MANUFACTURABILITY OF MICROCELLULAR FOAMED PLASTICS: DESIGN OF GAS-ADDITION DEVICE

by

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Submitted to the Department of Mechanical Engineering on June 3, 1991 in partial fulfillment of the requirements for the degree of Bachelor of Science.

Abstract

The process for manufacturing with microcelluar foamed plastic was investigated. A device was designed for the purpose of delivering large amounts of gas to a molten polymer stream and mixing the two homogeneously. The device was integrated into the entire extruding process.

Initial results are promising. The extruder system works with the gas addition device attached, though no microcellular foamed plastic has been produced. Sealing and mechanical strength have been determined to be acceptable.

Thesis Supervisor: Professor Nam P. Suh
Title: Ralph E. & Eloise F. Cross Professor of Mechanical Engineering

Dedication

To my father, Dr. Thomas A. Cole, and my mother, Lynda R. Pealer.

Acknowledgements

Many people contributed to the success of this project. I am indebted most of all to Professor Suh who supported the project and believed in my design. I appreciate the time which he spent with me.

Two people deserve a huge thanks - Chul Park, the graduate student who got me started on the project, and Fred Cote, the man in the machine shop. Chul was a great source of information and contributed signifigantly to the projects success - especially the in last few weeks. If it weren't for the exceptional help of Fred Cote, the gas addition device probably never would have been finished. He stuck with me from start to finish - even when the going got rough and the deadline got near.

John Freeman of the Material Science and Engineering Welding Laboratory braze-welded the gas-addition device. I thank both John and Professor Thomas Eagar, who allowed me to use the welding lab.

Thanks to Dan Baldwin and Sung Cha, two graduate students in the Microcellular Plastics Consortium, who provided constant inspiration. Maria Yang, also of the Microcellular Plastics Consortium, answered some important questions for me. Lynn Festa served as the liason between the Professor Suh and me as we were seldom both in the same area and gave me some great advice on how work such devices as the Fax machine. Also, thank you to Jeff Myjak for letting me borrow his computer so I could type the bulk of this thesis on the varsity heavyweight crew trip to Wisconsin.

And finally, to Laura, who gave me the incentive to make it the whole way.

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Chapter 1

Introduction

Plastic is a very versatile and common manufacturing material. One great advantage to plastic is its flexibility - it can be shaped easily and inexpensively. Because of this, parts which were made with wood, aluminum, or other materials are now being manufactured with plastic. As for all materials, it is advantageous to use as little plastic as possible to make the product.

In high volume production of plastic parts, the cost of material is about 60 percent of the total cost of manufacturing. [Martini 81] Thus, it would be very valuable to industry to devise a method of reducing the amount of material used in manufacturing. Some progress can be made by designing the production process to have as little scrap as possible and to design the part to contain as little unnecessary material as possible. However, for a radical change in the amount of material used, it is possible to make the part out of an air/polymer mixture, or foam.

Foamed plastic is not a new idea. However, the foam which is currently used in industry is made up of large air bubbles mixed into the polymer. Extensive research has shown that a part made from conventional foamed plastic has much poorer mechanical properties than a part made of pure polymer. [Waldman 82] Thus, for applications that require good fracture toughness, impact and tensile strength, and stiffness, a solid part must be used.

Microcellular foamed plastic (MFP) is a novel alternative to conventionally foamed and pure plastic. MFP is defined as foamed plastic with voids of less than 10 micrometers in diameter. [Martini 81] Also, the density of the part should be as low as possible and still have good mechanical and structural properties. A part manufactured with MFP could have a material savings of up to 70 percent. [Waldman 82]

The reason that microcellular foamed plastic has an advantage over macrocellular has to do with the void size.[1] Structural mechanics has predicted that the critical void size inside many plastics is around ten micrometers. Any crack above this threshold would serve as a stress riser. A crack being propagated through the plastic would be easily continued when it met the void. However, any void below the ten micrometer threshold would not help propagate the crack. Crack-tip blunting and elastic deformation dictate the response at this size. A small void would easily deform and store the elastic energy of the crack tip instead of allowing it to continue. Solid material would not deform and the crack would not stop. Thus, the small voids of microcellar foam are better for halting crack growth than solid plastic or macrocellular foam.

There are many unanswered questions about microcellular foam, though research has been proceeding at a quick pace since its conception by Professor Nam P. Suh in the late 1970s. A large amount of energy, time, and money has been dedicated to the goal of perfecting the process of achieving MFP. However, there has been little published research on continuous manufacturing of microcellular foam parts. In order to capitalize on the great possibilities of MFP, a high-volume manufacturing process must be devised. There are dozens of topics on manufacturing with MFP still to be investigated, but little has been done recently on the addition of the gas to the polymer being foamed.

The purpose of this thesis is to present one solution to the problem of adding gas to a polymer for the purpose of creating microcellular foamed plastic. It is necessary to describe microcellular foam, explain the theory behind the design of the gas addition device, present the final design,and ultimately decide if the device worked through experimentation.

Chapter two presents an introduction to microcellular foamed plastic. The benefits of MFP and the process for creating MFP are discussed. Methods of gas addition are detailed.

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[1]Macrocellular foam has void sizes of up to several millimeters

The theory behind the gas addition mechanism is detailed in the third chapter. The analysis includes the factors behind the concept used for the device and the effect that the device has on the polymer and the extrusion process.

