THE APPLICATION OF SINGLE-SCREW PLASTIC MOLDING TECHNIQUES IN CHOCOLATE PRODUCTION

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THE APPLICATION OF SINGLE-SCREW PLASTIC MOLDING TECHNIQUES IN CHOCOLATE PRODUCTION

A Major Qualifying Project Report Submitted to the Faculty of the
WORCESTER POLYTECHNIC INSTITUTE

In partial fulfillment of the requirements for the
Degree of Bachelor of Science
in Mechanical Engineering

Submitted by:

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2. Chocolate
3. Food Texture

Approved by:

___________________________________
Prof. Satya Shivkumar, Major Advisor
Abstract

Chocolate is typically produced with gravity fed, solid or shell molding techniques. The objective of this study is to examine the feasibility of molding chocolate with single-screw plastic processing techniques. Samples similar to miniature chocolate bars were produced using single screw extrusion and injection molding machines. The textural properties of these samples were tested using XRD, DSC, and three-point flexural tests. Improvements were seen in both the crystallinity and the texture of the chocolate after injection molding and extrusion. Single screw molding methods can also increase production rates and eliminate some post-processing operations and thus may be considered for commercial manufacture of chocolate products.
Acknowledgements

The authors of this MQP would like to thank ProtoPart Inc. in Hudson, New Hampshire for their help and services in performing the injection-molding portion of our project. Without the use of their injection-molding machine we never would have been able to complete the testing portion of our project. Thank you to UMASS Lowell and Professor Malloy for supplying their facilities and guidance and allowing us to perform extrusion experiments on our chocolate. We would also like to thank the Gateway facilities for providing the resources to perform our XRD and DSC testing. We would like to specifically thank Andrew Butler and Professor MacDonald of Gateway facilities for helping us operate testing machinery and helping us to understand our results. Finally we would like to thank Professor Shivkumar for his endless guidance throughout the completion of this project.
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1.0 Introduction

In 2010, approximately 3.6 billion lbs. of chocolate was consumed in the United States [1]. Considering the large market for chocolate in the United States alone, it can be assumed that the production of chocolate products must be consistent and efficient. Production is not only based on the molding of a chocolate product, but also on the trade of cocoa plants from all over the world. Once a cocoa bean has been harvested, chocolate companies will select beans based on their flavor potential. For some well-known chocolate manufacturers, they may reject up to 40% of the cocoa beans during the selection process. After the final selection, the cocoa beans are roasted, changing the color to a rich brown, and developing the aroma commonly associated with the flavor of chocolate. The roasting process hardens the shell of the cocoa bean, which makes it easier to remove leaving the meat on the inside referred to as the ‘nib’. For some production companies, such as Ghirardelli, the beans are double roasted to enhance flavor [2]. In most cases, after the nibs have been shelled, they are strained and sorted according to size by passing through a series of sieves. This process is referred to as ‘winnowing’. Once winnowing of the nibs has been completed, the grinding process is begun. During this process, friction produces enough heat to melt the fat within each nib, changing the consistency to liquid form known as cocoa liquor. The cocoa liquor is the primary ingredient in common forms of chocolate. The distinguishing factor between dark, milk, and white chocolate is how much sugar and milk is added to the chocolate liquor [3]. It is important to take into consideration all of the components the make up a chocolate product. The basic ingredients of milk chocolate are sugar, milk powder, cocoa butter, cocoa liquor, emulsifier of lecithin, and vanillin flavor. Chocolate consists of a high concentration (50%-60% by volume) of suspended solid particles consisting of mostly sugar crystals, cocoa, and milk solids dispersed in cocoa butter and milk fats [4]. Cocoa butter and white sucrose are highly crystalline materials; a characteristic that greatly affects the final texture and properties of chocolate products. Type V crystal structures are highly desirable in chocolate because they are what defines the properties of a molded piece of chocolate. Ultimately, chocolate products should have a glossy finish and a good snap, a quality that is directly related to the texture of the chocolate in the mouth. To ensure the formation of type V crystals, a tempering process must take place. In the tempering of chocolate, small chocolate solids are added to a partially melted portion of chocolate while mixing to apply a shear and evenly distribute the crystals within the material [5]. At room temperature chocolate is a solid, however it has a low melting temperature of approximately 47°C [4].

Cast molding is the primary method of chocolate molding in the confectionary industry. There are different types of cast molding such as solid molding, classic shell, cooled punch, one-shot, and hollow molding. Solid molding is the method used for developing chocolate bars and requires the chocolate to be melted, tempered, deposited into the mold, vibrated to settle the chocolate and release air bubbles, cooled, and finally demoulded [6]. Although this process is used consistently all over the world, there are some disadvantages. The first being the time required to complete the entire process. The manufacturing process allows for approximately 24 molds per minute to be filled at one time and after that, the molds must spend time in a series of temperature and humidity
controlled refrigeration units for cooling. The cooling process alone can take anywhere from 20 to 40 minutes [7]. Aside from time, the development of type V crystals is heavily dependent on proper temperature control and shear. It is challenging to ensure that all of the molds are a consistent temperature when the molten chocolate is deposited, and it is even more challenging to ensure that the large amounts of melted chocolate are a uniform temperature through the entirety of the tempering process.

