The structure property correlation forms the basis of our successful utilization of foams in a multitude of applications. Most properties associated with foams are endemically related to its inherent microstructure i.e. open/close cells, solid/hollow strut and cell size/density, which in turn is fundamentally tied to its processing.

2.1. Stiffness

Stiffness is primarily governed by the glass transition temperature of the polymers [4]. Generally, a foam is flexible above its glass transition temperature, so if the latter is below room temperature, the foam exhibits flexible behavior.

2.1.1 Rigid foams

Rigid foams typically exhibit high specific load bearing properties, over 90 % closed cell content, and permanent deformation with definitive yield points. Generally, such foams are used for load bearing applications.

2.1.2 Semi Rigid foams

In terms of properties, semi-rigid foams lie in the intermediate region between rigid and flexible foams. These foams do not possess high density integrated skins, and in the automotive sector, are used as shock absorbing pads, like in console box lids, door trims and sun visors.

2.1.3 Flexible foams

Flexible foams are characterized by low stiffness and high resilience. They are typically used in nonstructural applications like seat cushions.

2.2. Cell type

Open and closed cell foams exhibit a large range of various properties. Some of these properties, along with their structural differences, have been summarized in subsequent sub-sections below. Figure 2 shows both open and cell foams.

2.2.1 Closed cell foams

In closed cell foams, gas is trapped in the polymer matrix in individual isolated cells. Compared to open cell foams, closed cell foams are denser, less permeable to heat and vapor, exhibit higher R- Values and rigidity, and require more material for unit volume, making them more expensive.

2.2.2 Open cell foams

Open cell structures contain interconnected cells, are permeable to vapor, and insulate sound by capture of sound waves which get repeatedly reflected and absorbed between interconnected cell networks. They are softer, mechanically weaker, less dense, and exhibit lower R-values compared to closed cell foams.

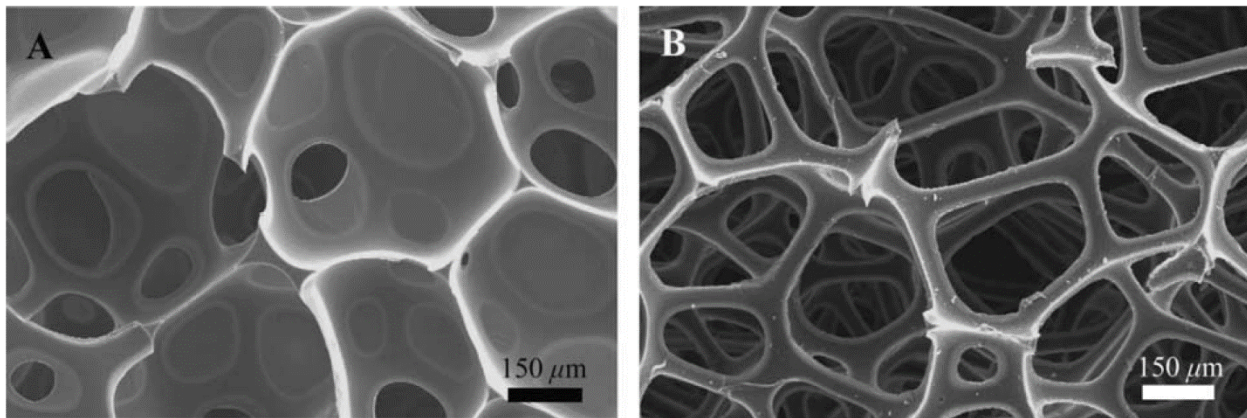




Figure 2: Open cell foam, left; Closed cell foam, right. [5]

2.2.3 Cell diameter

Generally, cell size varies throughout the foam due to two factors: random nucleation of cells in the polymer matrix, and growth of cells by diffusion of gas. Based on cell diameter (size), foams are classified as macrocellular, microcellular, ultra-microcellular, and nanocellular foams. Cell diameter has a significant influence on multiple foam properties – for example, cell size is

inversely proportional to foam resilience. The effect of cell diameter on important foam properties has been described in Table 1.

Table 1: Variation of foam properties with cell diameter[6]

	Average Cell diameter	Mechanical Strength	Foam density
Macrocellular foams	$d > 100 \mu\text{m}$		
Microcellular foams	$1 \mu\text{m} < d < 100 \mu\text{m}$		
Ultra-Microcellular foams	$0.1 \mu\text{m} < d < 1 \mu\text{m}$		
Nanocellular foams	$2.1 \text{ nm} < d < 100 \text{ nm}$		

2.3. Structural foams

Currently, structural foams are of special interest to the automotive sector, especially to manufacture of trucks. These foams are constituted of a foamed inner core, and a high density skin whose porosity is negligible compared to that of the foamed core [7]. This variation in porosity is due to the fact that the foam skin cools faster than the inner core as it is in immediate contact with the atmosphere. Consequently, more cells get accommodated in the inner core, with fewer cells making it to the already stiffened surface.

Generally, during formation of structural foams, the resin retains most of its properties, such as its thermal and chemical resistance; however, dielectric constant of the foam increases radically when compared to that of the solid resin [8]. Structural foams are suitable for structural applications due to a number of properties:

- a) High strength-to-weight ratios: generally 2-5 times that of any metal [4]
- b) High rigidity due to higher wall thickness
- c) High stiffness imparted by high density skin, along with superior impact absorption properties imparted by the foamed core
- d) Significant sound dampening characteristics

Example of structural foams that are of interest to the automotive sector include modified phenylene oxide, polyoxymethylene, polystyrene, polycarbonate and in some cases polyethylene and polypropylene foams.

2.4. Structure of strut

The strut, or typically the cell wall structure, influences multiple foam properties. Depending on the strut, foams are broadly classified into two categories described in sub-sections below.

2.4.1 *Solid strut foams*

Solid strut foams constitute the bulk of manufactured foams, and their properties have been extensively studied. They possess a cell wall made of homogeneously distributed material across the strut thickness.

2.4.2 *Hollow strut foams*

In case of hollow strut foams, as Figure 3 shows, the cell wall itself constitutes an outer wall while the inner core of the wall is empty. This foam structure does not naturally result from any conventional foaming technique; however specific manufacturing methods have been developed to fabricate them. Their macroscopic deformation is largely governed by strut geometry and structure, with many recent studies showing improved mechanical properties (Young's modulus, creep performance and plastic collapse strength) compared to solid strut foams with same relative density [9]. This can be explained using the fact that the bending stiffness of any hollow cross-section is higher than that of a solid cross-section prism, thus augmenting the bending stiffness of the strut, and resulting in enhancement of macro-mechanical properties.

Young's modulus between the two strut structures – hollow and solid – was compared by Ashby and Gibson [10], showing an insignificant difference in favor of hollow strut foams. Steady state creep resistance and plastic collapse strength of both types of foams was compared by Andrews [9], indicating a significantly higher creep resistance and less-significant but higher plastic collapse strength of hollow strut foams compared to solid strut foams; the former difference easily exceeding an order of magnitude [9].

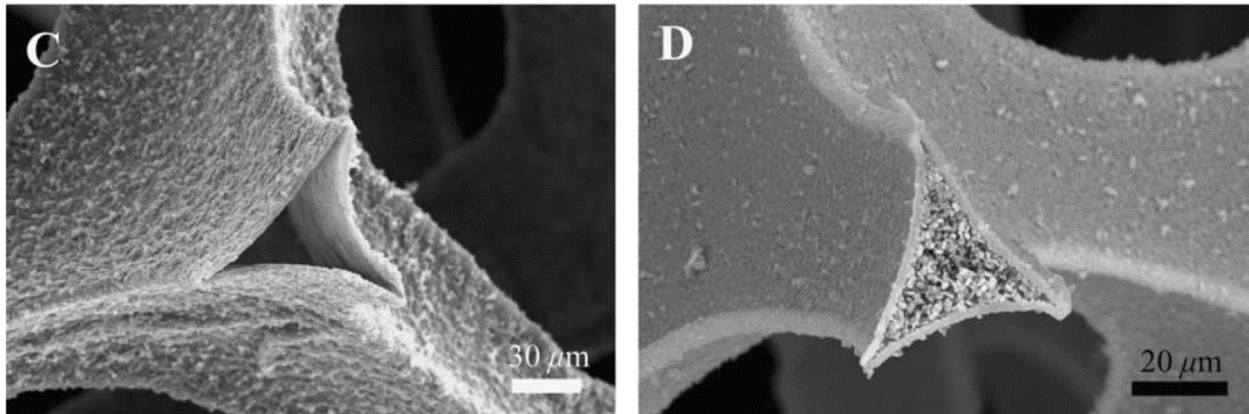


Figure 3: Hollow strut foam (left); Solid strut foam (right) [5]

2.5. Blowing agent

The means by which foaming is induced must be examined in order to predict structural changes brought about by such means. Physical and chemical foaming remain the two primary methods for foaming polymers. Due to ease and simplicity in processing, chemical foaming has been in existence for quite some time, while physical foaming has been undergoing development and continuous modification since 1980s till date [11]. Both foaming processes are typically performed independently, though cases exist of concurrent performance to achieve greater foam expansion. Key aspects of both processes are discussed in Figure 4 and subsequent sub-sections [11].