Chapter four describes the design process. The factors important in the design of the device and the rationale behind the final design are presented.

In chapter five, the experimental procedure for determining if the device actually fulfills its goals is outlined. The actual extrusion process is detailed and possible problems with the device are discussed.

The results of the experiments are presented in the sixth chapter. A decision is made whether or not the device actually worked and an outline for future work concludes this paper.

Chapter 2

Introduction to Microcellular Foamed Plastic

This chapter details some past research as it pertains to the manufacturing process. Benefits of MFP and the process of creating MFP are two relevant topics. As gas addition is the object of this research, that topic is discussed in detail.

2.1 Benefits of MFP

A part manufactured with microcellular foamed plastic offers many advantages to a part made with pure polymer or conventionally foamed plastic. These benefits include improved mechanical and structural properties, a reduction in the amount of material used, and no restriction on the size of the part.

Waldman, Yang, and others have investigated the mechanical properties of MFP. Maria Yang has determined that a part made from microcellular foamed polystyrene has an impact strength four times a conventionally manufactured piece. Other materials do not perform as well, but all have greater foamed strengths. [Yang 91] In addition, foamed parts have a much improved strength-to-density ratio.

The most obvious benefit of MFP is the reduction in material. The advantages to this were discussed in chapter 1. Densities - the ratio of the polymer volume to the total volume - as low as ten percent have been created [Waldman 82], though it seems that densities of between 30 and 70 percent are feasible and cost-effective to manufacture.

A serious restriction on macrocellular foam is that parts from which it is made must be at least five millimeters thick [Waldman 82]. There is no such restriction for MFP. In MFP, as the voids are very small and the skin is smooth, the part can be made very thin.

2.2 Process of Creating MFP

Extrusion was the process used in this research project to investigate the manufacturability of MFP. There are four parts to producing the plastic foam - plastication, nucleation, void formation, and gas addition. The forming of the part occurs as the pressure drops and the voids grow. Gas addition is discussed in the next section. Figure 2-1 schematically shows the first three steps in the process.

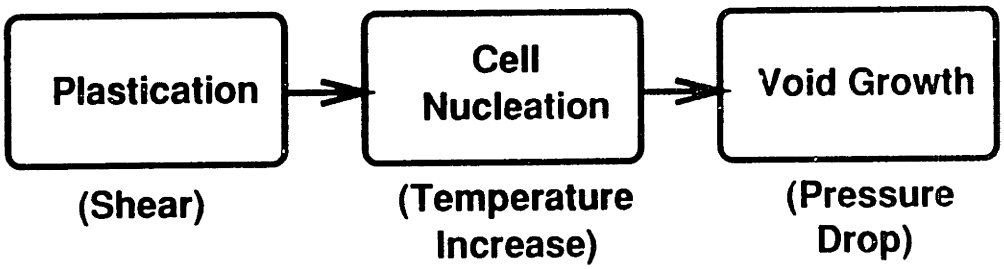

Figure 2-1: Schematic of MFP Process

In an extruder, the plastication (melting) of the polymer takes place in the barrel. The screw turns and forces the plastic from the hopper to the nozzel. In doing so, the shear forces of the screw and heat from band-heaters melt the polymer. The polymer must be molten in order to both properly form the voids and the part being extruded.

The nucleation of the voids comes next. After the gas has been added and homogeneously mixed, the polymer goes through a sudden temperature increase. This

increases the ability of the gas to move in the polymer. Thus, the gas molecules come together in small nuclei. The high pressure inside the extruder keeps the voids from becoming too large. The ideal size for these initial voids is less than one micrometer on diameter.

A sudden pressure drop induces the growth of the voids to their size of around 10 micrometers. The freezing of the polymer stops the void growth. This last step occurs as the material is formed - in this case, a fiber is extruded. Also, since the skin freezes first and the fact that the gas diffuses out of the outer layer of the plastic first, the skin produced is smooth and uniform. [Martini 81]

2.2.1 Manufacturability of MFP

There are several factors which affect the manufacturability of MFP. These are: 1) thermal stability of the foam; 2) expansion of the part upon foaming; and 3) speed of heat transfer into and out of the foam.

Thermal stability is a factor if the part must be heated after forming. If a foamed part is heated above its glass-transition temperature, then the voids, as they are pressurized, could expand. This can be avoided if the pressure of the environment is above the pressure of the voids.

Since plastic is incompressible, the size of the part will increase as the voids grow. This can be taken into consideration when mold which forms the part is designed. As plastic is a good thermal insulator, heat transfer out of plastic is slow. The designer of the MFP process must be careful to account for this. After the part is formed, it is desirable to cool the part as quickly as possible to halt the cell growth. If the part is cooled too slowly, then the voids could be too large. [Martini 81]

2.3 Methods of Gas Addition

A fourth part of the MFP process is the addition of the gas. There are several different methods of actually introducing the gas into the polymer. These include using blowing agents, the use of pre-saturated pellets, foaming the part after it has been formed, and adding the gas after plastication and before the part forming takes place. The latter is the method used in this project.

A blowing agent is an additive to the raw plastic which releases a gas upon heating. Often small pieces of carbon are used as the additive. Plastics with a blowing agent included are more expensive than their pure counterpart and have less predictable responses.