Single-screw molding machines are most commonly used for molding plastics. The benefits of using this process are high production rates and low cool times. These methods provide high shear pressures during the melting and molding process similar to those needed in tempering of chocolate. The purpose of this work is to implement these methods in chocolate production. The pressure used in single-screw molding allows for lower melting temperatures and ultimately a shorter cool time. Single-screw molding in chocolate production could eliminate the need for a separate tempering step as well as significantly lower the cooling time. Aside from increased production, these molding methods can also allow for the production of more complex solid 3D shaped chocolates. The pressure forcing the chocolate into the mold can ensure even filling of the chocolate within the cavity.

The use of single-screw plastic molding techniques for the production of chocolate is evaluated in this paper. Proof of concept, property analysis and production benefits are all addressed in determining the feasibility of using these molding techniques for chocolate.
2.0 Objectives
The objectives of this work are to:

1. Examine the feasibility of using plastic processing techniques to mold chocolate
2. Determine the optimum processing and post processing conditions for chocolate
3. Evaluate the properties of the chocolate produced by plastic processing techniques in terms of chocolate properties such as texture and gloss
4. Compare the properties of the chocolate produced by plastic processing techniques with regular chocolate
3.0 Procedure

Materials

The main focus of this investigation was to analyze the effects that injection molding and extrusion methods can have on the properties of chocolate, in order to determine the feasibility of this molding technique in chocolate production. Semi-sweet chocolate chips from a North American chocolate manufacturer were used and can be seen in Figure 1. Semi-sweet chocolate chips were selected because of their low fat content, their achievability in bulk quantities, and availability from the manufacturer. A lower fat content was desired for this purpose because it ensured that the chocolate data was not strongly impacted by amorphous ingredients such as the milk fats. The chocolate was also received in chip form because the chips most closely resemble the pellets used in traditional plastic injection molding.

![Figure 1: Semi-sweet chocolate chips from North American supplier used as raw material](image)

Methods

The chocolate was put through two different molding procedures. The first was an experimental procedure performed on a single screw and barrel extruder at UMASS Lowell in Lowell, Massachusetts. Extrusion testing was performed by fluctuating the temperatures in the three different chambers of the barrel, in order to obtain a high viscosity material. The first chamber, closest to the hopper, was left the coolest at around 24°C to ensure that the chocolate was entering the barrel in solid form. This also ensured that the chocolate would feed properly as it proceeded further into the barrel. The remaining temperatures were held at around 27°C to melt the chocolate further into the barrel. The screw speed was raised to around 1.7 Hz to expose the chocolate to the shear forces necessary to promote further melting. Extruded chocolate can be seen leaving the extruder in Figure 2. The knowledge obtained during the extrusion test was applied to injection molding methods.
Injection molding was performed at ProtoPart Inc. in Hudson, New Hampshire using a NE85UA machine shown in Figure 3. The machine and services were donated by employees of the company, which limited the availability of molds that could be used for chocolate testing purposes. A basic, two cavity steel mold was selected due to its simple design. The selected mold produced two rectangular prisms of dimensions 2.54x5.08x0.64cm. The mold allowed for chocolate to enter and fill into one half of the mold while the other half remained flat to allow for the chocolate to adhere to the flat surface and allow for ease of removal. The mold was sprayed with an available silicone release agent to ensure that the chocolate could be easily removed from the mold after injection molding. After performing several trials, the final molded chocolates were manufactured using a constant chamber temperature of 25°C, a screw speed of 1.1 Hz, back pressure of 61 MPa and a front pressure of 31 MPa.

![Figure 2: Extruder in use with chocolate as the feed material](image2.png)

![Figure 3: Injection molding machine at Proto Part in New Hampshire used for injection molding chocolate](image3.png)
For comparative purposes, chocolate was hand molded in order to determine the qualities of the chocolate chips that are molded without tempering. The samples were produced using two different molds of similar dimensions: the same steel mold used for injection molding purposes and a plastic mold meant for at-home chocolate molding. Molded samples of both are shown in Figure 4. The chocolate was melted by placing the chips into a ceramic mug and heating them in 20 second intervals in a standard microwave. The chocolate was removed every 20 seconds and stirred to prevent it from burning. The chocolate was then poured into the two 25.4mm x 44.5mm x 6.35mm molds. The chocolate was left at room temperature to cool, a process that took roughly between one to two hours. The chocolate was cooled at room temperature in order to prevent the chocolate from seizing in the mold and also to limit the potential addition of moisture that could cause unwanted fat bloom. This molding technique was over simplified from production gravity molding techniques due to the investigative purposes of this molding method.

