Re-Usability of Plastics

By

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Submitted to the Department of Mechanical Engineering in Partial Fulfillment of the Requirements for the Degree of

Bachelor of Science

at the

Massachusetts Institute of Technology

June 2005

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ABSTRACT
A research project was designed in order to learn more about the quality of recycled plastics when compared to new material. The study was carried out by researching and learning about how the recycling process operates. Further research was then conducted on the seven different types of resins that exist in the recycling world today. After collecting the data, an experiment was devised in order to learn more about the capabilities of using recycled plastics for regular household applications.
The results of the experiment showed that most of the seven recyclable plastics could actually be used again as along as special care was taken to ensure that the quality of the recycled product was equivalent to that of the virgin material. However, it was determined that a more rigorous recycling program for plastic would be feasible but it is not a practical endeavor for economic purposes. As a result, many of the manufacturers within the plastics realm prefer to use new plastic as opposed to recycling their products.

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Introduction

Plastics are valuable resources which are utilized in several applications today. They can be seen in products such as medicine bottles, soda bottles, detergents, food trays, grocery bags, and car battery casings. With all these different types of products in mind it is clear that the demand for plastic is quite high because there are numerous applications that it can be used for. In fact, plastic usage has continually been increasing from previous years. Despite the advantages of using plastic, these numbers should also be concerning. Plastics have a possible half life of hundreds of years and will stay in the landfills and other places where they are stored after usage. Therefore special efforts should be to recycle these products in order to remedy the growing spacing problems in the current landfills.

The purpose of this thesis study is to research and learn more about the world of plastics as well as to consider the possibilities of using recycled plastics in the remaking of their original products. One of the main objectives will be to determine what types of plastics are in fact able to be recycled and to what degree they can be used again. Another issue which will be addressed is whether material properties of recycled products are affected after going through the recycling process. Regrind products will also be considered in this search as it will be important to find out whether plastics material properties are drastically changed when plastics are mixed and combined. Finally, a recommendation will be provided on whether a greater effort to recycle and reuse plastics should be pursued for conservation of plastic in appliances today.

What are Plastics?

Plastics are composed of polymers which are chains of molecules that are mostly comprised of carbons. In order to create plastics, several polymers are layered on top of one another until the molecules covalently bond and bind together. In this case there are a few different ways in which these plastics are able to link together. The initial type of bonding of polymers results from linear bonding. Here, the monomers which are reacting with one another bind in such a way that they have a purely linear molecular structure. (As shown in Figure 1) This type of polymerization can be characterized by plastics like polyethylene.

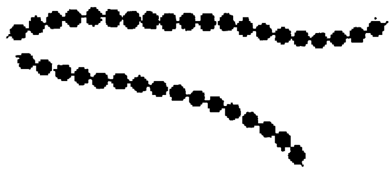

Figure 1: A Linear Polymer

The second type of bonding occurs when there are branches on the molecular structure of a plastic which is formed (Figure 2). These types of polymers are still similar to their linear counterparts except for the fact that they contain side chains which are connected to a linear strand. This polymer is apparent in plastics such as LDPE or low density polyethylene.

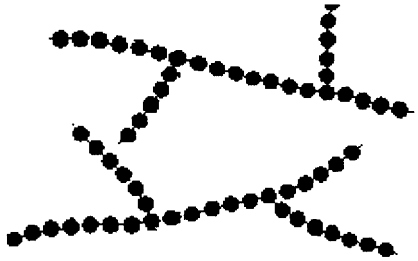

Figure 2: Example of a Branched Polymer

Lastly, the last type of bond which occurs among polymers is in reference to cross linked bonding. In a cross linked polymer the bonds are placed in between different linear bonds as illustrated in Figure 3.

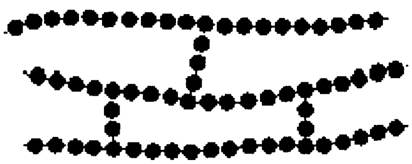

Figure 3: Structure of a Cross- linked Polymer

This occurrence changes the material properties of the desired plastic as it would be more difficult to remove these bonds after they are set. Depending upon which type of bonding is used; plastics are able to achieve a wide range of material properties based on their molecular structure.

In fact the bonding of polymers dictates what types of plastics can actually be recycled or used again. These two types of polymers are known as thermosets and thermoplastics. The cross linked polymers mentioned above develop into plastics which are known as thermosets. Thermosets are plastics which cannot be re-molded after initially being created. This is due to the fact that the bonds which are cross linked will have difficulty in recombining themselves. The three dimensional shape of the plastic is broken down and thus cannot be reconstructed after being heated. Consequently these types of plastics can only be made once and cannot be setup for recycling. Thermosets are plastics like melanines, epoxies, polyesters, and silicones.

Thermoplastics on the other hand refer to plastics which have linear and branched bonding in their structure. These plastics can be reformed due to the fact that the simple structure of their molecules can be heated, remolded, and covalently bonded several times. Thermoplastics become soft when exposed to heat and harden when cooled no matter how often the process is repeated[1]. The applications of such plastics are much greater due to the fact that they can be used over again instead of just being thrown out.

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[1] Swanson, Robert S. Plastics Technology: Basic Materials and Processes. Bloomington, IL: Mcknight & Mcknight, 1965.p 17

Thermoplastics make up a greater percentage of the plastics which are available for use; they include such plastics as Polystyrene, Polyethylene Terephthalate, Polypropylene, and Polyvinyl Chloride.