Waldman declared that the use of pre-saturated pellets was the best way to get the gas into the polymer. [Waldman 82] Plastic pellets are placed in a sealed chamber pressurized with a gas (usually nitrogen or carbon dioxide). Often the pellets are heated to speed up the diffusion of the gas into the polymer. However, it could take as long as 24 hours for enough gas to diffuse into the plastic. The pellets are then fed into the extruder as normal. However, this is not a continuous process. In order to use this in an industrial situation, a different method must be developed.

A third alternative for gas addition is the slowest method discussed here. After the part has been formed, the gas is added through diffusion and then the voids are then formed. For a large part, such as one that has been injection molded, the time to achieve the desired gas concentration would be prohibitively long. Smaller parts, such as fibers or thin sheets could be continuously foamed this way, but the equipment for this method could be very expensive.

The fourth method also has several ways which it can be implemented. The gas can either be added during the plastication process or immediately after the screw has delivered

a molten stream of polymer. The earlier the gas is injected, the more time it has to mix with the plastic - a desirable condition. However, problems can develop if a gas line is connected to the extruder too close to the hopper. Without proper precautions, pressure from the gas could cause bubbles to be pushed backward through the barrel.

Research conducted on an injection-molding machine had a gas line directly connected to the barrel where the polymer was being plasticated. [Park 91] This use of a "port"-type device was shown not to be a viable option due to insufficient gas-delivery amount. Another problem was that often the polymer would shoot into the gas line and harden, making it necessary to replace the tube. A filter which would allow the gas through but keep the molten plastic from entering would be one way to solve this problem, but the delivery amount would still be of concern.

The most important reason, though, is that research in the past has shown that not enough gas is delivered to the polymer with a "port"-type device. Research conducted on an injection-molding machine used this method. [Park 91] Another problem was that often the polymer would shoot into the gas line and harden, making it necessary to replace the tube. A filter which would allow the gas through but keep the molten plastic from entering would be one way to solve this problem, but the delivery amount would still be of concern.

The method used in this research is similar to the above, but the gas is added downstream of the plastication process. On a normal extruder, a nozzel or die is located just after the screw. The polymer is melted and then extruded. In this design, the gas addition device is located where the die would be. A host of methods to actually add the gas were considered, but an annular device made of porous material was chosen. The details behind these decisions are presented in Chapters 3 and 4.

Before continuing on with the theoretical analysis, it is necessary to explicitly state the goals of the gas addition device. As the discussion above indicated, the two most important criteria are adding large amounts of gas quickly and mixing gas and polymer

homogeneously. Chapter 4 presents an overview of the design process for a device to fulfill the above goals.

Chapter 3

Analysis of Requirements of Gas-Addition Device

This chapter presents the governing theory behind the gas-addition device. The sections of this chapter include discussions of the gas-flow through porous material, diffusion versus gas-injection, and the pressure drop of polymer across length of porous tube. The proper mechanism for gas addition and the amount of gas required for saturation are determined here.

3.1 Gas Flow Through Porous Material

A porous material is simply a material which has tiny capillaries running from surface to surface. The size and concentration of these tubes, as well as the geometry of the material, determine how quickly a fluid will pass through the material. This quantity is the most important engineering variable of the gas addition device. Two fluids could possibly pass through the porous metal - the gas and the polymer. It is desirable for the gas to pass through the tube at a fast, controlled rate and it is also desirable for the polymer not to enter into the pores so as to avoid clogging them up.

It is necessary to derive an equation which describes the flow rate of a fluid through the porous metal. Once this is done, the actual variables of the system can be used to calculate the important flow quantities. For this analysis, the porous metal is modeled as a flat plate, with the gas on one side and the molten polymer on the other.

The flow through this plate is proportional to the pressure drop across the plate and the plate's area and is inversely proportional to the viscosity of the fluid and the thickness of the plate. Also, the flow is affected by the size and geometry of the pores. These pore factors can be included in one variable, K for the present. The symbolic expression of the equation for the flow rate Qis:

$$Q = \frac{A \Delta P K}{\mu x} \tag{3.1}$$

where A is the area of the plate, ΔP is the pressure drop across the plate (gas source pressure minus the extruder pressure), K represents the pore factors, μ is the viscosity of the fluid, and x is the thickness of the plate.

Two of the above variables need expanding. The distance which the gas must travel to get from one side of the plate to the other (the length of the pores) is not simply the thickness of the plate. Usually, the pores are longer by a factor β. This could vary between 1.0 (no abberation of path) and 2.0 (the pores double back on itself, making its length twice the thickness of the plate). The distance which the gas must travel is given by:

$$x = \beta \times h \tag{3.2}$$

where h is the thickness of the plate and β is the pore length factor, as explained above.

The amount of fluid which passes through the porous material depends on what the total pore area is. The size of the pores and the number of pores determines that area. The pore volume fraction, ε, is the percentage of space which is occupied by the pores - the total volume of the pores divided by the total volume:

$$\varepsilon = \frac{\pi (d/2)^2 n l A}{l A} \tag{3.3}$$

where n is the total number of pores, d is the diameter of the pore, l is the thickness of plate and A is the area of the plate. The length and area divide out.