![Figure 4: Hand molded chocolates made with semi-sweet chocolate chips. (A) Chocolate molded from plastic mold. (B) Chocolate molded from metal mold.](image)

The chocolate was analyzed using three main tests: X-ray diffraction (XRD), differential scanning calorimetry (DSC), and three-point snap analysis. The main purpose of these three tests was to determine if there were any major changes to the crystal structure and the textural properties of the chocolate pre and post single screw processing. XRD was performed at Gateway, the Life Sciences and Biotechnology Center on the Worcester Polytechnic Institute’s campus in Worcester, MA. Samples of the original chocolate chips, injection molded chocolate, and extruded chocolate were shaved into a fine powder by using a single edged razor blade. Approximately 100-500 milligrams of sample shavings were placed into a XRD tray cavity that was three millimeters deep and had a diameter of three centimeters. The samples were placed in the XRD machine and a graph was outputted that identified the crystallinity peaks in each sample. In order to identify some of the peaks that occurred in the different chocolate graphs, samples of two crystalline components, cocoa butter and white sucrose, were also tested in powder form and placed in the same cavity use to test the chocolate. Testing was completed using a Bruker AXS D8 Focus powder x-ray diffractometer.
DSC testing complimented the XRD data by identifying the latent heat energy of the different molded chocolates in order to determine the percent crystallinity of the samples. Testing was performed on a 2920 Modulated DSC-TA Instrument at Worcester Polytechnic Institute in Worcester, MA. Two samples were obtained for each of the injection molded, extruded, and plain chocolate. Samples were weighed to be between two and ten milligrams. Each sample was placed into an individual, Texas Instrument, aluminum DSC pan and placed one-by-one in the machine. The pan was heated to 149°C at a rate of roughly 5.6°C per minute. The Universal Analysis 2000- TA Instrument V3.1E software plotted graphs that resulted in different peaks. Samples of white sucrose and cocoa butter were tested using the same procedure as the chocolate, in order to determine whether these two materials were the cause of the two peaks in the graph. Upon identification, the various graphs were compared to each other in order to determine if any changes occurred.

The final test method was a three-point bend test that evaluated the snap of the chocolate. An Instron machine was used at Worcester Polytechnic Institute to obtain the compression data for extruded, injection molded, hand molded, and commercial chocolate samples. The injection molded, extruded, and hand molded samples were all tested on the same mount that supported the chocolate ends 4 cm apart. The commercially produced chocolate samples, due to their shorter length, were supported on a different mount with supports 3 cm apart. A pointed probe was lowered onto the center of each sample at a rate of 50 mm/min. One trial was performed on an injection-molded sample at 10 mm/min in order to determine the effects of the strain rate on the chocolate samples. The Instron software plotted a force versus elongation graph that was used to obtain flexural modulus and flexural strength values.
4.0 Results and Discussion

The results of this MQP are presented in one forum:

a) A journal paper was prepared as indicated below:


The paper is attached in the following section. The principal results from this MQP are provided in the journal paper. Some of the salient aspects of the results are given in this section.
The chocolate was molded using two different single-screw methods: injection molding and extrusion. The chocolate was extruded in order to determine the effects that shear and temperature had on the flow. The extrusion showed the temperature dependence of the chocolate by slowly dropping to a final molding temperature of around 26°C. This allowed for the chocolate to exit the extruder as a highly viscous sample. Additionally, chocolate viscosity increased as the screw speed approached 1.7 Hz. From these results, the viscosity of chocolate is shown to be dependent on both screw speed and temperature of the extruder. These results were carried over to injection molding in order to produce solid samples. Similar screw speed and temperature were applied to the injection molder. The additional consideration for the injection molder was pressure. This project was based off of the concept that shear forces occurring within the barrel of the extruder work in conjunction with the high pressures and would achieve the same crystal formation as tempering the chocolate. The final injection molded chocolate entered the mold at a lower temperature, 25°C, as opposed to the gravity molded chocolate that enters the mold around 32°C. This allowed for the chocolate to be cooled at around 100 seconds. Traditional gravity molding requires the chocolate to be cooled upwards of 20 minutes after exiting the molding machines. The lower melting temperatures of injection molding and the potential elimination of traditional tempering can potentially increase the production rates of chocolate because these two steps can be removed from the chocolate molding process.

Samples from both the extrusion and injection molding trials were tested to determine whether or not the chocolate qualities were improved by these methods. The samples were compared to hand molded, untempered samples, and current gravity molded, commercial chocolate. The hand molded sample comparison was used to show the difference between tempering and not tempering chocolate while the commercial piece was used to determine if the injection molded sample was comparable to mass produced chocolate. X-ray diffraction and differential scanning calorimetry were both used to examine the crystallinity of the different chocolate samples. XRD was performed first on the plain chips, extruded chocolate, and injection molded chocolate to see if the shear stress and/or pressures effected the crystal formations.
Figure 5: X-Ray Diffraction patterns for regular industrially molded chocolate (A), injection-molded chocolate (B), and extruded chocolate (C) demonstrating the similarity of crystal structures in all three chocolate mold methods.
Figure 5 shows the comparison between the plain chocolate, extruded chocolate, and injection molded chocolate and shows that the crystalline structure is the same pre and post single-screw molding procedures are the same. The spikes are occurring at approximately the same locations indicating that the crystalline materials are still present in the extruded and injection molded samples. The DSC test compliments the XRD results by further examining the crystalline structures.

![Figure 5: Comparison of crystalline structures in different chocolate types](image)

Figure 6 compares the plain chocolate, extruded chocolate, and injection molded chocolate samples. The first two peaks correspond to the two crystalline components of chocolate: cocoa butter and sucrose respectively. The final peak is a representation of the chocolate degrading. The graph shows that the two crystalline components are melting out of the chocolate samples at roughly the same glass transition temperatures for each method. Furthermore, the latent heat energy can be found as the area under each of the curves. The latent heat energies were used with pure samples of cocoa butter data to find the percent crystallinity of the material in each sample. The percent crystallinity was found to increase from the plain sample to the injection molded sample. The values were calculated to be 60.2% for plain, 77.3% for the extruded sample, and 83.7% for the injection-molded sample. This increase in percent crystallinity is due to the exposure of the shear stresses and the high pressures.