2.5.1 *Chemical Foaming*

In chemical foaming processes, solid chemical foaming agents, often in the form of a master batch, are mixed into the resin prior to additional processing. Master batches are made of a combination

of a chemical foaming agent (up to 70% of total mass) and a carrier polymer[12]. At processing temperatures, the foaming agent decomposes to generate fluids such as N₂, CO₂ and water[11]. These fluids dissolve and get homogenized throughout the polymer melt due to the mixing action of equipment used in the process. Following the decomposition of the solid foaming agents, the residues act as nucleation points for foaming, enabling the formation of a fine cell structure [12]. This decomposition reaction may be endothermic or exothermic – a critical factor to consider in evaluating the effectiveness of a given foaming agent. Commonly used chemical foaming agents are listed in Table 4.

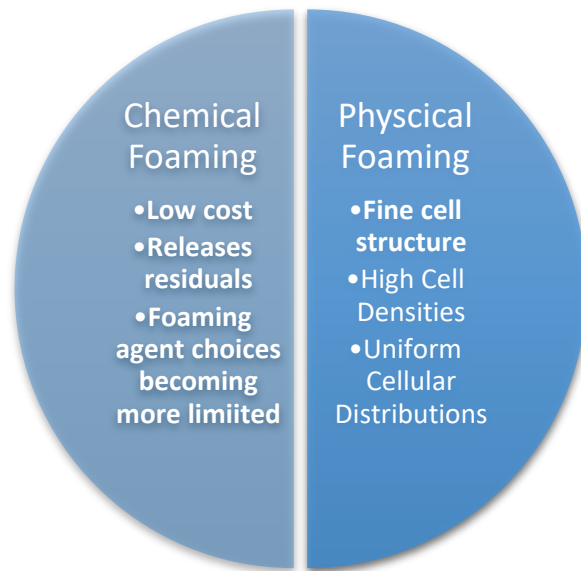


Figure 4: Key points on chemical and physical foaming [13]

2.5.2 *Physical Foaming*

Unlike chemical foaming, physical foaming does not involve chemical decomposition of the foaming agent. Instead, a fluid (compressed gas, volatile liquid, or supercritical fluid) is injected directly into the polymer melt and homogenized throughout the melt using distributive and dispersive mixing [12]. Upon this dispersion, melt viscosity is lowered significantly to levels lower than those achievable in chemical foaming. Increased temperatures or drop in pressure causes the fluid state to change, evolving a gas that results in formation of cells. A critical aspect to physical foaming is the selection of a foaming agent, as the latter has a significant effect on cellular structure obtained due to differences in solubility of different foaming agents in different polymer matrices. Historically, chlorofluorocarbons (CFCs) have been used as physical foaming agents, but are being phased out in favor of N₂ and CO₂ to avoid their associated environmental impacts and satisfy the norms set out in the Montreal Protocol [11,14]. Lower density parts are generally created using physical foaming instead of chemical foaming primarily due to the significant quantity of residuals released upon the use of large quantity of chemical foaming agent [11]. Commonly used physical foaming agents are listed in .

Table 2 [11].

Table 2: Frequently used physical and chemical foaming agents

Common Chemical Foaming Agents	Common Physical Foaming Agents
Azodicarbonamide	Isobutane
Modified ADC	Cyclopentane
4,4'-Oxybis (benzene-sulfonylhydrazide)	Isopentane
5-Phenyltetrazole	CFC-11
p-Toluenesulfonyl-semicarbazide	HCFC-22
p-Toluenesulfonyl-hydrazide	HCFC-142b
Sodium carbonate	Nitrogen
Citric acid	Carbon dioxide

2.6. Properties of Foams

2.6.1 *Thermal Conductivity*

Thermal conductivity (λ_t) of a foam can be defined according to Equation 1, as:

$$\lambda_t = \lambda_g + \lambda_s + \lambda_c + \lambda_r \quad (1)$$

Here λ_g represents thermal conductivity through the gaseous phase, λ_s refers to conductivity through the solid phase, λ_c denotes the thermal convection term, and λ_r refers to thermal radiation heat transfer.

In general, if pore size falls below 4 mm in closed cell pores [15] and below 2 mm in open cell pores [16], the convection effect can be neglected due to the small cell size. However, for cell diameters below 0.1 μm , it is assumed that the radiation wavelength is smaller than pore size. Based on this concept, it has been established that the radiation effect can be neglected when relative density is above 0.2 [17]. However, this model cannot be extended to nanocellular foams where cell size and radiation wavelength are comparable. Recent studies on nanoporous materials have shown though that radiation effect can be neglected even at lower densities [18]. Thus, a shift in scale from microporous polymer foams to nanoporous polymer foams leads to observable significant variation only in gaseous and solid phase conductivities.

With regard to conduction, thermal conductivity of gaseous phase is expected to reduce, as can be explained using the Knudsen effect [19,20] – when cell size is smaller or comparable to mean free path of gas particles, gas particles collide more frequently with the surrounding solid walls compared to other gas molecules, leading to lower conductivity through the gaseous phase. Equation 2 is known as the Knudsen equation and is used to describe the effective thermal conductivity (λ') of gaseous phase comprising air in porous media as:

$$\lambda' = \frac{\lambda'_{g,o}}{\left(1 + \beta \left(\frac{l_g}{\phi}\right)\right)} \quad (2)$$

Here, $\lambda'_{g,o}$ is thermal conductivity of free air (0.0260 W/m-K at room temperature and 1 atm pressure), β accounts for energy transfer between gas molecules and the surrounding solid (2 for air), l_g is the mean free path of air molecules (70 nm at room temperature) and ϕ is the average pore diameter. It is obvious from the nature of Knudsen Equation (Equation 2) that if cell diameter falls below 0.1 μ m, a significant reduction can be obtained in the thermal conductivity of gaseous phase as well as of the foam.

2.6.2 Mechanical Properties

While polymeric foams have gained attention in the automotive industry as lightweight and less energy sensitive materials, the industry has struggled to compensate for their poor mechanical properties, specific properties of common automotive foams are illustrated in figure 6. Dependence of physical properties of foams on their relative density is well described by the Gibson and Ashby equation [21] as shown in Equation 3. In Equation 3, P_f refers to physical property of the foam, P_s is the physical property of resin/solid phase, ρ_f refers to foam density, ρ_s represents the density of parent resin, n describes another constant with a value between 1 and 2, and C describes a constant with a value of 1 for most polymer foams. It has been observed that mechanical properties of nanocellular and microcellular foams are far better than those of conventional foams, with the former having the best properties.

$$P_f = CP_s \left(\frac{\rho_f}{\rho_s}\right)^n \quad (3)$$

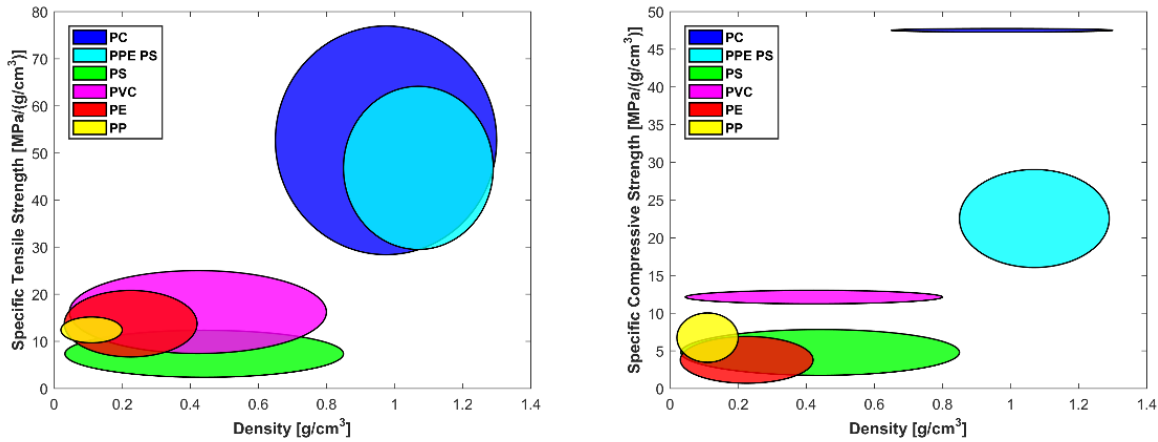


Figure 5: Specific mechanical properties of various thermoplastic foams [22–27]

2.6.3 Response to Compression

Figure shows the stress-strain curve to explain the behavior of foams on being subjected to uniaxial compression. The curve can be broadly divided into three sections; changes in cell and foam structure corresponding to these three sections have been described below.