Plastic Manufacturing

After being made, plastics are prepared for several different types of manufacturing processes. These include using machining techniques such as Extrusion, Blow Molding, Film Molding, and Injection Molding. Before the plastics can be used for any one of these processes, they are prepared by being placed in pellet or flake form. This type of formation helps make the job of molding the plastics into the desired shape much easier. Despite the differences in the methods which are used above, all of these processes consist of similar mechanical parts shown below in Figure 4[2].

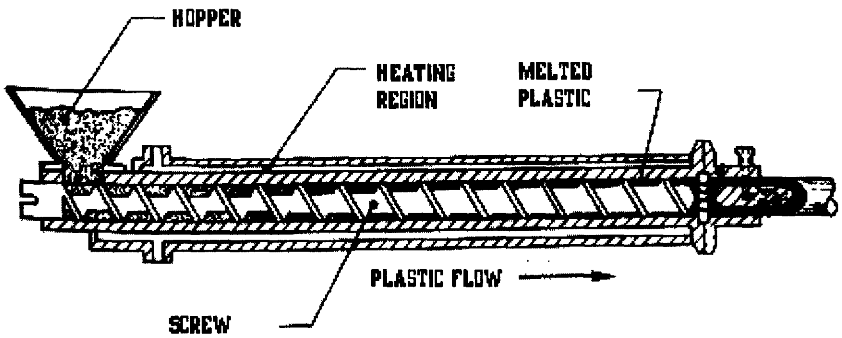

Figure 4: Typical Plastic Manufacturing Parts

Based on the picture above, these machines consist of some sort of a loading mechanism, a screw, and some sort of die. Generally, plastics are installed into the loader where they sit and are prepared to be processed. As the plastic reaches the screw, it then is heated and brought to a melt. A piston is normally included within the screw to push the plastic melt forward and towards the surface where the plastic is actually pressed into a die. With this process in mind, there are three other notable types of processing for plastics.

[2] http://class.et.byu.edu/mfg130/processes/descriptions/consolidation/extrusionmolding1

Extrusion of Plastics

This process is one of the most common plastic machining techniques currently being used today. Extruding plastics is typically a process of continuously making a specific type of product[3]. It is used to make such plastics like drinking straws and garden hoses. Therefore it is intended to let the plastic create shapes which are long and sharing the same dimensions over a certain distance. Extrusion machines generally have simple operations as well. The plastic pellets which are initially received are placed in a loading area or a hopper. Afterwards, the plastic is heated until it turns into a liquid form. It is then fed through a screw which helps keep the plastic hot and forces the hot plastic through an office with the desired shape. In terms of using the machine several different dies are placed on the other side of the plastic orifice. Here the hot plastic is molded into a specific shape and cooled until it hardens. Therefore extruding plastics can be used to make channels, table edging, or simply long products which not have a lot of wall thickness variation.

Blow Molding

Machining Plastics using blow molding is very similar to that of the process of extrusion. Once again plastic powder or pellets is fed into a hopper heated and placed in a screw for maintaining heat and applying pressure to the plastic. However, this type of processing differs in respect to extrusion due to the orientation of the plastic while it is being heated. Instead of a horizontal feeding process, the softened plastic is forced downwards into a circular type of die and sits a hollow plastic tube. This tube is known as a parison[4]. After the plastic is contained in this tube, it is placed into a mold for a specific shape. Next air is added to the tube in order to make the plastic inflate and merge into the contours of the outer mold. As a result, the plastic acts as a thin film in the shape of the die. Soon when the plastic is allowed to cool for a certain time period the plastic is ejected with its new shape. This type of process is mainly used to make items such as plastic bottles which have a hollow interior and round outer wall.

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[3] Plastics Technology Robert V. Milby p68

[4] http://www.jobwerx.com/plastics/extrusion.htm

Blown Film Molding

This technique uses plastic in the form of pellets in order to make very thin products. Similar to the other techniques, the plastic is loaded into a hopper and melted in the shaft with a rotating screw. After melting the plastic, it is pushed forward and sent upwards into the desired die which is attached at the end of the apparatus. After being forced into the die, the plastic begins to take on the desired shape. Here dies for film molding are generally circular in shape. As a result, the plastic enters the die and finally air is added in order to expand the material which is present. Finally, the air which was just used to inflate the product is removed and the plastic is run through flat rollers which then have a cutter on the end to make several parts. Therefore plastic with a very thin wall thickness is forced through a machine and setup so that it is divided into sections. This type of process is more apparent when looking at applications of making grocery bags or plastic bags in general. Clearly one can see that the bags have been cut and formed based on the seams which are on the bottom of the bag.