When solved for the number of pores, the equation (3.3) can be used to find K, the pore factor, by substitution into the following equation:

$$K = \frac{\pi n (d/2)^4}{8} \tag{3.4}$$

The result is:

$$K = \frac{\varepsilon d^2}{32} \tag{3.5}$$

Equations (3.2) and (3.5) can be substituted into equation (3.1) to arrive at the governing equation for fluid flow through a porous material.

$$Q = \frac{A \varepsilon (d/2)^2 \Delta P}{32 \beta h \mu} \tag{3.6}$$

The area of the tube in contact with the polymer is simply the circumference of one end of the tube multiplied by the length of the tube, or:

$$A_{tube} = 2 \pi R_{tube} L_{tube} \tag{3.7}$$

Table 3-I lists the values of the variables used to solve for the gas flow for the annular porous tube. The results show that there is considerable gas flow with a 6 inch tube. However, one problem is if the porous capillary diameter is not actually 0.5 micrometers. If it narrows down at some point then there will be less gas delivery to the polymer.

3.2 Diffusion Versus Gas-Injection

There are two different mechanisms for adding the gas to the polymer - diffusion and gas-injection. Each mechanism requires a different design for optimal gas saturation of the polymer. The ideal saturation is one percent of polymer to be gas by mass ratio.

Diffusion occurs when one material enters another at a very low rate - molecule by molecule. Usually, diffusion occurs when the gas sorption rate is high - which depends on the temperature and pressure of the material and gas. It is advantageous to heat the sample being saturated and have a high gas pressure for saturation. However, if the sample is

Table 3-I: Values Of Variables Used To Solve Equation (3.6).

Name	Symbol	Value
Pore Volume Fraction	ε	0.5
Pore Diameter	d	1.97×10^{-5} inches
Length of Tube	L_{tube}	6 inches
Radius of Tube	R_{tube}	0.1875 inches
Area of Tube	A_{tube}	9.42 sq. inches
Pressure Drop	ΔP	100 psi
Pore Length Factor	β	2.0
Tube Thickness	h	0.0625 inches
Gas Viscosity	μ	2.64×10^{-9} lbf s/in^2
Flow Rate	Q	4.32 cubic inches per sec^2

malleable (such as a polymer above the glass-transition temperature), then it could be deformed by the high pressure required for diffusion. As diffusion occurs very slowly, a long length of time is required to achieve the desired concentrations of gas.

Gas-injection is a much quicker process. The polymer is heated and easily deformable and thus, with a high enough pressure, bubbles of the gas could be forced in. If gas injection is used to get the gas into the polymer, there must be some sort blending of the mixture. The gas bubbles will be large - macrocellular. However, with proper mixing, these will be broken into tiny bubbles. Further saturation will occur as the gas in these bubbles diffuses into the molten plastic.

3.2.1 Determination of Gas Needed for Saturation of Polymer

It is necessary to perform an order-of-magnitude calculation for the pressure required for diffusion and compare that to the probable pressure inside the device. If the gas pressure is comparable to the required pressure, then the device needs to be designed so the polymer is properly saturated through the diffusion mechanism. Otherwise, the device must be designed for gas-injection.

The first step is to find the required mass flow rate of the gas. The polymer is forced through the device at about one cubic centimeter in 60 seconds. The mass flow rate, $\dot{m}$, is given by:

$$\dot{m} = Q \times \rho \tag{3.8}$$

where Q is the volume flow rate and ρ is the density.

Through previous experimentation, the desired mass flow rate of the gas is one percent the mass flow rate of the polymer. [Park 91] Thus, the required volume flow rate of the gas can be given by:

$$Q_{gas} = \frac{Q_{polymer} \times \rho_{polymer}}{\rho_{gas}} \tag{3.9}$$

The polymers used all have densities of around one gram per cubic centimeter and the density of the gas can be calculated after the volume of gas at the experimental temperature and pressure has been found from the ideal gas law:

$$V = \frac{m R T}{P} \tag{3.10}$$

Where V is the volume of the gas, m is the mass, R is a gas constant, T is temperature, and P is the pressure. Using the experimental values of m = 1 kg, T = 500 F, P is 2000 psi, and R, the gas constant for Nitrogen, is 0.297, the volume is 40.6 cubic feet. If the mass is

divided by this volume, the density is found to be 0.054 pounds per cubic feet, after solving equation (3.9), the volume flow rate of the gas is 0.012 cubic inches per second.

The next step, now that the amount of gas needed is known, is to determine the gas source pressure required to force this much gas through the porous material. Equation (3.6) can be solved for ΔP. The pressure drop is determined by using the variables in table 3-I and the volume flow rate of the gas. This is found to be 0.03 psi. This pressure differential is much to low to accurately be maintained in the extruder. This says that if the pressure of the gas is more than 0.03, then more gas is being added than required. If this happens, then bubbles of gas will be injected into the polymer. Since this seems to be the case, it is better to design the device for gas injection than diffusion.

3.3 Pressure Drop of Polymer Through Tube

As the molten polymer flows along the porous tube, there will be a pressure drop due to the interaction of the polymer with the tube walls. The flow rate of the polymer axially through the annular device depends on the pressure at the two ends of the tube. The flow through the tube will further be blocked by the presence of a static mixer. The pressure inside the tube also also affects the speed at which the gas is forced into the molten plastic.

The gas addition device is attached downstream of the extruder. The pressure will be highest at this point - about 1500 psi. There is around a 500 psi pressure drop through the tube, so the pressure at the other end will be 1000 psi. The gas source pressure will be constant, 1600 psi, along the entire length of the tube. Thus, the gas will be added slowest where it is attached to the extruder and highest at the other end. Figure 3-1 qualitatively shows the above discussion.