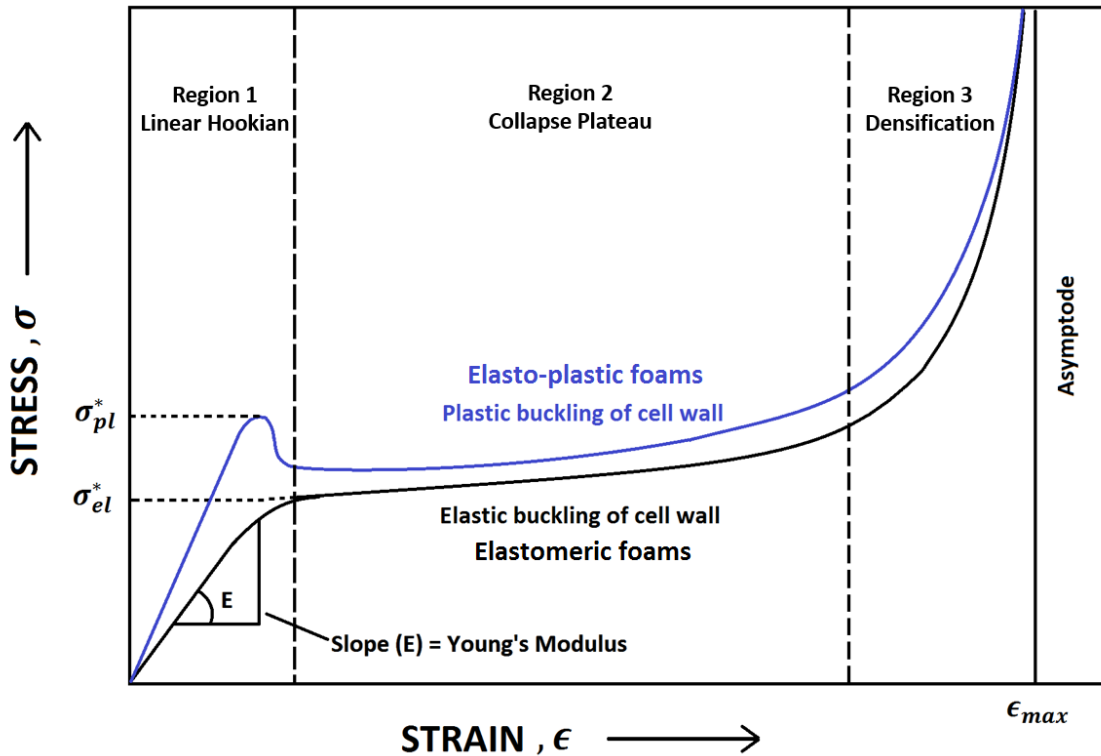


Figure 6: Stress – Strain relationship curve, deformation of foams under compression [28]

- Region 1 illustrates the linear Hooke's behavior, with the reciprocal of slope of the curve used to calculate Young's modulus. This region is characterized by bending of struts in open cell foams, and by simultaneous stretching and bending of adjacent elements of cell walls along with slight compression of cells in case of closed cell foams. This region represents the elastic region, and any strain observed is reversible.
- Region 2 shows dramatic increase in strain for slight increment in stress. This is credited to permanent strut buckling in case of open cell foams, and to rupture of cell walls in closed cell foams due to which deformation is rendered plastic. This is true for all thermoplastic elasto-plastic foams. However, an exception to this rule is elastomeric foams, where all deformations tend to be elastic even in the plateau region.
- Region 3 is marked by complete rupture of cell walls resulting in the opposite sides of cell walls coming into contact. At this stage, any further application of stress leads to compression

of the solid. Thus, application of large amount of stress does not lead to substantial increase in strain, but does contribute to growth in the density of solid. Hence, this region is termed the “densification region”.

2.6.4 Response to Tension

Foams largely exhibit different responses to compressive and tensile loading – for example, a foam exhibiting plastic deformation under compression can undergo brittle fracture under tension as cracks developed during tensile loading lead to stress concentration at a single point, leading to more rapid fracture in comparison to compressive loading.

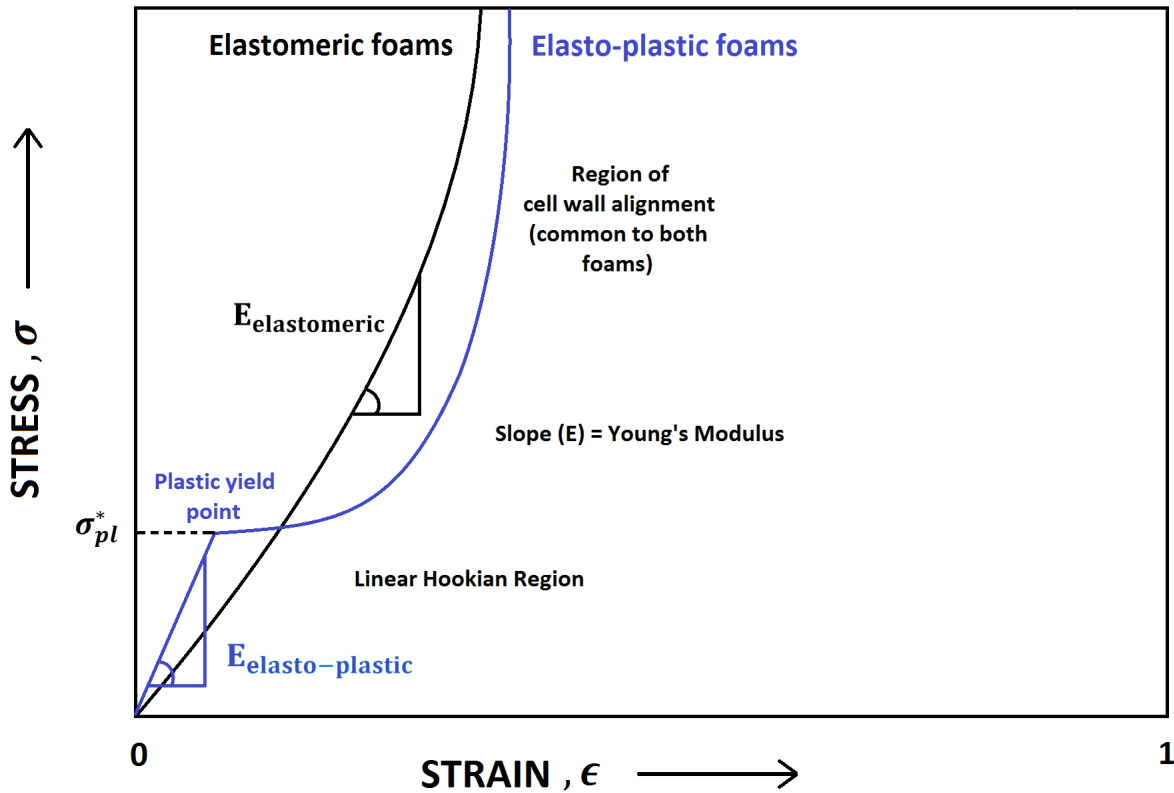


Figure 7: Stress – Strain relationship curve, deformation of foams under tension [28]

On being subjected to tensile loading, foams initially undergo linear elastic deformation obeying Hooke’s law. Subsequently, elasto-plastic foams escalate to the plastic yield point, where temporary reduction in stress is observed; further increase in load leads to increase in stress. During linear elastic elongation, cell walls stretch in the opposite direction to that of buckling in compression. At plastic yield point, cell walls rupture and plastic deformation is initiated, followed by a region of cell wall alignment along the loading direction, at which point foam density tends to increase till it becomes equal to that of the original resin at high strain values.

In elastomeric foams, the plastic yield point is not observed and the foam progresses directly to the cell wall alignment region. The difference in the behavior of elastomeric and elasto-plastic foams can be observed in Figure .

2.6.5 Melt strength

Melt strength is defined as the maximum tensile force that can be applied to a polymer resin in its molten state, and is essentially a measure of extensional or elongation viscosity of a polymer. Thermoplastic polymer resins constitute long polymer chains entangled with each other even in the molten state. On application of strain to the melt, these chains become disentangled and slide. At the molecular scale, melt strength can be understood as the resistance offered by polymer chains to being disentangled and sliding over each other. Important polymeric properties that affect such entanglement or disentanglement of polymeric chains, and thereby its melt strength are molecular weight, molecular weight distribution and molecular branching of the polymer. With regard to all three properties, increase in any of these properties leads to augmentation of melt strength. Due to this reason, linear polymers like polypropylene and high density polyethylene (HDPE), and polymers with short branches like linear low density polyethylene (LLDPE) have low melt strength, while heavily branched polymers like low density polyethylene (LDPE) have high melt strength. This intrinsically affects foaming as polymers that possess low melt strength have cell walls separating the cells do not have enough strength to bear extensional force resulting in rupture and decreased foaming.

2.6.6 Fire retardancy

The prime function of fire retardants is to either impact fire ignition or to reduce the rate of spreading of a flame. Owing to the global problem of fire emergencies, the global market for fire retardants has escalated to a multi-billion-dollar market. Polymers do not burn, but disintegrate into low molecular weight, inflammable, volatile compounds and combustible gases; these in turn ignite and result in a flame. The flame retardancy of any polymer is generally measured in terms of its material flammability, or the ability of a material to ignite and/or sustain combustion. Flammability is expressed using various measurable parameters and ratings; this text describes two most commonly used criteria to measure flammability in subsequent sub-sections.

