introduction to

structural foam

by stefan semerdjiev

processing series

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Foreword

Thermoplastic structural-foam molding is the result of the need to find economical ways of fabricating large, rigid plastic structures. Since its commercialization in the 1960s, the process has rapidly evolved from slow, low-pressure injection of commodity polymers containing unmeasured amounts of gas, into highly sophisticated processes where reinforced engineering resins are injected rapidly at very high pressures into mold cavities with moving elements, and where bubble nucleation and growth are carefully controlled and gases accurately metered. At the same time, engineers have learned how to design thermoplastic foam parts with near-solid integral skins and low-density cellular cores.

Thermoplastic structural-foam molding is the latest (and best) example of "world class" processing technology, which has seen simultaneous developments in England, West Germany, Bulgaria, Russia, United States, and Japan. Few technologists have been able to understand the relationships of the various developments as well as Stefan Semerdjiev. His earliest monograph (in Bulgarian) was the first published anywhere in this field, and there have been subsequent revisions and rewritings in German and Russian. This writer considers Dr. Semerdjiev a professional colleague and friend, and urged him several years ago to translate his work into English. The result is the first English-language, single-author monograph in thermoplastic structural foam.

The Society of Plastics Engineers is dedicated to the promotion of scientific and engineering knowledge of plastics and to the initiation and continuation of educational activities for the plastics industry. To this end, SPE has sponsored books of this nature since 1956, with publication of at least one new technical volume annually in emerging segments of plastics not adequately covered in the literature. The Technical Volumes Committee is charged with the responsibility of surveying and determining the need for new topics, identifying authors and editors, recommending content and level of material and, most importantly, reviewing final manuscripts for accuracy and relevance of technical material.

The Society prides itself in bringing to the plastics community high-quality programs in meetings, seminars, educational courses, and publications. Its membership of more than 23,000 practicing plastics engineers, its greatest resource, makes SPE the largest technical organization in plastics in the world.

Dr. Semerdjiev's book has been written specifically for SPE and the English-speaking plastics community. He carefully leads the reader through the nuances of this technology. He discusses the characteristics of the process, the various machinery options needed to process a foamable resin, the important aspects of structural-foam part design, and the various applications that have enjoyed commercial success. The casual reader should find this book an enjoyable reading experience. The practitioner will undoubtedly find new insights into this most-difficult-to-understand process. And some of us will secretly wish that we could have said it first (or as well).

This volume is a significant addition to SPE's growing paperback series.

James L. Throne, Chairman, Technical Volumes Committee
May 30, Naperville, Illinois.

Preface

Since its commercial introduction in the late 1960s, structural foam has made a quantum jump from an insulating and cushioning material to an entirely new range of materials suitable for molding relatively large, thick-walled parts with structural properties that compare favorably with solid molded parts and even with parts made from nonplastic materials. Structural foams are now moving into such key markets as furniture, transportation, electrical appliances, business machines, building products, packing containers. In that comparatively short time, a great deal of know-how has been accumulated. Structural foam has now come to be recognized as a unique material; now no longer merely regarded as a solid plastic with cellular voids interspersed throughout its cross section, it has become accepted as a material system with a structure and properties of its own. Designers have found that structural foam points to new ways to solve old engineering problems, from part design to material selection, because of its potential for simplified designs and less-costly production methods. The advantages of structural-foam parts over conventionally injection-molded solid parts, basically, are: greater overall strength and rigidity, less weight, fewer component parts necessary, less resin used, improved productivity.

The annual growth rate of structural foam since its commercial introduction has been 50 to 100 percent, and future growth rates of 25 to 50 percent worldwide are being projected. This unusually high rate of growth means that engineers and decision-makers on the production floor are no longer ignoring structural foam as a major material for producing large parts of high dimensional stability.

Nobody believes that structural foam will totally replace conventional solid parts now in wide use. Specific conditions will be the deciding factor. What is certain is that structural foam will replace existing materials (plastic and others) in applications thought to be otherwise impenetrable and, in addition, invade new applications that until now were impossible for any plastic, particularly on grounds of cost or failure to meet mechanical requirements. Structural foam would seem to have a great future in such large parts as equipment housings and material-handling containers.

The chapters that follow are intended to present the reader with an engineering overview of the properties of thermoplastic structural foams and the problems associated with their production and application. Only specific features of structural foam are covered, to the exclusion of those basic facts already known from the literature and from the practice of conventional injection molding and extrusion.

SI metric units or their suitable multiples or submultiples are used in accordance with European standards, followed by English equivalents (approximate values) in parentheses.