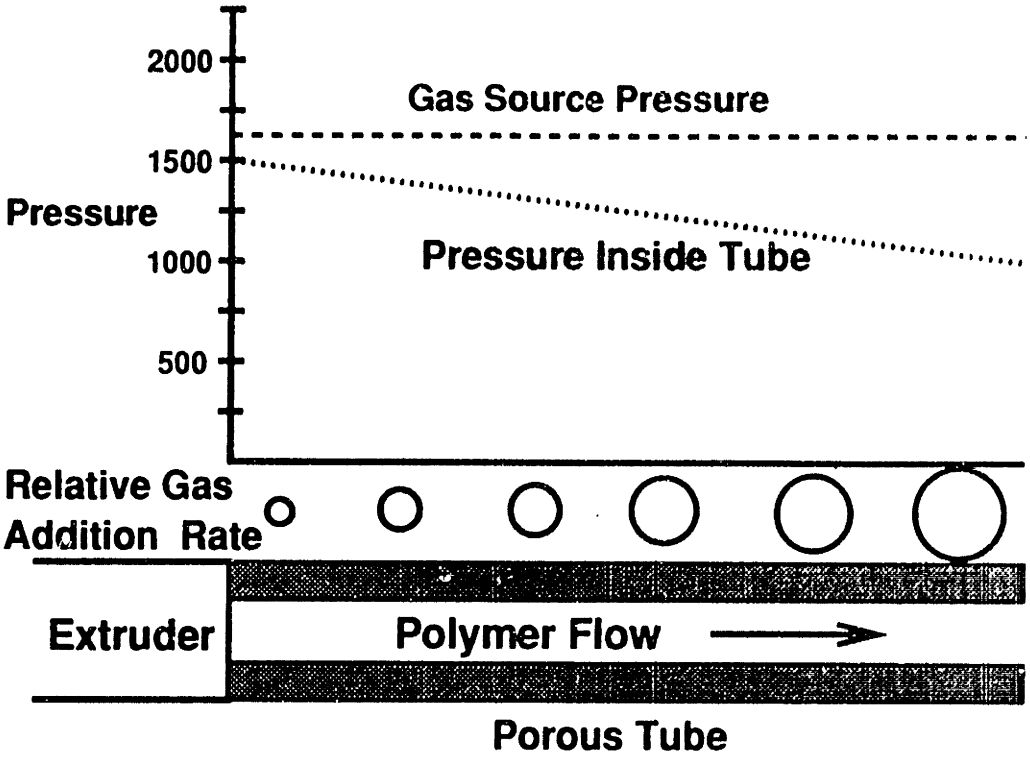

Figure 3-1: Pressure Profile Along Length of Porous Tube, Showing Relative Gas Addition Rates

3.4 Conclusion

The discussions of this chapter will be used in the design of the device. The decision that the gas addition device should be designed for gas injection is the most important contribution of this chapter. The discussions in section 3.1 and 3.3 will be used for the size of the device and the mixing of the polymer and gas.

Chapter 4

Design of Gas Addition Device

4.1 Introduction

This chapter presents the design for the gas addition device, based on the discussions of the last few chapters. There are a large number of criteria which must be considered in the design. These are mixing, sealing, mechanical strength, size, and gas delivery. The chapter is concluded with the final design.

4.2 Design Considerations

The design of the device was surprisingly difficult due to the high pressures and temperatures involved. The gas addition device is inserted between the diffusion chamber and the extruder. Beyond the diffusion chamber piece is the heating element and finally the nozzle, which forms the extruded fiber. Figure 4-1 shows the experimental set up schematically.

4.2.1 Mixing

Though not used to get the gas from the porous tube into the polymer, diffusion is necessary to forced the gas molecules into the plastic after the bubbles have been added. To do this, it is necessary to make the surface area of the voids as large as possible and increase the time which the gas has to diffuse. If there are large pockets of gas present before the nucleation and void growth phases, the gas bubble will probably become larger than the upper limit of 10 micrometers. Some device must be used to break the bubbles into very small voids and mix them evenly through the polymer. After the mixing, a diffusion chamber will give the gas time to diffuse into the molten plastic.