How Recycling Works

In order to gain some insight into how recycling operates, some research was done in order to learn about what MIT does for its recycling process. MIT EHS or Environment, Health and Safety Office was contacted to discuss MIT's current recycling scheme.[5] The basic process begins with general collection. Plastic bottles and other products are collected in the blue recycling bins which are distributed all over campus. Afterwards, the plastic is brought into the processing facilities here on campus. The plastic is then partially sorted and placed in a large compactor for storage. While in wait, the plastic is being prepared for shipping to a recycling center that actually finishes the task of sorting and recycling the plastic. When these plastics arrive at a variety of centers but the most notable one for MIT is FRC- located in Charlestown. Once the plastic arrives there, it is then sorted by category as there are seven different types of plastics divisions which can be prepared for recycling. (A more detailed explanation of the categories will be provided in the next section.) After being sorted, the plastics are then treated and purified to remove contaminants which come from labels, epoxies, and other materials which are

[5]Email Contact with Justin Adams from MIT EHS.

placed on different plastics. Special care must then be taken to ensure that when the process is done that the desired plastics were actually cleansed properly. Otherwise the recycled plastic will not be as good in quality. Therefore plastics are ground into small flakes and treated in order to ensure that impurities have been fully removed. After being heated, burned chips or flakes are removed from the plastic and the rest is prepared for a new use or application. From here, the remaining flakes of plastic are bailed and prepared for distribution to plastic manufacturers who can use the flakes to remake or create new products.

Although this procedure highlights the recycling process, some of the steps still need to be highlighted more clearly. As mentioned before, collection is the first step of the recycling process. Here plastic can be placed in recycling bins or sent directly to a recycling center for processing. Secondly, sorting is the next important step in recycling materials. In terms of plastics, the SPI or the Society of the Plastics Industry[6] has created a code which would help identify specific types of plastics. Such a code would be very helpful in sorting as it can be quickly determined which plastic type is using through a numbering system. This numbering system ranges from 1-7 with each displaying a particular type of plastic that can be recycled (Shown in Table 1 below)

[6] http://www.plastics industry.org

Table 1: SPI Resin Codes for Recycled Plastic

1 PETE	Polyethylene Terephthalate
2 HDPE	High Density Polyethylene
3 V	Polyvinyl Chloride
4 LDPE	Low Density Polyethylene
5 PP	Polypropylene
6 PS	Polystyrene
7 OTHER	Other

After completing the sorting stage, the next phase of actually cleaning the plastics is referred to as reclamation. Here the plastic is ground, washed, and treated in or to be set back up for usage. The treatments are necessary to remove the impurities from usage. In Figure 5 one can see what PET looks like when it is first ground and after it has been cleaned and purified for usage

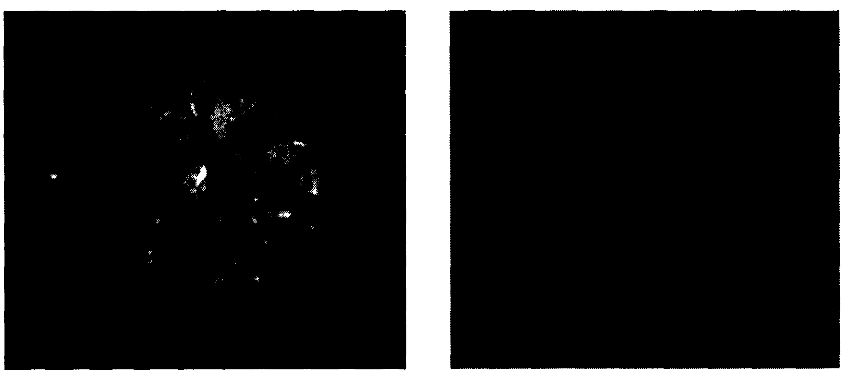

Figure 5: PET Ground/ Purified State

After thoroughly cleaning the recycled parts, the newly remade plastic is then put up for sale so that a manufacturer or the company can reuse the plastic for some applications. Generally, towards the end of the process some additives are added into the recycled material in order to help it retain more of its original material properties. Therefore the recycled price of materials is slightly lower than the prices of having new plastic. This can be seen in the reference for all the plastics in Appendix A.

Recycled Plastic Types

The Plastics which were described in the previous section are the main types of plastics that can be recycled today. The codes which specify the type of plastic give clues to the material properties of the resin. Therefore the resin codes can break these plastics up effectively. The following section will go into more specific detail about the seven categories of plastics.

PET- Polyethylene Terephthalate

PET is one of the most abundant recyclable plastics which are being used today. It is essentially a linear polymer and therefore can be recycled several times before losing some quality. In fact some studies have shown that PET can be reused between 25-40 times before it starts to become useless to recycling[7]. Generally PET is known for its high strength, high stiffness, and as a strong gas barrier. The resin is also known for its heat and chemical resistance properties as it can withstand mild temperatures and specific solvents for an extended period of time. Physically, it appears as though it is transparent despite having a crystalline structure. As a result of these attributes, PET is used in applications such as soda bottles, microwavable films, and packaging for other food based products.

In terms of its ability to be recycled, PET is one the most recycled products but there are several cautions which must be taken into account. For example, during the sorting and purification process, one must make sure that the PET being reground does not have impurities. This occurs because this resin is mixed with other types of plastics like PVC in order to make certain other products with special material properties. Therefore special care must be made in the recycling process to remove all impurities otherwise the material properties will be greatly affected.