![Figure 6: DSC for regular chocolate (A), extruded chocolate (B), and injection-molded chocolate (C) demonstrating changes in latent heat energy for cocoa butter and sucrose crystalline materials](image)
The final test performed on the chocolate samples was a three-point fracture test that examined the snap qualities of the chocolate samples. Snap characteristics are directly related to the texture and mouth feel of the chocolate. A poor snap would result in a soft and flexible chocolate or a very hard chocolate and in turn would not be enjoyable to consume.

Figure 7 shows the snap characteristics for commercial chocolate, hand molded chocolate, extruded chocolate, and injection molding samples. The injection-molded sample is shown to have the highest snap of the four tested samples. This shows that the injection molding process increases the textural qualities. The flexural modulus was calculated for these samples in order to verify the results from this graph. The flexural modulus for commercial chocolate was found to be around 81 MPa, 24 MPa for hand molded chocolate, and 134 MPa for injection molded chocolate. The higher flexural modulus of injection molded chocolate shows that the injection molding process improves the snap qualities of the chocolate and therefore improves the texture of the chocolate to be better than that of commercially produced chocolate.
The Application of Single-screw Plastic Molding Techniques in Chocolate Production

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Abstract

Typical chocolate is molded in gravity fed systems at a relatively low rate. The objective of this study is to examine the feasibility of utilizing single-screw molding methods in chocolate processing to improve the production rate and the textural qualities of chocolate. Samples similar to miniature chocolate bars were produced using an injection molding machine. The textural properties of these samples were tested using XRD, DSC, and 3-point bend tests. Comparing the newly molded samples to existing market chocolate and additional hand molded chocolate, testing proved that it is possible to use these molding methods to eliminate the need for tempering. These methods also allowed for the chocolate to be cooled at significantly lower rates. Therefore, the results indicate that the properties of the single-screw molded chocolate were improved from the traditional gravity fed cast molded chocolate, with the added benefit of potentially increasing production rates.

1.0 Introduction

The current manufacturing methods of chocolate are completed using a variety of molding techniques. The most common being cast molding, enrobing, and drop molding. Traditionally, a basic chocolate bar is cast molded and chocolate is poured into a 15° drafted mold at approximately 47° C. This process requires the tempered chocolate to be deposited into a mold which is then vibrated to settle the chocolate and release air bubbles, then finally cooled and demoulded. Because chocolate has a low melting point and a high yield value, it has a high viscosity and it is necessary to pump the molten chocolate into mold cavities. Typical molds are made using polycarbonates or derivatives of polycarbonates. In typical chocolate molding no release agent is used due to the contraction of the chocolate being 0.3-0.8% shrinkage by volume. The manufacturing process allows for approximately 24 molds per minute to be filled at one time, which does not account for the time spent in a series of temperature and humidity controlled refrigeration units for cooling; a process that can take anywhere from 20 to 40 minutes to complete. Chocolate is highly temperature sensitive and the rate of cooling can influence the development of form V crystals.
Chocolate consists of a high concentration (50%-60% by volume) of suspended solid particles consisting of mostly sugar crystals, cocoa, and milk solids dispersed in cocoa butter and milk fats [3]. The solid components of the chocolate make up 65%-75% of the chocolate composition depending on specific manufacturers and 20% of the solid components is milk powder [4]. However, chocolate properties are largely dependent on the characteristics of the cocoa butter. Ideally, the cocoa butter will contain form V crystals due to their demolding properties, resulting in a glossy finish and smooth texture. In order to ensure the development of type V crystal structures, tempering is applied to control crystallization through cooling and heating of chocolate. [5] It is also necessary to consider that at body temperature, approximately 37°C, chocolate is predominantly viscous and can possess a low yield stress of approximately 10-20 Pa. [3]. Due to its yield stress and non-Newtonian flow behavior, chocolate is considered to be a Casson plastic material [4].

Consequences of improper crystal structure patterns have resulted in flawed chocolate products. A noticeable flaw is fat bloom, which is due to an increase in the number of pores present on the surface of chocolate which allow for the pooling of liquid cocoa butter and the resulting formation of fat crystals on the surface of the chocolate. The porosity of chocolate can be controlled through the tempering process due to the porosity being directly related to chocolate viscosity before molding. Fat bloom seems to develop during the transformation of crystals from structure V to structure VI [6]. Ideal properties of chocolate also include proper snap and gloss characteristics. Chocolate will have these ideal properties when its cocoa butter crystal structures fall within Beta form and melt between 18-35°C [7][8]. The manufacturing processes can be enhanced substantially if the refrigeration process could be eliminated while still maintaining the crystal integrity of the chocolate. Ideally, a process could be implemented that would eradicate the time required to heat, cool, and shear chocolate in the tempering process as well as cool the chocolate at a rate much quicker than the existing 20 minute minimum.