Stefan Semerdjiev
May 30, Sofia, Bulgaria

Contents

1 Introduction

Structural foam is usually interpreted to be a molded or extruded part having a cellular core and an integral solid skin, the transition from skin to core being gradual. This solid skin gives the molded part its form and toughness, while the cellular core contributes to the high strength-to-weight characteristics normally associated with this type of structure.

This sandwich-like skin-and-foam structure is, of course, not new. However, means of obtaining this type of structure have been limited until the 1960s, when the development of a number of new processes came into being.

There are two basic types of plastics available for foaming. In the area of thermoset materials, we are familiar with the polyurethanes. This versatile family of materials is produced by polyaddition of reactive components such as polyol and isocyanate. The exotherm generated by the reaction vaporizes a blowing agent that causes the mixture to expand. However, the greatest volume of structural foam is presently being produced in thermoplastic materials, to which physical or chemical blowing agents are added. The reason is obvious. These materials do not undergo chemical change on the production line and are commercially available in many forms and at economical prices.

Despite their totally different chemical nature, thermoplastic and thermoset structural foams have similar properties. Therefore, if the choice of material is not determined by special technical requirements, it will depend on production costs and on the availability of raw material.

The capital cost of equipment for polyurethane molding is lower than that for thermoplastics molding. On the other hand, raw-material costs associated with the polyurethane process are usually higher. In addition, the polyurethane process usually involves longer mold setup times. For these and other reasons, manufacturing costs for the two processes will vary considerably. How these costs are spread over each component produced will depend on the length of the production run. In general, polyurethane molding can be said to be better for small runs. For higher-volume requirements, due to longer mold setup times, polyurethane molding will require an increasing number of molds and mold mountings to achieve the same production rates as injection molding. Thus, there is a crossover point beyond which polyurethane can involve higher capital expenditure. As the wall section thickness decreases, the length of run required to achieve the crossover point will also be reduced. The weight of the part also has a decisive influence on this choice. When larger quantities are required, and these cannot be achieved in a polyurethane plant with a single mold, then injection molding becomes the more attractive of the two. The crossover point at which the component cost is equal for both materials varies. According to literature data, it is from 2,000 to 10,000 pieces.

Table 1-1 has been compiled to give a comparison between thermoplastic and thermoset structural-foam technologies. It gives generalized information for the present state of processing by both methods, as well as an economic comparison. Obviously, there is a large area of overlap in which the achieved performance and characteristics of the molded part, as well as economy, are of special importance in the choice of process.

Structural-foam parts are not comparable to conventional injection-molded solid parts either by processing method or properties. Wall thickness of conventionally molded parts usually does not exceed 4 mm (0.16 in.). The wall thickness of structural-foam parts, on the contrary, is usually not less than about 4 mm to gain full advantage of a proper foam structure, although there is no minimum wall thickness that can be molded. Hence structural-foam molding should not be viewed as competitor of conventional injection molding.

A significant characteristic of structural-foam injection molding is the possibility of producing thick wall sections. Structural-foam parts are characterized by an almost total absence of sink marks even in the case of unequal section thicknesses. This is due primarily to the residual gas pressure in the cells, which allows the material to expand internally while the part cools, thus holding the skin firmly against the mold walls.

The ability to mold large parts in structural foam far in excess of what can be produced by conventional injection molding is also an important advantage that should be utilized whenever possible. What before was an assembly of several parts can be regarded as one part, thereby saving labor and eliminating components.

Because of their cellular structure, structural-foam parts are virtually stress-free. Bowing and warpage are therefore greatly reduced.

A prime advantage of a structural-foam part is that owing to its cellular

Table 1-1. Comparison of the basic processes for the production of structural foams.

Material	Thermoplastics	Polyurethanes
Maximum unit weight of moldings, kilograms (pounds)	25 (55)	150 (330)
Maximum wall thickness, millimeters (inches)	50 (2)	100 (4)
Overall density, grams per cubic centimeter	1 to 0.5	0.9 to 0.1
Maximum flow path length to thickness ratio	(50 to 100) to 1	(100 to 250) to 1
Cycle time, minutes	1 to 8 Depends on wall thickness (thermal conductivity of the plastics)	4 to 15 Not dependent on wall thickness (chemical process)
Part configuration	Complex parts with holes and slots	Less-complex parts
Surface quality	Depends on process (rough, smooth)	Smooth
Color	Can be self-colored	Can be self-colored (black only)
Machine cost for equal weight of molding (coefficient)	1.5 to 3	1
Tooling cost (coefficient)	2	1
Raw material cost (coefficient)	1	1
Storing of raw materials	No problems	Temperature 15 to 25°C
Temperature of processing environment	No problems	19 to 24°C
Reuse of waste	Yes	No
Multiple-part molding	Yes	No

structure, the resin used to make it can be used more economically than for making its solid counterpart. Thus, a part three to four times more rigid than the solid part of the same weight can be produced. This provides an opportunity to use commodity plastics such as polystyrene and polyethylene in load-bearing applications.