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[7] Brandrup, Johannes,et al. Recycling and Recovery of Plastics. Munich: Hanser Publishers, 1995.p670

HDPE- High Density Polyethylene

This is another very popular plastic which is used in many different applications. HDPE is linear in shape and does not contain any side chains. Therefore it can be heated and recreated somewhat easily. Typically HDPE is used in injection molding and extrusion machining processes. It also has the following characteristics: toughness, good dielectric properties, low water absorption, chemical resistance and ease to process. Physically speaking, HDPE looks transparent when it is in film form but, milk white in thicker sections. As a result of these types of features HDPE is generally used in packaging goods[8]. This applies to applications like containers for milk, bleach, or rubbing alcohol. Another important fact about HDPE is that it does have certain weaknesses. This resin has difficulty lasting in the presence of oils or different greases. It is also slightly difficult to recycle due to the fact that the plastics must be sorted by grade to lessen the chances of impurities. Other notable issues stand in the fact that it is very difficult to get HDPE to the same quality of the virgin resin after usage. HDPE has to be blended in order to create a product with close qualities. This is simply due to the fact that HDPE degrades and loses durability with each use.

PVC - Polyvinyl Chloride

PVC is primarily made in three different grades. The most common of these plastics is S-PVC or suspension PVC. This type of resin is best recognized for its good flow properties and rigid PVC applications. Here PVC is a branched type of resin with a Chlorine molecule bonded into one of the side chains. This addition of chlorine gives the plastic different types of material properties. Therefore PVC can be used for fire protection and electrical wire insulation. Its other mechanical properties include: chemical resistance, strength, longevity, and ductility. Typically PVC is used because it is known to last for at least 10 years[9]with little tear or wear. PVC is probably one of the best in terms of making recycled plastic in similar quality to that of virgin plastic. In fact the techniques which are

[8] Swanson, Robert S. Plastics Technology: Basic Materials and Processes. Bloomington, IL: Mcknight & Mcknight, 1965.p37

[9] Brandrup, Johannes,et al. Recycling and Recovery of Plastics. Munich: Hanser Publishers, 1995.p652

used today could even make recycled PVC stronger than the original plastic. However, this process does cost more than the regular recycling program. Once again while being recycled on of the greatest concerns is that of making sure that the final product can compare with virgin material. Therefore some PVC is blended with the original plastic in order to guarantee quality. Recycling this product is also a risky as the chlorine can be dangerous during manufacturing processes.

LDPE – Low Density Polyethylene

LDPE is very similar to its counterpart HDPE. The main difference between the two stems from molecular structure and ultimate application. LDPE is formed from a branched polymer which contains specific types of side chains. The material properties of LDPE are also somewhat similar. The resin has a good toughness, sealing abilities, and good optical properties. This particular type of plastic is generally utilized in film molding applications. The main types of products which result from the molding process are garbage bags or bread bags.

If this plastic is generally used in film form then it would most likely be very difficult to recycle its contents. However some effort is placed into making ground LDPE so that it can be applied to handbags and other applications where there is low impact. Otherwise very little is done in terms of recycling this type of plastic due to the fact that it would just cost extra money to make sure that a good quality product would be obtainable.

PP- Polypropylene

Polypropylene has many qualities which are similar to PET. It is very versatile due to the fact that it can be made flexible or stiff. This resin can also be soft to the touch or very strong in tensile strength. Its desired properties include: heat & chemical resistance, longevity, high melting point, resistance to scratches. Another interesting fact about PP is the fact that it is often used in terms of blending with other plastics. Currently there are blends with plastics like PE, PS, PVC, ABS, and even other PP copolymers. The combinations of such plastics allow new types of resins to appear with a good blend of material properties. Therefore special plastics can be made with the combined material properties of PP and another desired polymer. One example of this is PP with HDPE which is utilized to make plastic buckets more durable and resistant to cracks. Other blends such as PP and PS are used in products like yogurt cups.

Once again recycling this type of plastic would be somewhat difficult since it is blended with so many different types of plastics. In order for recycling to be effective these other plastics would have to be removed fully. For example if PVC is not removed from this plastic then the entire batch which is being recycled can be contaminated and therefore be of little use. Contamination is a big issue as it appears that in any given PP regrind there can be up to 10% foreign material[10]. The presence of these impurities can lead to a product which would be lacking in quality.

PS- Polystyrene

Polystyrene is polymer which also has several applications for use. This resin is known for its: rigidity, high surface gloss, excellent transparency, and impact strength. These properties make PS a perfect candidate for materials within the field of medicine. It can be used as food trays and containers which hold food. PS could also be used as the plastic container where needles and other objects are contained. One other notable quality is due to the fact that PS plastics are generally the lightest of all rigid plastics therefore it can be used in products which need to be transported easily. One setback however is due to the fact that Polystyrene is not designed to be an outdoor material due to its sensitivity to light[11]

In terms of its recycling capability, Polystyrene is a good product due to the fact that it is possible to get the same quality from recycled material that was obtained from virgin plastic. Once PS is ground and cleaned it can be prepared all in one step. Due to this capability, polystyrene is also used fairly commonly in blends. One of the most common blends using PS is with HDPE or LDPE. Other notable blends are with rubber, such a mix creates a High Impact resistance type of polymer.

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[10] Brandrup, Johannes,et al. Recycling and Recovery of Plastics. Munich: Hanser Publishers, 1995.p 604

[11] Swanson, Robert S. Plastics Technology: Basic Materials and Processes. Bloomington, IL: Mcknight & Mcknight, 1965.p39

Other

The final category in the SPI resin codes does not refer to one specific type of polymer. This section includes many different plastics like ABS (Acrylonitrile, Butadiene, and Styrene) or PC (polycarbonate). These plastics are used mostly for their abilities to make regrinds or blends with interesting sets of characteristics. This helps make numerous products like Tupperware. However the largest drawback to the seventh category is that none of the plastics from within this sector can actually be recycled. Therefore they will eventually be placed directly in dumps due to the lack of reusability.