2.6.6.1 Limiting Oxygen Index (LOI)

Limiting Oxygen Index (LOI) can be defined as the minimum concentration of oxygen required to support the combustion of a polymer. To evaluate LOI, a long prismatic sample, supported in a vertical glass column, is ignited at the top and allowed to burn downwards. A mixture of air stream, containing O₂ and N₂, is then passed through the column with a gradual reduction in percentage of O₂ in air stream. The minimum concentration required to just support combustion is recorded and quoted as a percentage. Although LOI is used as a measure of flammability of a material, it cannot explain the behavior of the same material when burnt in open atmosphere. LOI values for various thermoplastic resins have been mentioned in table 1.

2.6.6.2 UL94

UL94 standard primarily classifies a material on the basis of its ability to resist initiation and propagation of flame in various widths and orientations. Originally released by Underwriters Laboratories, USA, it has now been assimilated into many international standards for flammability. UL classification system consists of many methods, of which the two most important methods have been listed below as follows:


- a) Horizontal Burning Test (94HB)

In this method, a horizontal strip of specimen is ignited by a flame for either 30 seconds, or until the flame reaches a certain specified starting mark on the specimen, following which the specimen is allowed to burn freely. If the flame continues to a second mark made on the specimen, the time taken by the flame to reach the second mark is observed. If the flame extinguishes before reaching the second mark, the damaged length and burn time are observed. A material is classified as 94HB either when the burning rate is less than 76 mm/min for a specimen of length less than 3 mm (if burning continues to the second mark), or if the damaged length is less than 100 mm (if flame extinguishes prior to reaching the second mark).

b) Vertical Burning Test (94V)

In this method, a sufficiently long specimen is clamped vertically and burnt at its lower end by a 20 mm long, blue flame, such that half of the flame makes contact with the specimen. After 10 seconds of contact with the specimen, the flame is removed and specimen response is recorded in terms of two aspects: time taken by the flame to extinguish (after-flame time 1), and any dripping of material which ignites cotton balls placed below it. The specimen is again subjected to a similar flame for another 10 seconds, and the time taken by the flame to extinguish is similarly recorded (after-flame time 2) along with any dripping that may ignite the cotton indicator. It is important to note that in any case, the flame should not reach the top of the specimen. Based on this test, materials can be classified into three categories depending upon the response recorded, with the classification criterion summarized in Table 3.

Table 3: Criterion for classification as V-0, V-1 and V-2

After-flame time 1	After-flame time 2	Ignition of Cotton Balls	Dripping of material		 Flammability
Less than 10 seconds	Less than 10 seconds	Not allowed	Dripping of non-flamed material allowed	V-0	
Less than 30 seconds	Less than 30 seconds	Not allowed	Dripping of non-flamed material allowed	V-1	
Less than 30 seconds	Less than 30 seconds	Allowed	Dripping of flamed material allowed	V-2	

Broad differences are observed in properties with changes in various aspects of cell structure, processing techniques and other parameters.

2.6.7 Dielectric Constant (k)

With efforts on curtailing size of circuits and chips in the microelectronics industry, current research focuses on materials with low dielectric constants. With conventional materials like aluminum and SiO_2 ($k = 4.5$) still waiting to be replaced in the microelectronics industry, and taking into consideration the dielectric constants of polymers (generally less than 3 [29]) and air (close to unity for a broad range of temperatures and pressures), it is expected that polymeric foams will provide the desired low- k materials. Reflecting upon the requirement of developing extremely small components in microelectronics production systems, it is generally preferred for size of cellular pores to be an order of magnitude smaller than the element thickness used for producing the component [30]. Nanocellular foams provide a possible solution to the problem.

To evaluate the dielectric constant of a two-phase porous system, we make use of the Lichtenecker mixing rule, which provides us the upper and lower limits of dielectric constant. The general equation used to describe this mathematically is given as Equation 4, where k_t^α is the dielectric constant of the system, k_g^α refers to dielectric constant of the gaseous phase, k_s^α represents the dielectric constant of the polymer matrix, α is a dimensionless parameter governing the type of mixing used, and V_g is the volume fraction of inclusions. For $\alpha = -1$, the lower limit of dielectric constant is obtained, whereas at $\alpha = 1$, the upper limit of dielectric constant is achieved. A clear fall is observed in the value of dielectric constants from Equation 4 with rise in volume fraction of voids when the former is plotted against the latter.

$$k_t^\alpha = k_s^\alpha(1 - V_g) + k_g^\alpha V_g \quad (4)$$

3. Processing Routes

As foamed automotive components are required in a variety of shapes and need to possess different properties, there exist different thermoplastic processing methods specifically tailored for their production. These processes generally use one among three types of equipment: injection molding machines, extruders, and compressors. Though the specific processes used to produce thermoplastic foams can vary in significant measure, all such processes involve the creation of a structure of cells or voids, reducing both the total quantity of polymer used to produce the component and the overall cost of the component. However, this simple reduction is generally not the primary benefit sought; rather, the prime benefits being sought are improvements in thermal, acoustical, and mechanical properties along with lower densities.

3.1. Foam Extrusion

3.1.1. Free-foaming Extrusion

The process of foam extrusion begins with the addition of resin into the extruder, often after being pre-mixed with a chemical foaming agent. As the resin passes through the screw and is plasticized, either the foaming agent begins to thermally degrade and release a fluid (or a combination of fluids), or gas is injected into the plastic in the second half of the plasticizing barrel [31]. To ensure the obtainment of a uniform material, the gas and plastic must be completely homogenized through a series of distributive and shear mixing elements on the screw [32]. After this stage, the material is passed through a die with an orifice smaller than the size of final product. Nucleation begins

when pressure within the die drops below the partial pressure of blowing agent, but visible foaming is not observed until the material has moved past the die exit. As the extrudate cools and expands after exiting the die, it is often attuned to its final dimensions through use of a cold die [25,32], or by passing it through a water-cooled vacuum calibrator to ensure consistency among parts [31]. Once gas pressure has been reduced and polymeric viscosity enhanced up to a certain point, foam expansion ceases.

3.1.2. Controlled Foam Extrusion

This process is a modified form of free-foaming extrusion process with the same initial stages, but requires a modified die with a core plate [31]. This setup results in the creation of a tube-shaped extrudate, which is then passed into a vacuum calibrator attached directly to the die face. The calibrator shapes the extrudate and creates a solid outer skin on the material surface due to rapid cooling, even as the material core expands normally to fill the void created by the core plate due to its cooling at a lower rate. Post the completion of this step, the material is said to have achieved its final shape [25].

3.1.3. Tandem Extrusion

The above-mentioned processes can be optimized for low-density foams (as low as 0.024 g/cm³) through use of a tandem extrusion line with physical foaming agents. In this process, two extruders are used: one to homogenize the foaming agent within the melt, and the other to cool the melt. The first extruder pumps the gas/polymer material directly into the feeding section of the second extruder, where the material then cools to a temperature range where optimal foam properties can be achieved. Without the second extruder, greater probability exists of overblowing and cell rupture due to high partial pressure of the foaming agent and low melt viscosity [31]. Although setup costs are significantly higher, this process is required in cases where high material throughputs (up to 250-500 kg/h) must be achieved [14].

3.1.4. Low-Pressure Nitrogen Process

Among the most commonly used extrusion foaming processes is the nitrogen process, which specifically uses N₂ as a physical foaming agent. In this process – a modification of the general foam extrusion process – resin is added to an extruder and mixed with N₂ gas into the extruder barrel. The resultant two-phase material, composed of plastic and gas, is then transferred to an accumulator and held at low pressure (14-21 MPa). Once the material content filled in the accumulator is enough to partially fill the mold, the nozzle opens to release the material into the mold where it is held at a lower pressure (1-2 MPa) than the accumulator, enabling the material to expand and fill the interior of the mold. Use of such lower pressure allows the use of low strength materials like aluminum instead of tool steel, leading to significant lowering of tooling costs [25].

3.1.5. MuCell™

Although commonly known as the microcellular injection-molding process, MuCell™ was originally designed as a foam extrusion process. In this process, the plastic is injected with a supercritical fluid as it passes through the mixing region of the screw. The fluid forms diffused bubbles within the melt, that are broken apart by shearing action inside the extruder. This leads to

formation of a saturated, single-phase gas-polymer solution that is more fully homogenized than a two-phase material as it passes through the remainder of the screw. Through careful control of melt temperature and pressure, optimal properties can be maintained for the single-phase solution till the material reaches the die. Significant pressure drop occurs at the die, inducing homogenous nucleation due to thermodynamic changes in the solution, and resulting in the evolution of gas from the supercritical fluid. In addition to homogenous nucleation, heterogeneous nucleation is also observed to occur, though at a comparatively lower rate. Accordingly, high cell density and small cell size can be achieved, resulting in classification of the foam as microcellular foam. Due to the importance of nucleation stage in foaming, die design is critical as pressure drop must occur in the proper fashion to avoid early foaming from taking place [14,32].

3.2. Injection Molding Foam

A large number of processes exist for producing injection-molded foams when compared to extruded foams, with several such processes having undergone significant development over the past 20 years. In general, it is easier to control foams created using injection molding due to ease in maintaining mold temperature and pressure. Despite this, certain processes for injection foam molding have geometric limitations, requiring careful selection for the part at hand.