Listed below are some restrictions that still limit the application of structural foam currently produced by the most widely used processes:

a) surface pattern, a swirl effect, combined with a surface effect that is not as smooth as in conventional injection-molded parts;

b) it is not always possible to reproduce mold detail very well;

c) flow marks, resulting from uncontrollable foaming, make it difficult to produce homogeneously colored parts;

d) longer cycles—the result of the low thermal conductivity of structural foam (nearly one-fourth that of the solid base polymer), the internal gas pressure that must be reduced during cooling, and the considerably thicker plastic parts that are made using foam processes;

e) foam processes are not always suitable for small parts, requiring larger gates and sprues;

f) degating leaves exposed cellular structure, and therefore the position of the gate is important to the appearance of the finished part;

g) newness and lack of past history.

However, it should be borne in mind that structural foam is still in the initial stages of development. In the future, these restrictions will be overcome or minimized. This will extend the current range of structural-foam parts into more demanding areas where rigidity or a high-quality finish is of prime importance.

2 Properties of Structural Foams

Unlike those of conventionally molded solid plastics, the properties of structural-foam parts depend not only on the base polymer, but more importantly, on overall part density, density distribution, skin thickness, cell shape and size. All these parameters are affected by the processing method, process variables, wall thickness, and mold design.

The accumulation of useful data for the properties of structural foams is therefore more time-consuming than for conventional thermoplastics. The behavior of foams frequently differs markedly from those of unfoamed materials, the reason for which still requires basic investigation. Moreover, in many cases needed specific testing methods are still to be developed. Nevertheless, it is expected that in time engineering data such as creep, stress rupture, impact strength, and outdoor aging will be forthcoming, as well as the dependence of each on the base polymer and on the density and cellular structure of the part.

Density

A significant characteristic of structural foam parts is density, which varies across the part cross section and which is lowest in the core. This is illustrated in *Fig. 2-1*, which schematically shows the distribution of cells across the cross section of a structural-foam part. As the distance from the center of the foamed structure increases, the cells get smaller until they disappear completely into the outer skin. The change in density at the skin–core interface is not abrupt. As the cells get smaller, the amount of polymer remaining in the structure is greater.

The objective of most thermoplastic foaming is to achieve a part with high skin density and very low core density, without the presence of large voids.

In industry, it is usually the overall density of parts that is recorded, expressed as the part's weight-to-volume ratio. It relates to the total volume of the part, comprising also the cells and other voids. The density values thus obtained do not reflect differences in various zones and layers of the parts. Yet the physical and mechanical properties of structural-foam parts depend not only on overall part density, but also on the density-distribution profile across a part's section.

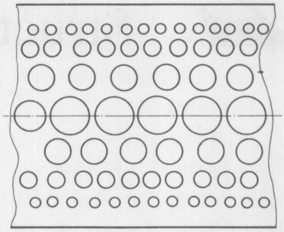

Fig. 2–1. Diagrammatic representation of cell distribution across the section of a structural foam part.

The density profile can be obtained by an alternate micromachining and weighing process. But it is not economical for industrial purposes.

To overcome this problem, a more effective method for plotting the density profile across the section of a structural-foam part was developed. The density of the part was determined quantitatively by measuring the amount of light transmitted through an x-ray photograph of the investigated part (1). An apparatus used comprises a source of directed light, a movable table on which the x-ray photograph of the part is fixed, a photo cell, a special aperture with a narrow transverse slit, a recording unit, paper, and a synchronous drive for the movable table.

A light beam of known measuring surface—5 by 0.03 mm (0.2 by 0.0012 in.), for example—is guided perpendicularly to the longitudinal axis of the structural-foam part over the image of its section. The light transmitted through the x-ray film negative is measured by the photo cell and the amplified photocurrent is recorded by the potentiometer recorder. In the density profile obtained, the high densities correspond to low densities in the x-ray film negative and, thus, to high light intensities behind this negative. The calibration of the ordinate is made on the basis of the x-ray photograph of a stepwise-machined solid-test specimen of the same base thermoplastic.

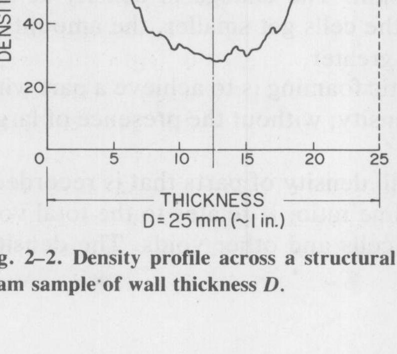

Fig. 2–2. Density profile across a structural foam sample of wall thickness *D*.