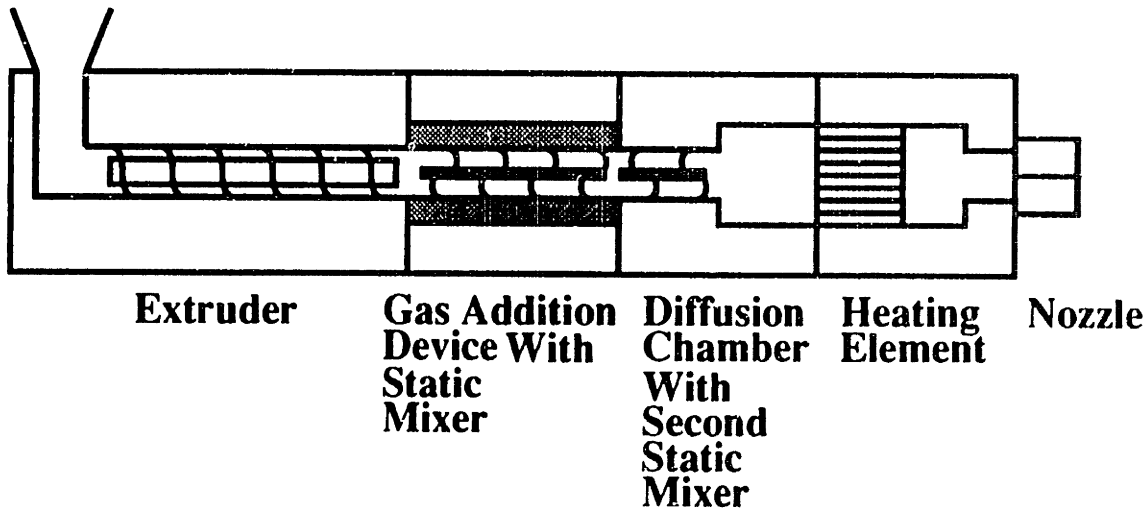

Figure 4-1: Schematic of MFP Manufacturing Process

A static mixer provides the simplest answer to the mixing problem. The static mixer is an insertable device with helical sections which separate the fluid into separate streams and mix them together. This device is very effective and reliable as there are no moving parts to break or become clogged up. The mixer can simply be inserted into the porous tube and is held in place by pushing against the next piece in the setup.

Section 3.3 discussed the relative speed of gas addition along the length of the tube. As the pressure drops, the gas will be added more quickly. Thus, the largest gas bubbles will be added at the downstream end of the device and the gas/polymer is the least well mixed here. Thus, it is necessary for further mixing downstream before the void nucleation phase occurs. A second static mixer is a viable option.

A diffusion chamber is simply a large chamber. As the polymer leaves the second mixer, it enters into this chamber, where the flow velocity is decreased. This increases the time which the polymer spends in the process, giving the gas a chance to be absorbed into the molten plastic. The second static mixer and the diffusion chamber can be incorporated into one device. Chul Park designed and built such the device which was used in this project.

4.2.2 Sealing

The sealing of the porous tube into the bushing can be accomplished in several ways. As it is imperative that the tube be well attached to the bushing, the seal must withstand axial pressures of up to 2000 psi. Welding and press-fitting are two options. This consideration makes it necessary to decide of what material the porous tube should be made.

Welding was used as it offers both the mechanical strength and the sealing required in this implementation. However, to weld, a metal tube must be used, as opposed to a tube made of porous ceramic. There are several types of porous metals on the market, but as strength and resistance to corrosion is of concern, a stainless-steel was chosen. Mott Metallurgical Corporation offers a wide variety of these metals. A Mott seamless porous tube made from 316L stainless steel was used in the bushing.[3]

The bushing used was made from a mild steel because of the extensive machining which had to be done. Though mild steel corrodes, the polymer never touches the bushing and this is not of concern. However, mild steel and stainless steel cannot be welded together in the traditional sense. Braze-welding must be performed. This involves heating a copper flux until it flows between the bushing and the tube, securely bonding the two

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[3]Mott Metallurgical Corporation, Farmington, CT. Catalog number: 1400-.500-.375-18-0.5.

together. This does destroy the pores, but since the welding only takes place a the two ends, this will not affect the gas delivery of the tube.

One area of concern is the seal between the gas addition device and the extruder and the device and the diffusion chamber. The proposed solution is to use thin doughnuts of soft metal between the three pieces. However, a sealing surface must be machined on each face for the metal seal to sit on. The sealing of the gas line to the bushing is accomplished by compression fittings and teflon tape.

4.2.3 Mechanical Strength

The braze-welding of the tube into the bushing should provide the necessary axial strength, as the tensile strength of a proper braze-weld is many times that of the pressure exerted by the polymer. [Halldin] However, the radial strength of the porous tube must be analyzed.

Though a stainless-steel tube would have the strength to withstand the polymer pressure, the a porous tube might not. The porous metal tube purchased was manufactured by sintering powered metal, a weaker material than poured steel. A tube could simply be inserted into the hole drilled into the bushing, but the gas would have no way to get to the whole length of the tube. This is another complication.

The solution to this problem is threading an hole which has been drilled axially through the bushing. The raised part of the thread supports the tube while the valleys of the threads serve as the plenum to deliver the gas along the length of the tube. Figure 4-2 is a close-up picture of a test piece showing the threading of the bushing with the porous tube in place. The inner-diameter of the threads must be the same as the outer diameter of the tube for the support to work. Once the threading is completed, a hole is radially drilled halfway through the bushing. The gas line is attached here. The gas then fills this hole and the threading along the length of the bushing and tube.