A potential option for improving the production rates of chocolate is to introduce the concept of single-screw plastic molding methods into the confectionary industry. These methods are conducted at high strain rates which would be beneficial in potentially eliminating the need for the tempering process prior to molding. With these rates and the non-Newtonian characteristics of the chocolate, significant shear thinning can be expected in the machine. Due to the shear forces acting within the barrel, the rate of shear can be maintained in order to guarantee consistent formation of form V crystals in the chocolate material. Alternatively, frictional forces from the screw will create enough heat to melt the chocolate while the machine maintains a lower barrel temperature, decreasing the amount of cooling time. Furthermore, the high pressure built up prior to molding can also enable intimate contact with the mold material and thus enhance cooling rates. These new rates can reduce the size of the cocoa butter crystals which could perhaps lead to a smoother finished texture. Aside from these improvements in current manufacturing techniques, it is possible for an injection molding machine...
pressures to allow for molding of chocolate to occur at lower temperatures. The purpose of this work is to further explore the feasibility of injection molding chocolate.

2.0 Procedure

2.1 Materials
Semi-sweet chocolate chips obtained from a North American supplier were used in all of the experiments. The chip form most closely resembles the plastic shot commonly used in plastic processing and can be seen in Figure 1.

![Figure 1: Semi-sweet chocolate chips used as the new material. The chocolate chips were obtained from a commercial manufacturer and used within 6 months of manufacture.](image)

2.2 Methods
All injection molding was completed using a NE85UA Single Screw injection molder at Proto Part in Hudson, New Hampshire. Molded chocolates were produced using a constant chamber temperature of 25°C, a screw speed of 1.07hz, back pressure of 60 MPa and a front pressure of 30 MPa. A Make N’ Mold Plastic candy mold, model 0229, was used in making hand molded chocolates. They were produced through pouring melted chocolate chips at a temperature of 27°C into both the metal mold used for injection molding as well as the plastic molds. The mold used for injection molding is made of P-20 tool steel and forms two rectangular prisms of dimensions 2.54x5.08x0.64cm. The mold contained a flat face and a face with two cavities. The mold is shown in Figure 2 with the inclusion of two molded chocolates.
Samples of chocolate chips, injection molded chocolate and extruded chocolate were shaved into a fine powder for use in X-ray diffraction (XRD). A stainless steel razor blade was utilized to form a powder with particles visually the same size as the cocoa butter granules. Powdered cocoa butter and white sucrose were also tested for comparison. Testing was conducted using a Bruker AXS D8 Focus powder x-ray diffractometer.

A 2920 Modulated DSC-TA Instrument was used for performing differential scanning calorimetry (DSC). Analytical software used was Universal Analysis 2000- TA Instrument V3.1E. Samples of white sucrose, cocoa butter, injection molded chocolate, extruded chocolate and commercially molded chocolate were all tested utilizing DSC. The pans were heated to 148.9°C at a rate of 5.6°C per minute. Two trials were completed for all samples except cocoa butter and white sucrose, which only had one trial each.

Gloss was analyzed qualitatively as there is no standard quantitative testing method. All chocolate sample forms used in prior testing were placed on a solid white surface with even overhead fluorescent lighting. Team members analyzed each sample for differences in surface gloss.

An Instron machine was used in conducting a three-point bend test for evaluating the snap within the chocolate. The Instron was used to acquire flexural data with hand molded, typical commercially molded, injection molded and extruded chocolate. The machine used a third point of force on the chocolate at a rate of 50mm/s. A minimum of ten samples were tested for injection molded and commercially produced chocolate. Extruded and hand molded samples were tested 5 times each. Data was collected and graphed within the Instron software to display force versus elongation.
3.0 Results and Discussion

3.1 Single-Screw Molding Methods

Table 1: Date obtained during the extrusion of chocolate in a single-screw extruder

<table>
<thead>
<tr>
<th>Trial</th>
<th>Zone 1 Temp (°C)</th>
<th>Clamp Temp (°C)</th>
<th>Screw Speed (Hz)</th>
<th>Pressure (MPa)</th>
<th>Temp of Chocolate Exiting (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>61.1</td>
<td>N/A</td>
<td>1.0</td>
<td>0</td>
<td>N/A</td>
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<tr>
<td>2</td>
<td>27.2</td>
<td>38.9</td>
<td>1.5</td>
<td>0.1</td>
<td>40</td>
</tr>
<tr>
<td>3</td>
<td>25.0</td>
<td>32.2</td>
<td>2.1</td>
<td>0.1</td>
<td>31</td>
</tr>
<tr>
<td>4</td>
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<td>2.1</td>
<td>0.1</td>
<td>31</td>
</tr>
<tr>
<td>5</td>
<td>25.0</td>
<td>30.0</td>
<td>1.8</td>
<td>0.2</td>
<td>29</td>
</tr>
<tr>
<td>6</td>
<td>24.4</td>
<td>28.9</td>
<td>1.7</td>
<td>0.2</td>
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</tr>
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<tr>
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<td>24.4</td>
<td>28.9</td>
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</table>