Figure 2-2 shows a typical graph depicting the density profile across a structural-foam part of thickness D, recorded by the described method. The density, ρ, is given in percent of the base polymer density, assumed to be 100 percent.

The quick and objective measurement of the density profile can provide a means for effective control of process conditions. Such graphs give a clear image of local density variations in the investigated section. Deviations from an ideally symmetrical density profile indicate process shortcomings such as nonuniform blowing-agent distribution or variations in temperature. Another advantage is the possibility of using such a technique for quality control of molded parts.

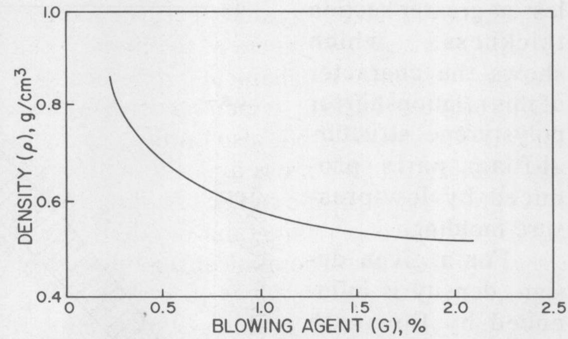

Fig. 2–3. Effect of blowing agent level *G* on overall density ρ, which decreases sharply before leveling off. Material: high-density polyethylene. Chemical blowing agent: azodicarbonamide.

Overall density of structural-foam parts depends on the type and quantity of blowing agent, the base thermoplastic polymer, part configuration, and the method and conditions of molding. Density can be controlled in determined limits by varying process parameters.

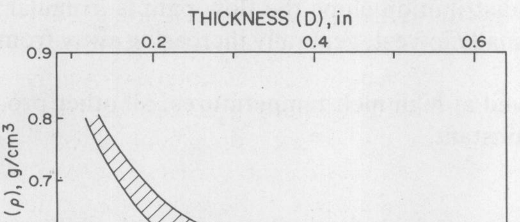

Fig. 2–4. Effect of part thickness *D* on density ρ.

At equal molding conditions, overall density decreases with an increase in the amount of blowing agent to a specific level (*Fig. 2-3*). An increase of blowing-agent concentration over this level will result in processing difficulties and the possible creation of large voids in the part. A higher-viscosity material results in overall higher part density. From *Fig. 2-4*, it is obvious that density can be less at greater section thickness, which shows the character of this relationship for polystyrene structural-foam parts produced by low-pressure molding.

For a given design, density is influenced by flow-path length. It can be seen from *Fig. 2-5* (valid for low-pressure molding) that the weight of a part will increase with greater flow-path length or a higher value of the ratio of flow-path length to cavity thickness. Moreover, the density distribution along the flow path is irregular; near the gate, the density is usually lowest, generally increasing away from the gate.

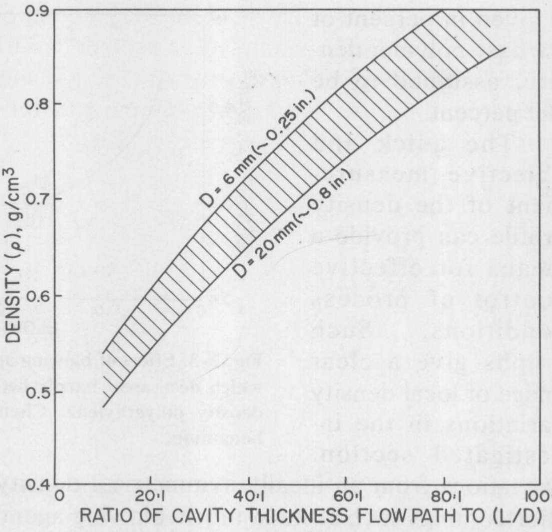

Fig. 2–5. Dependence of density ρ on flow-path length L for polystyrene parts of different thickness D.

Low densities are achieved at high melt temperatures, all other process parameters remaining constant.

Mechanical properties

A major advantage of structural foam lies in the processor's ability to mold thick-walled parts and the consequent considerable improvement of all properties, particularly rigidity, as compared with solid parts of equal weight.

As is known, a real measure of load-carrying capability is stiffness: the product of flexural modulus E and moment of inertia I. Thus, stiffness N of a structural element, in the simplest case of a beam with width b and thickness H, will be

$$N = \mathrm{E}I = \mathrm{E}\,\frac{bH^3}{12}.$$

Therefore, one of the characteristics determining stiffness that is used to calculate part deflection is flexural modulus E.