3.2.1. Low Pressure Injection Foam Molding

In this process, prior to injection molding, a chemical foaming agent is combined with resin in a processor. As the foaming agent-resin mixture is passed through the screw and are homogenized, the foaming agent begins to thermally degrade, releasing gas in the process. This polymer/gas mixture then accumulates in front of the screw to form the shot, which is then injected into a low pressure mold, only filling it partially. Gases released due to thermal degradation of the foaming agent cause polymeric expansion to completely fill the mold due to significant pressure drop following injection of the polymer, causing homogenous nucleation to occur [33]. This process can also be performed by injecting a physical foaming agent into the barrel instead of using a chemical foaming agent. Regardless, due to use of low pressures, often additional equipment (i.e. hydraulic booster circuits) are required to increase injection speed and prevent drooling during plasticization [25].

3.2.2. High Pressure Injection Foam Molding

In this process, polymer/gas mixture is injected into the mold at high pressures, leading to complete filling of the mold. As the mixture begins to foam and expand following pressure drop, the mold itself expands or mold inserts are removed, foam expansion continues, resulting in obtainment of a slightly larger-yet-lower density part. Through careful adjustment of melt and mold temperatures, this process can be used to create a solid skinned part with a cellular core, both of which fuse together as the cycle comes to completion [33]. Due to use of high pressure during filling and the packing phase that follows, the solid skin is capable of being relatively free of surface defects [11].

3.2.3. Gas-Assisted Injection Molding

Unlike previously discussed processes, the gas introduced in this process does not mix with the plastic at all. Instead, a polymer is first injected into a mold in a typical fashion, and a gas (i.e. N₂)

is then injected into the polymeric melt while it is in mold, forming a continuous void within the polymer melt instead of numerous cells. This gas can be injected from gas pins or through a nozzle on the injector. Through addition of multiple gas channels to mold design, gas pressure can be spread evenly, enabling the creation of voids encompassing up to 50% of the volume of the part. These voids enable the creation of structural support within the part, thereby leading to significant increase in the stiffness-to-weight ratio of the part [25,32].

3.2.4. Co-Injection Mold Foaming

In this process, a part with two different foamed polymers can be formed through sequential injection of a skin and core using low or high-pressure injection foam molding. This is done by keeping the mold hot and having a short cycle time. The first shot is only partially injected with partial filling of the mold, but the second shot forces the material from the first shot to edges of the mold. Through adjusting the quantity of foaming agent, the degree to which different shots fill the final part can be manipulated. Accordingly, unique parts containing cores and skins that are either foamed and/or solid can be created [32].

3.3. Microcellular Foaming

3.3.1 MuCell™

The most prominent microcellular foaming process for injection molding, MuCell™ enables the creation of thin-walled, low density parts without warpage or sink marks. As the resin travels through the screw and plasticizes, gas in its supercritical fluid state is injected into the polymeric melt in two locations as the screw moves backwards during each cycle. Supercritical fluid and polymer, initially a two-phase solution, get homogenized into a single-phase solution in the mixing section by a specially designed screw. The accumulated shot at the front of the screw, containing the single-phase solution, is then injected into a low pressure mold at which point, homogenous nucleation results in the creation of cells throughout the core of the material. These cells are generally distributed evenly and are similar in size, a property typically difficult to achieve. Due to fluid movement in the mold, polymer bubbles get destroyed by shear action at the mold surface, resulting in obtainment of a structural foam and in turn, makes for a poor surface finish. However, when counter gas pressure is combined with MuCell™, significant reduction is observed in surface roughness [12]. Another unique aspect of this process is the elimination of pack and hold phases of injection molding, enabling reduction in cycle time and tonnage [32].

3.3.2 Ergocell™

Ergocell™ process is quite different from other injection molding foaming processes. In this process, the polymer leaves the injector gate to enter the injection module. Unlike other processes, polymer has already been plasticized prior to the addition of foaming agent. Inside the injection module, gas (generally CO₂) is injected via a nozzle and a mixing element is added to homogenize the gas/polymer mixture. A plunger then injects the mixed material into a mold where it expands into a microcellular form upon drop in pressure [34]. This process occurs concurrently with normal injection molding process as polymer is delivered into the injection module forward of the screw at the same rate as the rate at which material is moved forward by the screw [12].

3.4. Bead Foaming

3.4.1 *Bead Production*

In order to create beads needed for steam chest molding, polymer is pelletized and impregnated with a hydrocarbon gas (such as pentane) at elevated temperature and pressure conditions within a slurry. These pellets are then expanded into foamed spheres with diameters ranging from 4-5 mm [14] to make them suitable for manufacture of bead foams.

3.4.2 *Steam Chest Molding*

Steam chest molding is used in producing foams from aforementioned virgin beads impregnated with a physical foaming agent. These beads are blown into a metal mold sealed and evacuated of air. Compressed steam is then injected into the mold with venting to heat and soften the beads, resulting in their further expansion. This is followed by injection of pressurized steam into the mold, resulting in fusion of beads. Upon cooling of the mold, the part takes its final rigid form. However, it often takes more than 24 hours to fully treat most parts, making this a poor method for producing certain components [14]. A unique advantage associated with this process is the occurrence of controlled expansion during steam injection, resulting in fine cell structure of the final product [25,32,35].

Table 4: Thermoplastic foaming methods

Pressure Range	Process	Advantages	Disadvantages	Component Types	Ref
HIGH	High Pressure Injection Foam Molding	High surface definition and structural integrity, uniform cells, solid skin	Significant tooling costs, expandable mold required	Large parts, small parts, solid and foamed regions	[25,33]
HIGH AND LOW	MuCell (Injection)	No warpage or sink marks, low tonnage, uniform cell distribution	Requires machine tailored for operation	Small, thin-walled parts (3 mm and below)	[32]
	Ergocell	Low tonnage, significant reduction in material usage, process separation	Designed for Ergotech machines	Common parts	[34]
	Co-Injection Mold Foaming	No swirls on surface, high surface	Polymer compatibility	Solid and foamed regions	[25,32]

		definition, can use different materials for skin and core	must be considered		
LOW	Gas-Assisted Injection Molding	No swirls on surface, warpage reduced, low tonnage, voids up to 50% part volume	Difficult to control gas direction	Thick and thin parts (down to 0.007 inches), parts with internal voids	[25,32]
	MuCell (Extrusion)	Microcellular extrudate, improvement in surface finish	Limited geometry	Slabs, sheets, rods, profiles, roll stock	[14,32]
	Low-Pressure Injection Foam Molding	Low tonnage, minor machine modifications with chemical blowing agents, low cost molds, solid skin formation	Requires machine tailored for operation with physical blowing agents, swirl pattern on surface	Common parts	[25]
	Low-Pressure Nitrogen Process	Low tooling costs, solid skin formation	Poor surface quality	Bendable parts	[11,25]
	Free-foaming Extrusion	Density reduction	Limited geometry	Slabs, sheets, rods, profiles, roll stock	[25,32]
	Controlled Foam Extrusion	Density reduction, solid skin formation	Limited geometry	Slabs, sheets, rods, profiles, roll stock	[25]
	Tandem Extrusion	Very low density foams, proper cooling of foam achieved	Additional capital requirements	Slabs, sheets, rods, profiles, roll stock	[31]
	Steam Chest Molding	Fine-cell structure, very low density possible, easy to control part density	Low surface definition, long treatment times	Blocks, common parts	[25,32,35]

4. Automotive application of thermoplastic foams

The future of automotive sector is irrevocably tied to the design and manufacture of thermoplastic foams in multi-material or sandwich structures due to the latter's vital link with light weighting and fuel efficiency. Current automobiles house several components designed and manufactured using these foams, as shown in Figure 5.

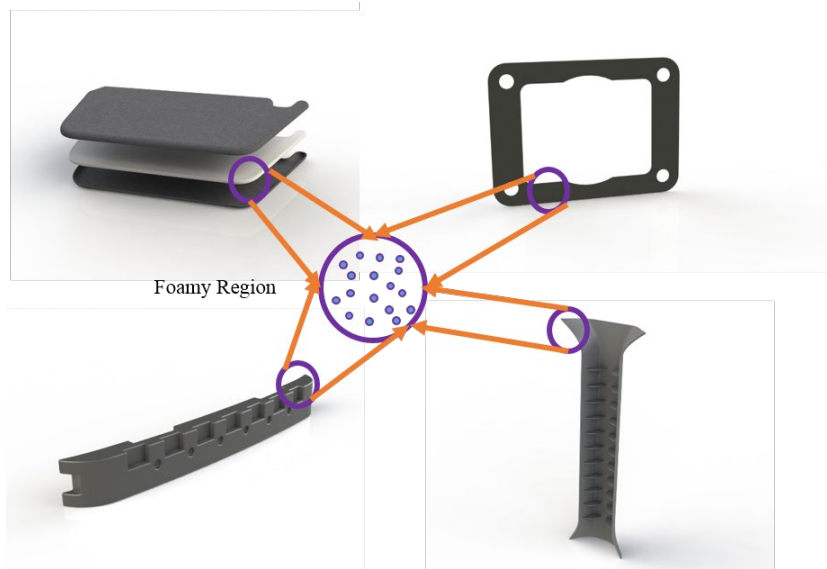


Figure 5: Foamed components from Left to Right : a) Sun-Visor b) Gasket c) Bumper beam d) Reinforced pillar trim

Table 5 consists of foamed automotive components along with design and mechanical requirements of these foamed components.