The Experiment

In order to learn more about the capabilities of recycled plastics, an experiment was devised to see how well the different types of plastics listed above can handle being manufactured for a specific application. As a result, it was decided that plastic pellets should be purchased for each type of plastic ranging from 1-6. Plastic #3 or PVC was excluded from this experiment due to its toxic properties during heating. After acquiring the different types of plastics, they would be prepared for use in the injection molding machine. Here the plastics would be setup to be processed in one of the yoyo dies from the 2.008 yoyo manufacturing lab. After processing all the parts, a quality test would then be performed to investigate topics such as, finish, weld lines, ability to make small details, coloration defects, and failures.

Experimental Procedure

The first step in beginning this experiment was selecting an appropriate type of mold which would be able to create injection molded parts with the desired detailed parts. Therefore, several yo-yo molds in the LMP lab were investigated before an actual selection was made. Finally, a mold was selected from one of the previous classes of molds shown in Figure 6 below.

Figure 6: Yo-Yo Mold Selected

This particular type of mold was selected due to the sharp contours which were in the center of the circle. Part of the examination would be to determine how well certain plastics would be able to mimic such a detailed type of design.

The next step was to prepare the plastic for use in the injection molding machine. Plastics such as Polypropylene were placed in a cup to be added to the hopper of the machine. A small amount of material would be needed, as the focus of this experiment was to make a maximum of six parts per plastic. Figure 7 shows the plastic before it was added in the machine.

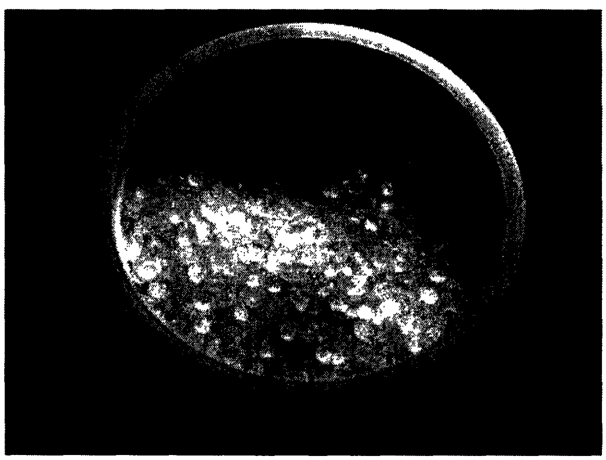

Figure 7: PET Plastic Pellets

Next, the plastic would be placed in the hopper of the injection molding machine. Afterwards, the plastic was heated and ready to be pushed through the screw of the machine (Figure 8).

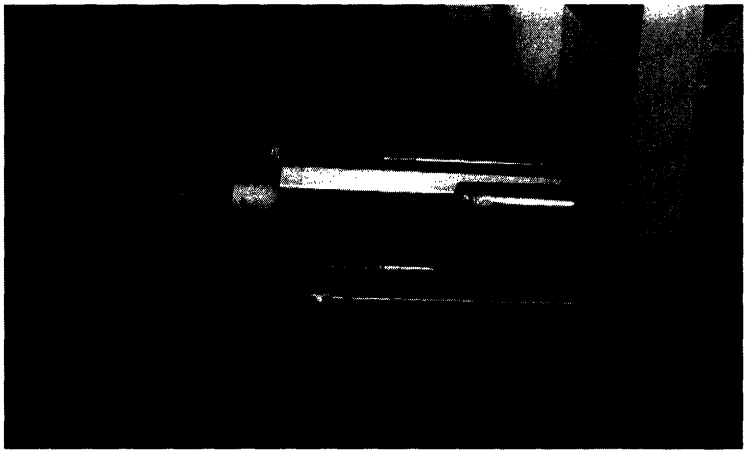

Figure 8: Injection Molding Machine Loading and Heating Mechanism

The settings would have to be selected so that the plastic could be run appropriately. One of the most important features during this process was temperature. Selecting the correct temperature was necessary to make sure that the plastic would successfully leave the screw and fill the entire mold. Otherwise there could be failures where the plastic could get stuck or leave holes in the desired product. During the experiment, the 2-3 different temperature shifts were created based on a specific plastic. For PP, the temperature was varied between 350°, 400°, and 450° F. Other features which were important during the test were packing time and cooling time. These two options also assist in making a better quality product. The packing time refers to how long the plastic is being injected in the mold. Adjusting the amount of time that it takes to move the plastic in the mold can drastically change the outcome of the piece, as sufficient time must be placed for the plastic to fill the mold. For the sake of this experiment, the packing time was left at approximately 8 seconds to ensure that the plastic was given enough time to fill.
The cooling time, on the other hand, refers to the time that the plastic is allowed to sit and cool down after injecting the plastic. Once again, this feature is important because if the plastic does not cool properly, it will deform or shrink more drastically from the mold size after the part is removed. This was one of the experimental parameters, as the cooling time was varied from 5 seconds to 10 seconds on different runs.
The quality tests will begin by using an optical comparator to observe elements like flash or cracking in the specific parts. The comparator outlines the body of the plastic part and

allows the dimensions to be determined through looking at the measurement lines on the screen displayed in Figure 9. Each line is approx. 0.125mm apart.