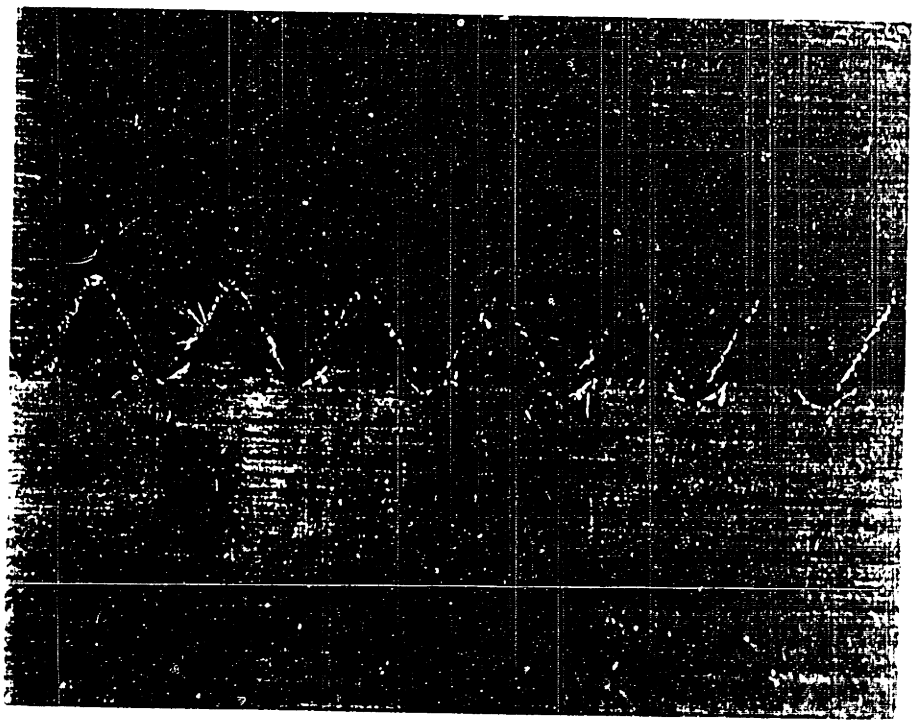

Figure 4-2: Close-up of Threading of Bushing and Porous Tube

The mechanical strength of the bushing itself is of little concern. Because it is made from mild steel and is three and one half inches in diameter, its strength is many times the pressure of the gas. The only areas which could fail are the weld spots, and this would only be due to improper welding.

4.2.4 Size

The size of the device is not a critical concern. The size of the device determines the amount of gas added to the polymer. It is better to over-size the device in the building phase than undersize it. If the gas amount delivered is too much, it is easy to use flow restrictors to control this. If gas supply is too little, then it is very difficult to increase the size of the device after it has already been built.

The inner diameter of the porous tube must be large enough to fit a static mixer. One commercially availably static mixer[4] has an outer diameter of 0.37 inches. Mott offers a porous tube with an inner-diameter of 0.375 inches and an outer diameter of 0.5 inches. Thus, the hole drilled axially into the bushing must be 0.5 inches wide. The length of the tube was set at six inches. Since there must be extra length on the bushing to attach the device to the extruder and diffusion chamber, the final length of the bushing was chosen to be 6.6 inches.

4.2.5 Gas Delivery

The plenum formed by the threading of the center hole delivers the gas to porous tube. There was some concern that there would be a large pressure drop as the gas flowed along the plenum. If there is a large pressure drop, then the pressure of the gas entering into the polymer could be lower than the extruder pressure. If this occurs, then the polymer might enter into the pores of the tube, clogging it up. This must be avoided.

To reduce the pressure drop, the threads were made to be very deep into the bushing. The flow through the porous tube will be fairly slow due to the relatively small pressure difference between the gas source and the extruder pressure. Since the gas flow through the plenum is not fast, the threads are large, and the viscosity of the gas is very low, then the pressure drop along the plenum will not be a factor.

4.2.6 Other Considerations

A heater is needed on the gas addition device to keep the polymer above its glass transition temperature. The extruder delivers molten polymer, but, due to the large mass of the device, the heat would quickly be lost due to thermal convection. A powerful heater should be used to reduce the time required to heat up the device before the manufacturing process begins.

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[4]Omega Engineering, Stamford, CT. Part Number FMX8452S

4.3 Result of Design

The above discussions determined the design of the gas addition device, schematically shown in figure 4-3.