Table 6 contains a summary of various foams used in the automotive sector and their properties with respect to flammability, melt flow, heat deflection and mechanical properties. Table 7 is a summary of various thermoplastic foams used for current automotive components.

Table 5: Functional need of thermoplastic foams for automotive applications

Component	Function and Need of Thermoplastic Foams.
Bumper Transverse Beam	Bumper beams are meant to transfer impact energy to crash boxes (placed to the left and right of bumper beam) and to longitudinal chassis elements uniformly during frontal and frontal offset impacts, thereby increasing crashworthiness. During such impacts, a very small region undergoes bending, while rest of the beam is subjected to rigid body rotation. Due to localized bending, resistance force and energy absorption abilities undergo a fall. Foam-filled bumper beams are structurally rigid and more capable of uniform load distribution [36].
Bumper Core	
Gaskets	Gaskets are wedged in between flanges and similar joints in order to avoid any leakage. A major application of gaskets in automobiles is to perform as mechanical seals between the piston and cylinder block, where it is known as head gasket. The material chosen for such gaskets should readily deform upon application of small amount of force in order to fill the defects of adjoining surfaces. It should also be impermeable to fluids [37].
Instrument Panel Padding	Materials chosen for instrument panels should not exhibit brittle nature even at low temperatures, while also possessing high energy absorption capacity given their direct interface with occupants and the possibility to come in contact with the latter in severe cases of airbag failure. The dashboard also contains several intricate structures, and so the material chosen for the same should be free flowing and fill the mold intricacies, while being easy-to-machine and possessing high heat resistance. It is also expected that the material does not show large variation in properties and has dimensional accuracy with differences in temperatures [38].
Instrument Panel Support	
Head-rest Cores	Head-rest should be a relatively stiff structure with an ideal thickness of about 3 cm. The design should also be shaped intricately to accommodate the skull base and cervical spine, and should offer sufficient shock absorption to protect the occupant in the event of a rear collision. Head rest should also be closely interfaced with the head to avoid large skull movement in case of a jerk [38].

Door lock mechanisms	During front and side impacts, the door is expected to remain locked, but is also expected to open after the impact without use of any tools. Noise produced due to locking of doors is also a critical parameter in determining door quality, and in order to reduce such noise, thermoplastic foams are used as a suitable alternative to metal doors [38].
Seat Cushion	The main aim of seat cushion foam and spring is to isolate the occupant's body from the vibrations transmitted to the cockpit through the vehicle's transmission, suspension and propulsion systems. While a simple spring mass system is suitable only for absorption of high frequency resonant vibrations, foam behavior can be compared to the combination of series and parallel spring mass systems, providing for ideal damping conditions at both high and low frequencies [38].
Seat cushion foam	
Interior panels	Interior panel is required for pillar plates, relative joints, drilled and puckered components, and to address aesthetic deficiencies in plate pressing. Materials employed in interior panels must possess high energy absorption capacity to keep the occupants safe in the event of a collision, along with high thermal and acoustical insulation properties for a comfortable drive experience [38].
Exterior mirror housing core	Exterior mirror housing core should possess sufficient impact absorption properties to prevent any damage to the mirror housing from door slamming, road and bench vibrations. It should be heat resistant and any large dimensional changes that could occur due to changes in temperature. It should also be impermeable to water and qualify the accelerated reliability test in the climatic chamber [38].
HVAC flapper doors	Evaporator and radiator mass housing allow easy discharge of water through appropriate drain systems. The housing must be protected by a grid of appropriate material to avoid the clogging of drains by leaves and dirt. Stagnation must also be avoided in the design in order to avoid any putrefaction and accumulation of foul smell in the cockpit [38].
HVAC housing	
Car boot liner	Materials for car boot liners should be impermeable to water, resistant to oils and chemicals, durable and flexible so that they can be removed for washing as and when it is needed [38].

Knee bolsters	For knee bolsters, materials forming structural components should elastically deform for large limits and retain extremely high impact absorption properties in order to protect the occupant's knees from injury during crash [38].
Pillar trim and head panels	Material used for pillar trim should be chemically compatible with support materials in order to warrant adhesion between the two material sets. Further, there should not be any defects on the material surface for aesthetic reasons [38]. Head panel or roof panel are exposed to snow load which exerts a pressure of about 1000-1500 N/m ² . The material is required to be mechanically stiff so that it does not undergo plastic deformation under aforementioned load. Mechanical stiffness should also be high in order to protect the occupant's neck and head in the event of a rollover [39],[40].
Automotive body panel	Automotive body panel is inserted into housings, and so materials used for this component are required to be flexible and easy to elastically deform. The material must be resilient even at low temperature, resistant to scratches, UV rays, chemicals and corrosion for long staying aesthetic finish. It should also not have metal sharp edges [38].
Sun Visors	It is impertinent that materials used for sun visors be mechanically rigid to ensure they don't bend, crack or crease along the midline due to repetitive opening and closing. Since sun visor is not a structural component, thermoplastic foams can be used for weight reduction.
Door Energy Absorbing Foam	Energy absorbing foam, watershields and interior trim covering, which make up for the door panel has a range of uses with respect to safety of occupants. It not only houses several features like armrest, side airbags, drawer, rear reflectors and courtesy lights, but is also critical in avoiding injury to occupants in the event of side impacts. Armrest and material covering the interiors of door panel should provide for aesthetic appearance and should possess high impact absorption properties, making foams ideal contenders for this application. Armrest should not be intrusive to thorax and abdomen of the occupant. Door panels also play a major role in absorbing noise and vibration due to external sources that may otherwise reach the cockpit.
Door watershields	
Door interior trim covering	

Table 6: Properties of thermoplastic foams used in by automotive OEM's

Thermoplastic Foam	Flammability (UL94)	Melt Flow Index (g/10 min)	Heat Deflection Temperature (°C at 0.45 MPa)	Young's Modulus (MPa)	Compressive Strength (MPa)	Tensile Strength at Break (MPa)
Polycarbonate	V-0/5V (UL94) [4]	20 (300°C/ 1- 2 kg load)	138 [4]	2068 [4]	37.9-62 [23,41]	22.7-50 [23,41]
Polystyrene	17.6 -18.3% (LOI, 23° C) [42]	9 [43]	85 [44]	1800 [45]	33.6 [45]	12.8 [45]
Expanded Polystyrene				-	0.09 – 0.965 (10% E) [23,46]	0.2 – 1.3 [23,46]
Expanded Poly-vinyl Chloride	V-2 (UL94) 26% (LOI)	25 (Sibur PL- 1GS Polyvinyl Chloride)	92 (at 1.88 MPa) [47]	993 (Thicknes s 10 – 25 mm)	0.5-5.8 [41]	0.9-20 [41]
Acrylonitrile Butadiene Styrene	V-0 (UL94) [4]	1-36 (220°C/10 kg load)	86 [4]	17237 [4]	30.33 (10% D) [4]	27 [4]
Polyphenylene Ether	32 % (LOI) [48]	16 (280°C, 5 kg load) (NORYL PVX516 PPE)	191 (at 1.86 MPa) [49]	-	-	-
Polyphenylene Ether - Polystyrene Blend	24% (LOI) [50]	9.2 (280°C, 5 kg load)	130 (at 1.8 MPa) [51]	-	20.7-27.6 [41]	28-29 [41]
High Density Polyethylene	HB (UL94) [52]	0.01 – 500 (Melt flow ratio 25 – 150) [50]	79 – 91 [53]	-	0.296 – 0.398 (Strain 10% - 50%)	1.72
Polypropylene	18.6%			545 [4]	19.3 [4]	13 [4]

Expanded Polypropylene	(LOI)	0.25 – 0.70 [50]	96 – 120 [54]	10 – 28 (PS Bead foam)	0.1-2 [41]	2.1 – 9.1 (2 - 8% E)
Polypropylene + Glass fibers	HB (UL94)	6 – 10 (300°C, 1.2 kg load) EPICHEM Epilen PP 20 GF	149 – 166 (40% glass) 143 – 146 (20 – 30% glass) [44]	3000 – 5500 [55]	20 [56]	-
Polypropylene + Talc	HB (UL94, 40% Talc)	4 – 10 (10 – 50 % talc) [57]	102 – 121 (40% talc)	-	-	-
Acetal or Polyoxymethylene	HB (UL94)	8 – 13 [58]	170	692.23 – 1012.44 [58]	-	-
Nylon 6 foam	V2 (<1.6 mm, UL94, cast sheet) [59]	130 (BASF Ultramid® B27 E01 PA6 (Dry))	>160 [59]	-	0.280 (50% S) [60]	1.30 (70% E) [60]

Table 7: Use of different foams in various automotive applications

	PP	PE	PS	PPE	EPP	EPS	PPE/PS	PP + talc	EPVC	PP GF	PA 6	PA 66	POM	ESI	PC	Ref
Bumper beam					•											[35,61]
Sun visors					•											[35]
Door energy-absorbing foam			•		•		•									[35,62]
Head-rest cores					•											[35]
Instrument panel padding	•				•											[1]
Car trunk liner	•	•														[35]
Knee bolsters					•											[35]
Door watershields	•	•														[35]
Exterior mirror housing core	•				•											[35]

Interior door trim coverings					•			•	•								[35,63]
Spare wheel holder					•												[35]
Interior paneling									•								[64]
Fan shrouds										•	•						[63]
HVAC housing								•									[63]
Door lock mechanisms	•										•		•				[63]
Seat cushions	•																[65]
Instrument panel support	•																[66]
Pillar trim and head panels					•	•											[8]
Acoustical insulation	•	•												•			[67]
Gaskets									•								[68]
Automotive body panels																•	[69]
Roof liners						•											[35]

5. Outlook

Current environmental concerns and governmental regulations are expected to transform the nature of plastics used in the automotive industry, particularly with respect to plastics sourced from practically non-renewable resources like crude oil. An imminent transformation is on the horizon with regard to the use of sustainably sourced or biosourced plastics that are likely to be seen in three phases. The first phase is likely to focus on attempts towards developing bio-based precursors for synthesis of conventional polymers such as bio-nylon, bio-polyethylene, bio-epoxy and bio-polyurethane. While these foams are structurally and chemically similar to petroleum-based plastics, they would also help in conserving crude oil for other significant applications while promoting sustainability.