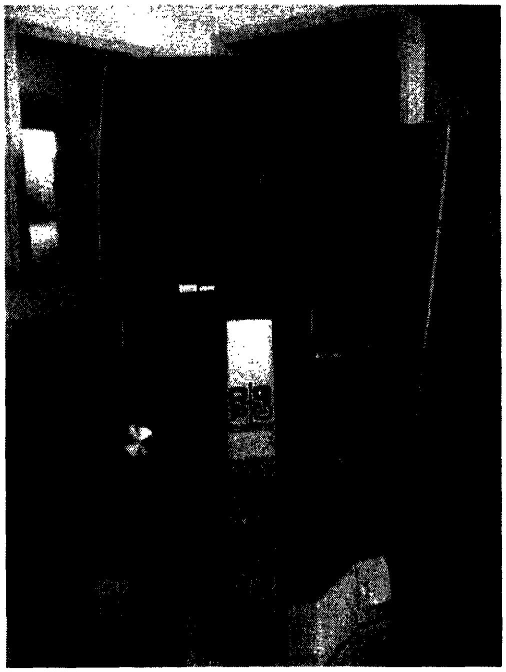

Figure 9: Optical Comparator

After completing this stage other parameters in the quality measurement will be looked at for evaluation.

Experimental Results and Analysis

PP

The very first plastic which was tested was Polypropylene. This plastic was retrieved in pellet form and prepared for the injection molding process described in the previous section. The initial parameters were based on temperature, and cooling time. At that moment, the machine was set to 350° F and the cooling time was set to 10 seconds for proper cooling within the part. The results of this experiment yielded the following results in Figure10.

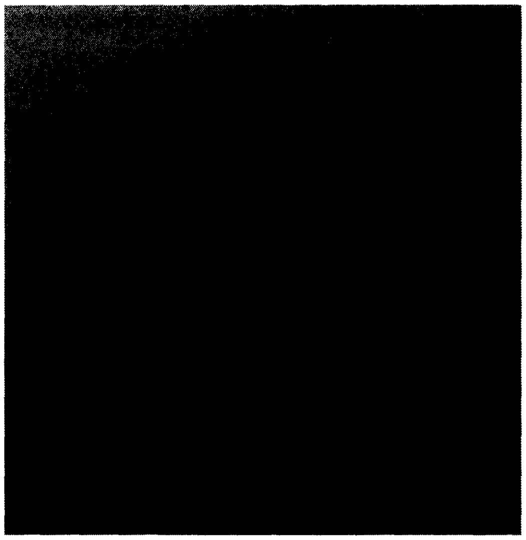

Figure 10: First PP Part from Analysis

Here it appears as though the PP was able to make an adequate part. The optical comparator was then utilized to test how well the part was able to handle the small detailed curves within the mold's geometry. The polypropylene was loaded onto the machine and examined for defects as seen in Figure 11.

Figure 11: Flashing Viewed On Comparator

The most noticeable trait is the flash which shows up between the crevices of the part. The flash was measured to be at least two lines on the comparator meaning that there was flash up to 0.250 mm on that part. Despite the minor flash, the polypropylene did a good job in terms of making the part. Through a careful eye examination, there were no discolorations or visible blemishes which would have resulted from the molding process.

The weld lines of the part were visible but were minor in terms of the surface of the part. The characteristic toughness of PP was also evident was the part was very solid and had a good tensile strength.

Another parameter which was considered was shrinkage. In order to make a calculation on this part, the dimensions of the mold were measured. The yoyo mold had an outer diameter of 1.703 inches. The part was then measured with calipers and it was determined that it had an outer diameter of 1.650. The percentage of shrinkage was then determined by finding the error between the two values which is defined by Equation 1

$$100\times(\frac{M_d - P_d}{M_d}), \tag{1}$$

where M_d is the mold diameter and P_d is the diameter of the part which is being measured. The percentage of shrinkage in this case was 3.1%.

Two other products were made by varying the temperature and the cooling time. The second and third experiments used temperatures of 400°F and 450°F. The cooling time was then moved between 8s and 10s. The results were demonstrated in Figure12 below.

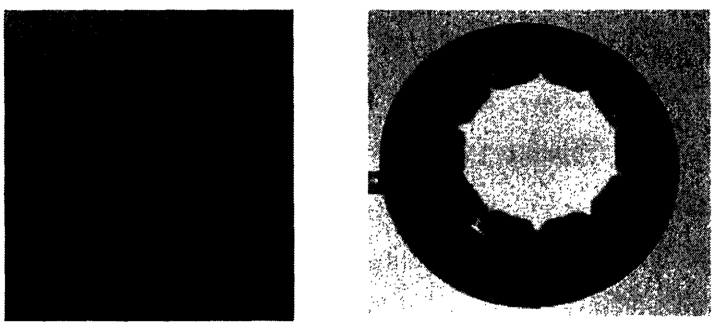

Figure 12: Second and Third PP Test Parts

Each of these plastics had slightly different results. The results demonstrated that there was less flash as the temperature was increased. The final test proved to be a much better production in terms of quality.

From a shrinkage point of view, the shrinkage lowered significantly from 3.1% to 1.6% and 1.9% for the other tests. Therefore these processing improvements helped yield a better part.