The chocolate was extruded in order to determine the effects that shear and temperature had on the flow of the chocolate. The screw and barrel system was divided into three sections, the first of which was kept at the lowest temperature in order to grind down the chocolate and guide it through the barrel over the screw. The temperature was slowly dropped until the machine was able to read a pressure output. The testing criteria can be found in Table 1 and demonstrates the temperature, screw speed, and pressure relationship. From trial one to trial two, the pressure on the system increased from the decrease in zone one temperature and from the increase in the screw speed. Zone one was the first zone that needed the lowest temperature to ensure proper feeding into the machine. By the final trials, the temperatures over all had been dropped as low as they could while still producing a solid, flowing chocolate sample. The higher pressure towards the end of the experiment shows that the chocolate is more solid in the chamber as it is pushed through the die. Chocolate is described as a Non-Newtonian fluid with a viscosity that varies according to the rate at which it is sheared. Additionally, chocolate is highly temperature sensitive and will start to melt roughly around 32°C. As chocolate starts to melt, it experiences a decrease in its viscosity [2]. Lowering the screw speed resulted in an increase in the pressure as well as a more solid extruded chocolate. Figure 3 (a) demonstrates the constant flow of the chocolate out of the machine while Figure 3 (b) shows the extruded sample once it had been removed from the machine. At higher temperatures the extruded chocolate experienced low viscosity and inconsistent flow. As the temperature lowered, the chocolate’s viscosity increased and the flow was consistent.
Figure 3: a) Chocolate (A) exiting from extrusion machine. Die (B) and barrel (C) portions are also visible in image. b) Photograph showing the uniformness and the relative flexibility of the extruded chocolate.
Table 2: Injection molding inputs and outputs the show changes that were made in order to reach final molding results

<table>
<thead>
<tr>
<th>Trial</th>
<th>Sample ID</th>
<th>Back Pressure (psi)</th>
<th>Front Pressure (psi)</th>
<th>Chamber 1 Temp (F)</th>
<th>Chamber 4 Temp (F)</th>
<th>Screw Speed (rpm)</th>
<th>Shot Size (mm)</th>
<th>Cool Time (sec)</th>
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Injection molding was first performed at higher temperatures, as seen in the Table 2 above. A higher screw speed was combined with these higher temperatures and resulted in a low viscosity chocolate that was the consistency of putty once removed from the mold. Using the extrusion data, it was decided to perform the process at lower temperatures such that the chocolate feeding into the hopper remained solid until it progressed further down the screw and melted from the shear. The ending screw speed was also lower than initial trials to ensure that the chocolate didn’t enter the mold at a temperature that was too high. During trials four and five, the chocolate was completely solid in the mold and could be removed in one piece as can be seen in Figure 4. Shot size was also gradually increased until the resulting molded chocolate was completely solid. Pressure was a key consideration in the injection molding process as it is the factor that would most impact the crystallization of the chocolate. The backpressure needed to be equal or higher than the front pressure of the chocolate to effectively inject the chocolate into the mold. The various trials of injection molding demonstrated the temperature dependence of the chocolate and also showed the effects of pressure and screw speed on the viscosity of the chocolate. Chocolate resulted in much lower injection temperatures than common plastics because it is more sensitive to temperature and can melt at temperatures as low as 25°C, without any exposure to other forces such as shear.

![Figure 4: Injection molded chocolate immediately after top (A) and bottom (B) of the mold separated](image-url)
3.2 Material and Mechanical Testing

Figure 5: Surface gloss comparison of industrially molded typical chocolate (A), hand molded chocolate (B), and injection molded sample (C). The hand molded chocolate was produced in the current investigation as indicated in Section 2.

The surface gloss of the injection-molded sample was found to be comparable with current industrial cast molded samples as seen in Figure 5. The gloss finishes were roughly the same, both having a higher luster than the hand molded sample. The surface finish of the injection-molded sample also lacked any signs of fat bloom or other imperfections, even several weeks after having molded the samples. This shows that the shear of the screw and the pressures from the injector never heated the samples to a point that would result in the separation of the components.
Figure 6: X-Ray Diffraction pattern of plain chocolate (A), and two main crystalline components cocoa butter (B) and white sucrose (C). The figure shows that the major diffraction peaks in chocolate generally correspond to the principal ingredients.
Figure 7: X-Ray Diffraction patterns for regular industrially molded chocolate (A), injection-molded chocolate (B), and extruded chocolate (C) demonstrating the similarity of crystal structures in all these chocolates.
The X-Ray diffraction testing validates that chocolate is a highly crystalline material as seen from the high peaks that occur in the graph in Figure 6. The crystallinity of the material is largely due to its two crystalline components: cocoa butter and sucrose. The presence of these materials was confirmed when the X-ray diffraction results for sucrose and cocoa butter were placed over the plain chocolate graph. As seen in Figure 6, several of the larger peaks in chocolate occur in the same locations as the sucrose and cocoa butter. Figure 7 demonstrates that the three different mold methods overlap at every peak, indicating that the crystals that were present before injection and extruded chocolate are still in the same locations after. For extruded chocolate, no change shows that the shear effects that occur inside of the screw and barrel do not degrade the chocolate or impact the desired type V crystals. For injection molding, no change shows that the high pressures also do not negatively impact that formation of these crystals. In traditional manufacturing, plain chocolate must be tempered to achieve correct crystal formation, a time consuming process that improves the quality of the chocolate after molding. By having the injection molding and extruded crystals present in the same locations as the plain chocolate confirms that the shear stress on the chocolate in the screw and barrel essentially temper the chocolate and produce the desired type V crystals.