The second phase is synthesis of new bio-based plastics such as polyhydroxy alkanates and polylactic acid. These plastics are chemically and structurally different from conventional plastics, but are similar to latter in terms of properties, making them potential alternatives. However, both these phases are likely to generate concerns about the use of food-based precursors for synthesis of plastics, as this will divert crucial food resources meant for human and animal consumption.

This would in due course of time lead to the third phase of transformation, wherein all precursors are derived from non-food based resources. A significant step in this direction will be the development of bio-based thermoplastics from CO₂ (e.g. polyalkyl carbonates). Overall, these transformations will not only help us conserve our environment via lowered carbon footprint, but also provide an expedited closed-loop system for producing plastics. Table 8 details the melt flow

index, heat deflection temperature, compressive strength and tensile strength at break of bio based thermoplastic foams that are being investigated.

Table 8: Properties of commonly used thermoplastic foams

Thermoplastic Foam	Melt Flow Index (g/10 min)	Heat Deflection Temperature (°C at 0.45 MPa)	Compressive Strength (MPa)	Tensile Strength at Break (MPa)
PLA	1-32 [70,71]	55 [72]	0.06 [73]	33.3 [74]
PHBV	2.4-13.9 [70,75]	107 [76]	-	29.8 [74]
PBS	1.5-30.1 [70,77]	70-90 [74]	-	26 [78]
PPC	5.6-8 [72]	73-110 [41]	0.050-0.4 [79,80]	-
PLA/PHBV	-	60 [76]	-	30.4 [74]

6. Summary

Thermoplastic foams have gained a major foothold in automobile manufacturing. Their ability to lightweight cars, combined with a range of advantageous properties ranging from better strength-to-weight ratios, have made them a necessity in today's automotive sector. This chapter has presented an overview on thermoplastic foams, their properties, processing and applications in various components housed in today's automobiles. The reasons and advantages associated with use of foamed materials used in different parts of a car have also been discussed. Finally, this chapter presents a brief outlook on the future of thermoplastic foams vis-à-vis the automobile industry, opening new directions with the onset of responsibly sourced bio based foams being viewed as viable alternative. Hopefully, such enhanced usage can help improve fuel economy, reduce carbon emissions and help contribute to mankind's fight against global warming and climate change.

7. References

- [1] U. EPA, Regulations and Standards: Light-Duty | Transportation and Climate, (n.d).

- <http://www.epa.gov/oms/climate/regs-light-duty.htm> (accessed June 19, 2015).
- [2] B.B. (B/T Books), *Advanced Automotive Technology: Visions of a Super-Efficient Family Car*, Business/Technology Books (B/T Books), 1997.
<https://books.google.com/books?id=uYu-AAAACAAJ>.
 - [3] C.-K. Park, C.-D.S. Kan, W.T. Hollowell, Investigation of Opportunities for Light-Weighting a Body-on-frame Vehicle Using Advanced Plastics and Composites, in: n.d.
 - [4] A.H. Landrock, *Handbook of plastic foams 1995 - Landrock.pdf*, Publictaion, Noyes, 1995.
 - [5] Y.J. Lee, K.B. Yoon, Effect of composition of polyurethane foam template on the morphology of silicalite foam, *Microporous Mesoporous Mater.* 88 (2006) 176–186. doi:10.1016/j.micromeso.2005.08.039.
 - [6] M.B. Gadi, Materials for Energy Efficiency and Thermal Comfort in Buildings, *Mater. Energy Effic. Therm. Comf. Build.* (2010) 681–708. doi:10.1533/9781845699277.3.681.
 - [7] M.J. Howard, *Foams*, edition 2, Desk-Top Data Bank, 1980.
 - [8] S.S. Schwartz, S.H. Goodman, *Plastic Materials and Processes*, 1982.
 - [9] E.W. Andrews, Open-cell foams with hollow struts: Mechanical property enhancements, *Mater. Lett.* 60 (2006) 618–620. doi:10.1016/j.matlet.2005.09.047.
 - [10] L.J. Gibson, M.F. Ashby, *Cellular Solids : Structure and Properties*, Cambridge University Press, Cambridge, 1997.
 - [11] W. Michaeli, A. Cramer, L. Flórez, Processes and Process Analysis of Foam Injection Molding with Physical Blowing Agents, in: *Polym. Foam.*, CRC Press, 2008: pp. 101–142.
 - [12] A.K. Bledzki, O. Faruk, H. Kirschling, J. Kühn, A. Jaszkievicz, Microcellular polymers and composites., *Polimery.* 51 (2006).
 - [13] J. Xu, *Microcellular injection molding*, Wiley, 2010.
 - [14] D. Eaves, T.L. Rapra, *Polymer Foams : Trends in Use and Technology*, Rapra Technology Ltd, Shawbury, Shrewsbury, Shrophshire, UK, 2001.
 - [15] J. Holman, *Heat transfer*, McGraw-Hill, New York, 1981.
 - [16] M. Alvarez-Lainez, M.A. Rodriguez-Perez, J.A. De Saja, Thermal conductivity of open-cell polyolefin foams, *J. Polym. Sci. Part B Polym. Phys.* 46 (2008) 212–221. doi:10.1002/polb.21358.
 - [17] E. Solorzano, M.A. Rodriguez-Perez, J. Lázaro, J. de Saja, Influence of solid phase conductivity and cellular structure on the heat transfer mechanisms of cellular materials: Diverse case studies, *Adv Eng Mater.* (2009).
 - [18] P. Ferkl, R. Pokorný, M. Bobák, J. Kosek, Heat transfer in one-dimensional micro- and nano-cellular foams., *Chem Eng Sci.* (2013).
 - [19] D. Schmidt, V. Raman, C. Egger, C. Du Fresne, V. Schädler, Templated cross-linking reactions for designing nanoporous materials., *Mater Sci Eng C.* (2007).

- [20] X. Lu, R. Caps, J. Fricke, C. Alviso, R. Pekala, Correlation between structure and thermal conductivity of organic aerogels., *J Non-Cryst Solids*. (1995).
- [21] L.J. Gibson, M.F. Ashby, *Cellular solids: Structure and properties*, 1990.
doi:10.2277/0521499119.
- [22] C.-C. Kuo, L.-C. Liu, W.-C. Liang, H.-C. Liu, C.-M. Chen, Preparation of polypropylene (PP) composite foams with high impact strengths by supercritical carbon dioxide and their feasible evaluation for electronic packages, *Compos. Part B Eng.* 79 (2015) 1–5.
- [23] D. Rosato, *Designing with Plastics and Composites: A Handbook*, Springer Science & Business Media, 2013.
- [24] S. Doroudiani, M.T. Kortschot, Polystyrene foams. II. Structure--impact properties relationships, *J. Appl. Polym. Sci.* 90 (2003) 1421–1426.
- [25] M.L. Berins, ed., *Plastics Engineering Handbook of the Society of the Plastics Industry, Inc.*, 5th ed., Kluwer Academic, Boston, 1991.
- [26] S. Doroudiani, M.T. Kortschot, Polystyrene foams. III. Structure--tensile properties relationships, *J. Appl. Polym. Sci.* 90 (2003) 1427–1434.
- [27] W. Gong, J. Gao, M. Jiang, L. He, J. Yu, J. Zhu, Influence of cell structure parameters on the mechanical properties of microcellular polypropylene materials, *J. Appl. Polym. Sci.* 122 (2011) 2907–2914.
- [28] S. Wijnands, Volumetric behavior of polymer foams during compression and tension, (2010) 19.
- [29] R. Miller, In serach of low-K dielectrics., *Science* (80-.). (1999).
- [30] H.W. Ro, K.J. Kim, P. Theato, D.W. Gidley, D.Y. Yoon, Novel inorganic - Organic hybrid block copolymers as pore generators for nanoporous ultralow-dielectric-constant films, *Macromolecules*. 38 (2005) 1031–1034. doi:10.1021/ma048353w.
- [31] L.F. Sansone, *Process Design for Thermoplastic Foam Extrusion*, *Foam Extrus. Princ. Pract.* (2014) 267.
- [32] S.-T. Lee, C.B. Park, N.S. Ramesh, *General Foam Processing Technologies*, in: *Polym. Foam. Sci. Technol.*, CRC Press, 2006: pp. 73–92.
- [33] A.H. Landrock, *Handbook of plastic foams: types, properties, manufacture and applications*, Elsevier, 1995.
- [34] B. Bregar, Demag Ergotech introduces variety of technology | *Plastics News, Plast. News.* (2001).
- [35] D. Mann, J.C. Van den Bos, A. Way, *Automotive Plastics and Composites*, Elsevier, 1999.
- [36] Z. Xiao, J. Fang, G. Sun, Q. Li, Crashworthiness design for functionally graded foam-filled bumper beam, *Adv. Eng. Softw.* 85 (2015) 81–95.
doi:10.1016/j.advengsoft.2015.03.005.
- [37] J. Bickford, *Gaskets and Gasketed Joints*, 1997.
- [38] L. Morello, L. Rossini Rosti, G. Pia, A. Tonoli, *The Automotive Body*, Springer