PET

Since this is one of the most popular types of plastic being used in the industry today, PET was also tested to determine its abilities to make the part. In this experiment the PET was targeted for injection molding temperatures of 440-600°F. Therefore, it was decided that the first temperature should be 450° for a good product. The first test yielded the following results (Figure 13).

Figure 13: PET Trial Run at 450° F

One of the most noticeable features in the picture above is how clear the parts actually were. The material was basically transparent just like the soda bottles that it is used for within the industry. Other discernible traits were the fact that the product was extremely hard. It was clear here that the yo-yo part was very rigid and probably the hardest of the plastics which have been tested so far. The PET parts also had a slightly visible weld lines which was small in comparison to PP and PS parts. One drawback, however, was observable in the fact that there was trapped air within the part (Figure14). Here it could be seen that some air got stuck near the weld line during processing. Therefore special care must be made to reduce this.

Figure 14: Air Bubbles within PET

Another interesting aspect of this part can be seen in the way it is able to deal with sharp corners. This can be seen in the examination with the comparator. (Figure 15)

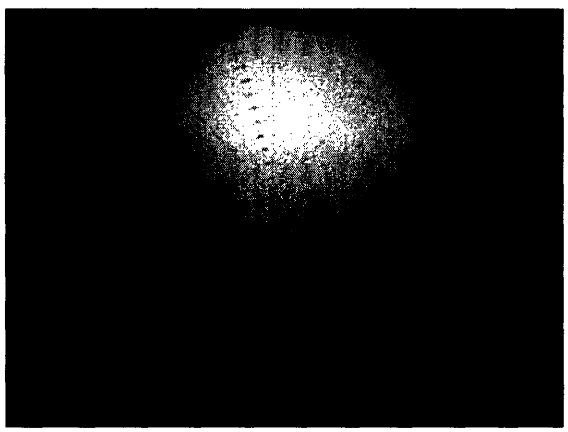

Figure 15: PET Contour Analysis

It can be seen that PET was able to flawlessly handle the contours of the part. There were no visible signs of flash or any other problems which could have occurred due to shrinkage or errors within the part. This is by far the best plastic examined thus far in terms of its ability to be molded in tight details.

The shrinkage of the part was excellent as well. The parts had an outer diameter of 1.7 inches which corresponded to shrinkage of 0.15%. Such a part would be excellent for mixing with other plastics currently on the market.

A second test was setup varying the plastic part by a 50 degree increment. Therefore the new temperature of the injected plastic was 500°F. This yielded the following yo-yo part (Figure 16).

Figure 16: PET Second Test Results

Once again, the properties were very similar and there were no other visible signs of blemishes or impurities in the part. However, air bubbles were visible as the air continued to be trapped inside the part as shown in the second picture of the figure above. One possible reason for this is the fact that when melted, the PET had a low viscosity and flowed almost too freely into the mold. A larger effort had to be placed in how the plastic was sent into the mold. This could help reduce air being trapped in some of the parts. The shrinkage also remained the same as it was about 0.15% over several parts.

Despite the small changes in temperature, PET was able to make an effective part. In general, the recycled plastic described here can be used in many different food applications such as soda bottles (Figure 17) as well as blends for materials with different material properties. Therefore, it is recommended that PET be used in most types of plastic machining processes as well, due to its performance during the experiment.

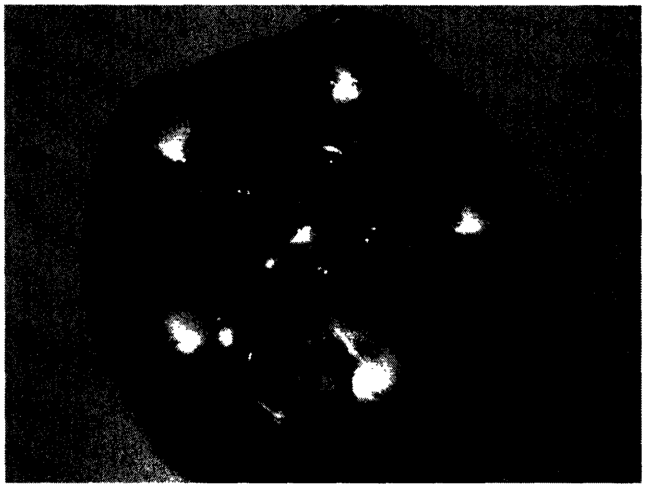

Figure 17: PET Soda Bottle Sample

PVC

PVC was difficult to examine due to the fact that it is difficult to find recycled parts. Recycling PVC is not an easy task as it must be separated by grade and type. The general type of PVC which was found was the hardened S-PVC which can be used in piping applications (Figure 14).