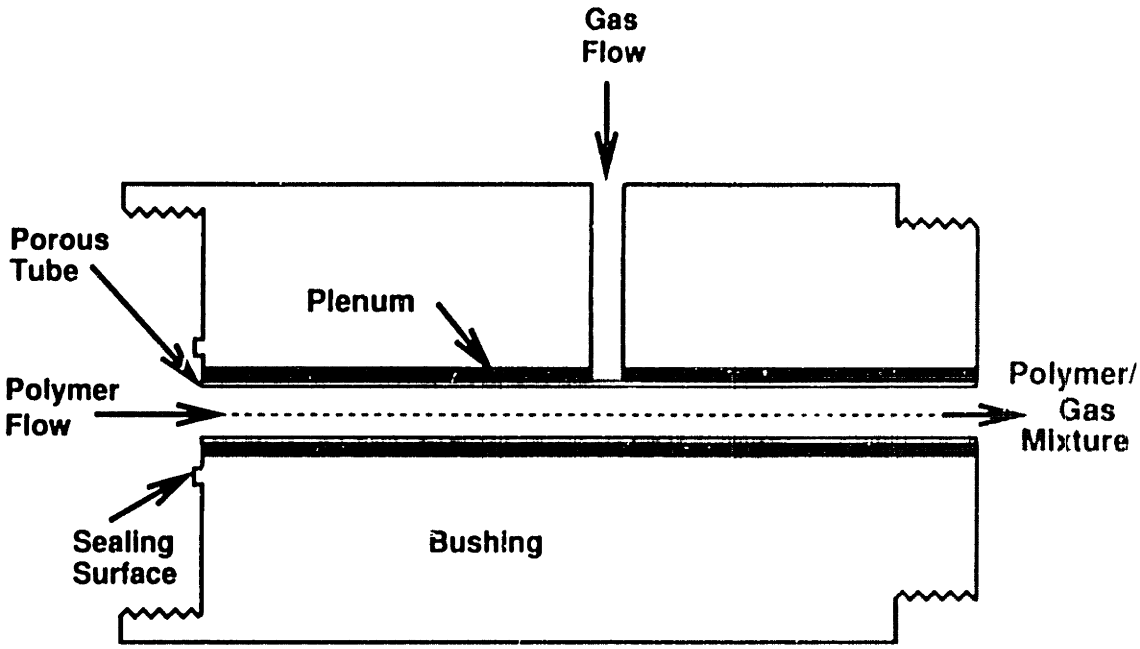

Figure 4-3: Schematic of Gas Addition Device

The device is designed to meet the goals set out in section 2.3. Secondary goals included ease of use flexibility and ease of use. The device is simple to attach to the MFP manufacturing set up. Also, because it is not permanently attached to the extruder it can be

removed easily and the process can be run without the device. Since there is only one connection to make - the gas line - set up time is very short.

Chapter 5

Experimentation

5.1 Experimental Setup

The bulk of the experimental set up has been described in the preceding chapters. There are many different controls and measurements needed. There are a total of six heaters on extruder and supplementary devices. Six thermocouples and three pressure transducers provide the measurements. The most important measurement for the gas addition device is the pressure reading between it and the extruder. If ever this pressure goes above the gas pressure, then the polymer has probably entered into the pores of the tube. Also, this pressure is what the seal feels. If too high, the seal will fail and send polymer squeezing out. This pressure must constantly be monitored.

5.2 Goals of Experimentation

There are several things which need to be checked before the device can be declared a success. The determination of whether or not MFP is produced or not is the most important of these. The sealing and the amount of gas addition are important steps.

The gas sealing is easily checked. After the device has been attached to the extruder and the diffusion chamber and the gas source connected and turned on, a leak check can be used. The simplest way is to use Snoop. The liquid is squirted on all connecting surfaces - exposed threads, compression fittings, etc. If the seal is not complete, then the liquid will bubble - the worse the leak, the more the liquid bubbles.

If the seal is gas-tight, then no polymer will leak either. Because the viscosity of the polymer is much higher than that of gas, it won't fit through any holes that the gas doesn't.

However, one worry was that the polymer would force its way into the pores of the tube or through any imperfections in the braze-weld. The only way to check this is to run an experiment and disassemble the device and check for polymer invasion.

5.3 Experiments

Initially, the goal is to get the system extruding. Once this is accomplished, then the goal changes to get the system extruding MFP. There are many variables which can be altered in the experimentation of the device. These include the material used, the gas flow rate, the polymer flow rate, temperature, and the combination of different elements.

The best material seems to be polystyrene [Suh 91]. The flow rate of the gas can be altered by changing the gas pressure source and inserting flow restrictor in the gas line. There is a range of temperatures which work best when extruding plastic. These can be determined from reference materials, such as the Modern Encyclopedia of Plastics. The extruder has a variable speed control.

The static mixers are not permanently attached to the devices which they are in. If the pressure drop is too great across either the gas addition device of the diffusion chamber piece, then the static mixer can be removed. This will reduce the pressure drop. Finally, the nozzle which forms the fiber can be changed to add or reduce flow resistance to the polymer flow.

During the experimentation phase, one must be careful to only change one variable at a time. Many of the above variables are coupled, that is changing one might affect several others. Since there are so many, a structured method of evaluating them all must be devised.

Chapter 6

Results and Conclusions

6.1 Results

Full evaluation of the gas addition device has not been completed. Initial results look promising. The critical areas of sealing and gas flow have worked so far. In an initial test, the pressure of the polymer exceeded 3500 psi and the sealing between the extruder and the device held without leakage - either gas or polymer.

MFP has not been produced. Fibers extruded have good gas concentration and integral skin, but the voids are too large. There is a problem with gas pockets. A large gas bubble traveling along the process line will cause an explosive depressurization when it reaches the nozzle. This will cause all the molten polymer to surge forward under the pressure of the extruder. The pressure difference at the gas addition device suddenly becomes very large and the gas surges into the polymer stream. This cycle keeps repeating itself until the effect of the depressurization is reduced.

A quick flow rate and a low steady-state pressure difference help the situation. Some success was achieved by manually stopping the gas flow into the device every time the gas pocket reached the nozzle. Future devices could have a vent of some sort to release the pressure.

It is necessary to have a very small forming nozzle. The size of this orifice determines the pressure at the void growth phase. Due to clogging in the extruder, a small enough nozzle could not be used. Future work will solve this problem and an appropriately-sized nozzle will be used.

In retrospect, the method of attaching the tube to the bushing should have either used

a press-fitting or been butt-welded instead of braze-welding. The mass and the geometry of the device made the braze-welding difficult. The device could have been manufactured with less mass. This would have decreased the two hours it took to heat up every day that experimentation began anew.

6.2 Future Work

The gas used should be Carbon Dioxide because its diffusion coefficient is much better than Nitrogen. However, very high pressure CO_2 is not commercially available. It would be necessary to build a pump to supply the gas at the required 3000 psi.

There is still much work to be done before the process investigated produces micro-cellular foamed plastic. The initial results are encouraging. With some time and energy, the gas addition device will be a useful addition to the process of manufacturing with MFP and brings the process one step closer to being viable for mass-production.

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