- Publications, n.d.
- [39] D. Friedman, C.E. Nash, ADVANCED ROOF DESIGN FOR ROLLOVER PROTECTION, (n.d.).
- [40] K.F. Orłowski, R.T. Bundorf, E.A. Moffatt, Rollover Crash Tests - The Influence of Roof Strength on Injury Mechanics, SAE Tech. Pap. Ser. (1985).
- [41] MatWeb: Material Property Database, MatWeb, 2016.
<http://www.matweb.com/search/datasheet.aspx?MatGUID=ff6d4e6d529e4b3d97c77d6538b29693>.
- [42] C.J. Hilado, ed., Flammability Handbook for Plastics, 3rd ed., Technomic, 1982.
- [43] N.M. Bikales, H.F. Mark, G. Menges, C.G. Overberger, eds., Encyclopedia Polymer Science Engineering, 2nd ed., John Wiley and Sons, 1989.
- [44] B. Ellis, R. Smith, Polymers : A Property Database, Second, CRC Press, Taylor and Francis Group, 2013. doi:10.1017/CBO9781107415324.004.
- [45] S.B.H. Gmbh, Integral / Structural Polymer Foams, n.d.
- [46] Alliance of Foam Packaging Recyclers, Properties , Performance and Design Fundamentals of Expanded Polystyrene Packaging, Tech. Bull. (2000) 0–3.
- [47] G. Pezzin, Plastics and Polymers, 1969.
- [48] D.A. Kourtidis, J.A. Parker, Polymer Engineering & Science, 1978.
- [49] M. Bauccio, ed., ASM Engineered Materials Reference Book, ASM International, 1994.
- [50] J.I. Kroschwitz, M. Howe-Grant, eds., Kirk-Othmer Encyclopedia of Chemical Technology, 4th ed., Wiley Interscience, 1993.
- [51] V.B. Elvers, Ullmann's Encyclopedia of Industrial Chemistry, VCH, 1992.
- [52] R. Kaps, R. Lecht, U. Schulte, Kunststoffe, 1996.
- [53] Modern Plastics Encyclopedia : guide to plastics : property and specification charts., McGraw-Hil, New York, 1987.
- [54] F. Bai, F. Li, B.H. Calhoun, R.P.C. Quirk, S.Z.D. Cheng, Polymer handbook, 4th ed., John Wiley and Sons, 1999.
- [55] M.R. Thompson, X. Qin, G. Zhang, A.N. Hrymak, Aspects of foaming a glass-reinforced polypropylene with chemical blowing agents, J. Appl. Polym. Sci. 102 (2006) 4696–4706. doi:10.1002/app.24770.
- [56] J. Yang, P. Li, Characterization of short glass fiber reinforced polypropylene foam composites with the effect of compatibilizers: A comparison, J. Reinf. Plast. Compos. (2015) 0731684415574142.
- [57] S. Kant, Urmila, J. Kumar, G. Pundir, STUDY OF TALC FILLED POLYPROPYLENE-A CONCEPT FOR IMPROVING MECHANICAL PROPERTIES OF POLYPROPYLENE, Int. J. Res. Eng. Technol. 2 (2013) 411 – 415.
- [58] N. Mantaranon, S. Chirachanchai, Polyoxymethylene foam: From an investigation of key factors related to porous morphologies and microstructure to the optimization of foam

- properties, *Polymer (Guildf)*. 96 (2016) 54–62. doi:10.1016/j.polymer.2016.05.001.
- [59] BASF, Ultramid S Polyamides, 1996.
- [60] ZOTEK® N B50 High Performance Nylon Foam, n.d.
- [61] E. Koricho, G. Belingardi, A. Tekalign, D. Roncato, B. Martorana, Crashworthiness Analysis of Composite and Thermoplastic Foam Structure for Automotive Bumper Subsystem, in: *Adv. Compos. Mater. Automot. Appl.*, John Wiley & Sons Ltd, 2013: pp. 129–148.
- [62] C.-K. Park, C.-D. Kan, W.T. Hollowell, S.I. Hill, Investigation of Opportunities for Lightweight Vehicles Using Advanced Plastics and Composites, (n.d.). <http://trid.trb.org/view.aspx?id=1226276#.Vvs59yELgYk.mendeley> (accessed March 30, 2016).
- [63] M. Berry, *Applied Plastics Engineering Handbook*, Elsevier, 2011. <http://www.sciencedirect.com/science/article/pii/B9781437735147100145> (accessed March 29, 2016).
- [64] J. Maxwell, *Plastics in the Automotive Industry*, Elsevier, 1994. <http://www.sciencedirect.com/science/article/pii/B9781855730397500015> (accessed March 28, 2016).
- [65] Frost & Sullivan, *Automotive Lightweight Materials 360 Degree View*, (n.d.).
- [66] J. Melzig, M. Lehner, Lightweight Construction Due to Thermoplastic Foams as Exemplified in an Instrument-Panel Support, in: 2006. <http://papers.sae.org/2006-01-1404/> (accessed April 5, 2016).
- [67] C. Park, M. Brucker, L. Remy, S. Gilg, S. Subramonian, New Sound-Absorbing Foams Made From Polyolefin Resins, (2000) 2–7.
- [68] M.S. Sylvester, Self-adhesive reinforced foam gasket, 2001.
- [69] C.R. Billiu, Automotive body panel molded from polycarbonate foam, 1975.
- [70] K. Zhang, A.K. Mohanty, M. Misra, Fully biodegradable and biorenewable ternary blends from polylactide, poly (3-hydroxybutyrate-co-hydroxyvalerate) and poly (butylene succinate) with balanced properties, *ACS Appl. Mater. Interfaces*. 4 (2012) 3091–3101.
- [71] Prospector, UL, Northbrook, 2016.
- [72] Universal Selector, SpecialChem, Paris, 2016.
- [73] J.-F. Zhang, X. Sun, Biodegradable foams of poly (lactic acid)/starch. II. Cellular structure and water resistance, *J. Appl. Polym. Sci.* 106 (2007) 3058–3062.
- [74] H. Zhao, Z. Cui, X. Sun, L.-S. Turng, X. Peng, Morphology and properties of injection molded solid and microcellular polylactic acid/polyhydroxybutyrate-valerate (PLA/PHBV) blends, *Ind. Eng. Chem. Res.* 52 (2013) 2569–2581.
- [75] M. Boufarguine, A. Guinault, G. Miquelard-Garnier, C. Sollogoub, PLA/PHBV films with improved mechanical and gas barrier properties, *Macromol. Mater. Eng.* 298 (2013) 1065–1073.
- [76] M.R. Nanda, M. Misra, A.K. Mohanty, The effects of process engineering on the

- performance of PLA and PHBV blends, *Macromol. Mater. Eng.* 296 (2011) 719–728.
- [77] S.-K. Lim, S.-G. Jang, S.-I. Lee, K.-H. Lee, I.-J. Chin, Preparation and characterization of biodegradable poly (butylene succinate)(PBS) foams, *Macromol. Res.* 16 (2008) 218–223.
- [78] S.K. Lim, S.I. Lee, S.G. Jang, K.H. Lee, H.J. Choi, I.J. Chin, Synthetic aliphatic biodegradable poly (butylene succinate)/MWNT nanocomposite foams and their physical characteristics, *J. Macromol. Sci. Part B.* 50 (2011) 1171–1184.
- [79] J. Jiao, M. Xiao, D. Shu, L. Li, Y.Z. Meng, Preparation and characterization of biodegradable foams from calcium carbonate reinforced poly (propylene carbonate) composites, *J. Appl. Polym. Sci.* 102 (2006) 5240–5247.
- [80] L.T. Guan, F.G. Du, G.Z. Wang, Y.K. Chen, M. Xiao, S.J. Wang, et al., Foaming and chain extension of completely biodegradable poly (propylene carbonate) using DPT as blowing agent, *J. Polym. Res.* 14 (2007) 245–251.