Differential scanning calorimetry was then performed on the gravity, extrusion, and injection molded samples. Figure 8 shows the three mold methods compared to each other. The first two peaks were expected to be the two most crystalline components of the chocolate samples, cocoa butter and sucrose. DSC was performed on pure samples of each of these comments, the results of which can be seen in Figure 9.
Accepted glass transition temperatures for cocoa butter and sucrose fall around 30-40°C [9] and 190°C [10] respectively. DSC results, Figure 8 and 9, confirm these accepted values and show that these two components are present in each molded chocolate and each component melted at roughly the same temperature. The third peak corresponds to the degradation of the chocolate. The area under each curve indicates the latent heat energy that the sample needs to melt the crystals at that temperature. The latent heat energy of the first peak was calculated to be 32.9 J/g, 42.2 J/g, and 45.7 J/g for the gravity, extruded, and injection molded samples respectively. The increase in the latent heat from gravity molded to injection-molded samples suggests that the high-pressure process improves the crystallinity of the material.

The second peak experienced an improvement in crystallinity as well, with values of 61.6 J/g, 62.2 J/g, and 67.4 J/g for the gravity, extruded, and injection molded samples. All three different mold methods roughly have the same crystallization temperatures as seen in the overlapping peaks. The consistency of the peaks compliments the XRD results because it demonstrates that the crystals present before injection molding and extrusion are still there afterwards.

Once it was confirmed that cocoa butter was present in each molded chocolate, the percent crystallinity of each component in each sample was calculated using the latent heat energies acquired from the area under the cocoa butter curve. Equation 1 below was used to calculate the percent crystallinity.

\[
\%\text{Crystallinity} = \frac{L_1}{L_2 \times 0.5} \times 100
\]

Where \(L_1\) is the area under the 1st peak and \(L_2\) is the latent heat of fusion for pure cocoa butter.

The amount of cocoa butter in chocolate can fluctuate based on the formula of the manufacturer [2]. Due to the propriety nature of the formulas, an exact value for cocoa butter percentage could not be obtained. The chocolate samples, therefore, were assumed to contain 50% cocoa butter. The latent heat was found to be around 109.2 J/g for pure cocoa butter sample.
and 110.2 J/g for pure sucrose sample. Table 3 below shows the change in percent crystallinity across the three analyzed mold methods. The purpose of this calculation was to show the increase in crystallinity from plain to injection molded chocolate. This shows that the strain in the extruder and the pressures of the injection molder both increase the percent crystallinity of the material.

Table 3: Percent crystallinity of cocoa butter and sucrose for gravity fed, extruded, and injection molded chocolate

<table>
<thead>
<tr>
<th>Component</th>
<th>Plain Chocolate (%)</th>
<th>Extruded Chocolate (%)</th>
<th>Injection Molded Chocolate (%)</th>
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<td>Cocoa Butter</td>
<td>60.2</td>
<td>77.3</td>
<td>83.7</td>
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The decrease in the latent heat values after exposure to the different molding methods suggests that the materials become less crystalline when added to the other components in chocolate as compared to their pure form. However, the components within each chocolate sample experienced an increase in crystallinity after exposure to extrusion shear and injection pressures. This concludes that the crystalline properties of chocolate are improved by the injection molding process.

Figure 10: 3-Point fracture for Hershey's dark gravity molded chocolate (A), semi-sweet hand molded (B), semi-sweet extruded (C), and sweet injection molded (D) at 50 mm/min
Table 4: Flexural strength and moduli of snap for various chocolate mold types

<table>
<thead>
<tr>
<th>Mold Method</th>
<th>Yield Strength (N)</th>
<th>Flexural Modulus (MPa)</th>
<th>Flexural Strength (MPa)</th>
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<tr>
<td>Hershey’s Dark Gravity Molded Chocolate</td>
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<td>Hand Molded Semi-Sweet Chocolate</td>
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<td>Extruded Semi-Sweet Chocolate</td>
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<td>621</td>
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<td>Injection Molded Semi-Sweet Chocolate</td>
<td>153</td>
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<td>3,887</td>
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Three-point compressive tests have been used in the food industry to determine the snap qualities of food. Snap is directly related to the texture of the food product and guides how the product would be expected to feel in the consumer’s mouth [11]. The compression test was set up as a three-point bend test using a constant load for Hershey’s gravity molded, extruded, injection molded, and hand molded chocolate samples. This test determined how the snap of the chocolate changed upon injection molding. Figure 10 demonstrates the overall force deformation curves for the four mold types and indicates that the injection-molded samples have a better snap over the hand molded, gravity molded, and extruded samples. Chocolate with poor snap is characterized by a compression graph with a gradual incline while a good snap would be characterized by a steep incline. A higher snap is desired in chocolate manufacturing because higher snap ensures that the chocolate will degrade more slowly and that chocolate packaging will be less likely damage the chocolate. Flexural strength and the flexural modulus values were calculated for the four molded samples in order to confirm the trends observed in Figure 10. As seen in Table 4, injection-molded samples have the highest flexural strength and modulus out of the four tested mold methods, showing that the injection molded samples had the best snap. The increase in snap is a result of the high pressures that the chocolate is exposed to during the injection molding process in conjunction to the shear experienced in the screw and barrel that force the chocolate’s crystals to temper. The improvement in texture compliments the DSC and XRD results, further showing the improvement in the quality of the chocolate through the injection molding process.
Figure 11: Three-point bend performed on injection-molded samples at 50 mm/min (B) and 10 mm/min (A) resulting in longer elongation at lower strain rate

The strain rate effects were also analyzed to see how the chocolate would change when exposed to a decreased strain rate. As seen in Figure 11, slowing the speed of the test down to 10 mm/min resulted in the chocolate experiencing a longer elongation but smaller force needed to fracture. Strain rate is directly related to the viscosity characteristics of the material. In a typical material, lowering the strain rate would lower the stress to fracture. This is an expected trend for chocolate material and this trend is confirmed in Figure 11. This further shows that the injection-molded chocolate continues to act similarly to traditional gravity molded chocolates even after exposure to high pressures and shear. Chocolate can be consumed at different rates and forces. Determining strain rate effects was important for understanding how the chocolate would respond when consumed.
Conclusion

The presented data proves that incorporating single-screw machines in the chocolate molding process can improve the properties of chocolate and provide opportunity to improve production rates. The crystallinity of the chocolate was found to be the same pre and post injection molding, which suggests that, the same quality of chocolate can be achieved with injection molding as with tempering and gravity molding. Additionally, the improvement in the latent heat energy of the injection-molded samples shows that the high pressures and shear stresses that occur during the molding process improve the crystallinity of the chocolate. Injection molding further improved the quality of the chocolate, specifically the texture as seen from the improved snap characteristics. With the improvements in the chocolate's properties, injection molding could be used as a technique that replaces current mold methods at a potentially decreased future cost to the company and increase in production. Current molding methods require time for tempering and cooling of the chocolate product, whereas it has been proved that the shear pressures within the barrel of the single-screw machine are enough to eliminate the need for tempering and allow for lower melt temperatures. With this, the data also proves that the cool time is decreased, as the injection-molded samples required less than 120 seconds to solidify. In addition to an improved production process, the consistency of a screw and barrel machine would allow for regulation of the crystal formation of the chocolate in the early stages of molding, thus ensuring that physical properties such as fat bloom development would be avoided in the final product. In conclusion, the proven benefits of injection molding chocolate should be considered for the future of the confectionary industry.

Acknowledgments

The authors would like to thank John MacDonald and Andrew Butler of Worcester Polytechnic Institute and Robert Malloy of UMASS Lowell for providing us with the testing equipment and guidance. The authors would also like to express their gratitude to ProtoPart Inc. in New Hampshire for providing the injection molding equipment vital for the completion of this project.
References


6.0 Conclusions

Semi-sweet chocolate was molded into steel molds at a speed of 64 rpm and a temperature of 25°C. The mold was filled completely despite the temperature being significantly lower than regular cast molding. Similarly, temperatures required for extrusion were also lower. Because of the lower melt temperature, it takes far less time for the chocolate to cool and solidify. Injection molding can also produce chocolate products that can be cooled in one to three minutes and can achieve a proper temper without the need to add a tempering step before molding. The shear forces acting in the screw and barrel work in conjunction with the high pressures of the injector to temper the chocolate and result in the formation of the desired type V crystals. Now that it has been proved that single-screw molding can eliminate the need for temper as well as decrease the cooling time, it can be said that the efficiency of the current chocolate manufacturing process can be improved.

Current processes rely heavily on accurately tempering chocolate before it enters into the mold in order to ensure that the chocolate has desirable properties. Under tempering or over tempering can result in either too low or too high of a snap that can negatively affect the texture of the chocolate for the consumer. Additionally, the current molding methods require that the chocolate molds be placed in refrigeration units for a minimum of 20 minutes, often times longer for more complex chocolates compounds, to achieve the desired solidity. The cooling process can be costly due to the operation of the refrigeration units and this process significantly reduces the production rate of the chocolates.

The material benefits of this process were confirmed through the crystallinity data obtained from the XRD and DSC testing. The XRD tests proved that the crystallinity of chocolate before single screw procedures is the same after these procedures. The DSC testing confirmed that these samples, when compared to the basic tempered chips, showed an improvement in the percent crystallinity when exposed to both the shear forces in the extruder and the high pressures of the injector. The results from these two tests show that the chocolate achieved a temper despite not having been tempered before molding. There were additional improvements to the chocolate textural properties as well. The three-point fracture test demonstrated that the snap characteristics of the injection molding chocolate were higher than that of hand molded chocolate, production chocolate, and extruded chocolate samples. Due to the increase in snap, the texture of the injection-molded chocolate is assumed to be better than that of current production chocolate. Future testing will have to be performed on the texture qualities of the chocolate to ensure that there is improvement. However, based on the results from this project, injection molding is a viable method for chocolate production that can be performed at higher production rates and at a potentially lower cost to the manufacturer.
References


Appendix

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<td>3</td>
<td>DSC results</td>
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<td>Injection Molding Visits and Results</td>
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