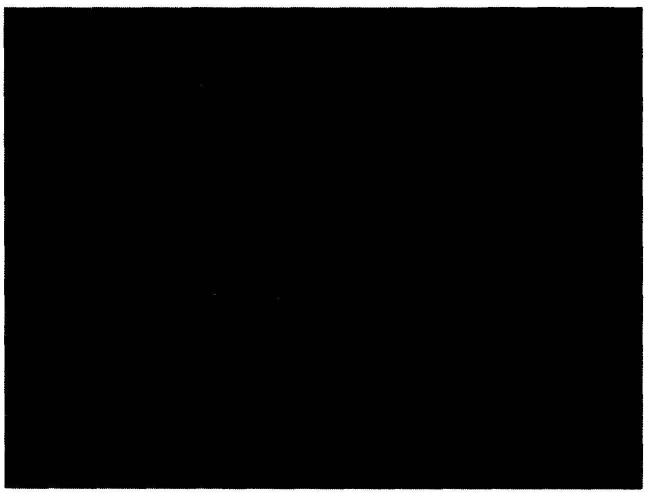

Figure 18: Extruded PVC pipe

Based on the properties of making this type of PVC one would suspect that it would be difficult to injection mold this material. It was most likely extruded into its current shape. The hollow center would also show this type of material which would not necessarily be the best for overall general use. In terms of shrinkage PVC is known for a low values due to its resistance to heat after being formed. The expected shrinkage in these types of parts is about 0.002mm-0.003mm. Despite these facts testing will not be done on PVC due to the chlorine in its structure.

HDPE

High Density Polyethylene was also run on the injection molding machine in the lab. Initially, parameters had to be chosen for operation so that an effective part could be produced. In this case, it was decided that HDPE should be run anywhere in a range from 350°-500°F. The first trial of yo-yo parts would be run at 350° in order to start off conservatively. Additionally, the cooling time would be chosen at 10s for sufficient hardening time for the part. The results of this run can be seen in Figure19.

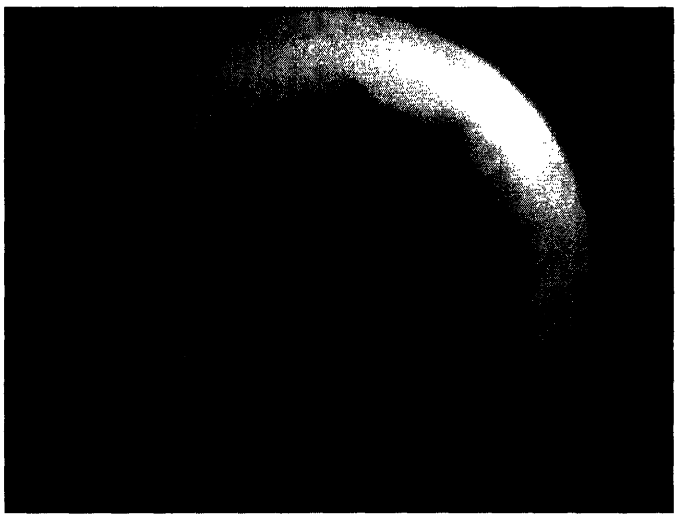

Figure 19: HDPE Yo-Yo Product at 350 F

After close examination of this part, it is clear that HDPE held to its characteristic properties. The products were milky white and rigid. The parts were in fact somewhat brittle due to the fact that when pressure was applied to the polymer, white abrasions began to appear within the plastic. This discoloration was not that good for appearance as it could be clearly seen on the sample. The other most notable factor on the parts was the fact that it appears as though some burning had occurred. There were visible dark spots on the HDPE samples especially within the inner ring of the part. The burn marks suggest that the temperatures of the injection molding machine were somewhat high but this was unlikely as the base temperature for molding was selected for the plastic.

The intimate details of the curved part were also investigated as one goal of this experiment was to determine how well this part could actually be molded into a specific design. The optical comparator yielded the following product in figure 20 below.

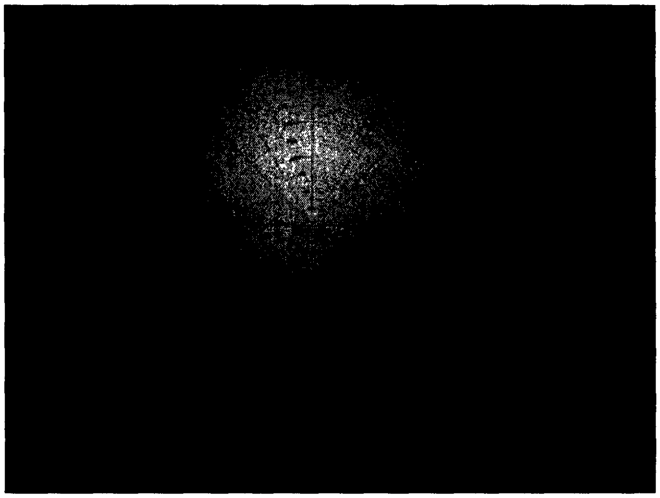

Figure 20: HDPE Optical Comparator View

Here, it is clear that HDPE can be used for many applications since it was able to handle the contours of the mold well. There were very few imperfections in terms of the quality of the part. The flash which was noticeable in PP was no longer present in this yo-yo part. One visible asset of this part was the dots which could be seen directly above the peak of the crevices. This slight abrasion appeared as though some of the part was being pinched when it was molded. A possible explanation for this is the fact that when shrinkage occurred, some of the plastic material was trapped and left in the forms of small dots. As a result, the shrinkage of the part was considered next for examination. In terms of shrinkage, HDPE had a mediocre performance. The outer diameter experienced about 1.4% shrinkage. Generally, the shrinkage for this type of material is higher than most of the other plastics ranging 1-6.

A second test was also run to vary the parameters and discover whether a slightly better product could be made. The temperature would then be increased to 400°F while keeping the cooling time constant due to the quality of the previous part. Once again the machine yielded a part similar in quality. (Figure 21)

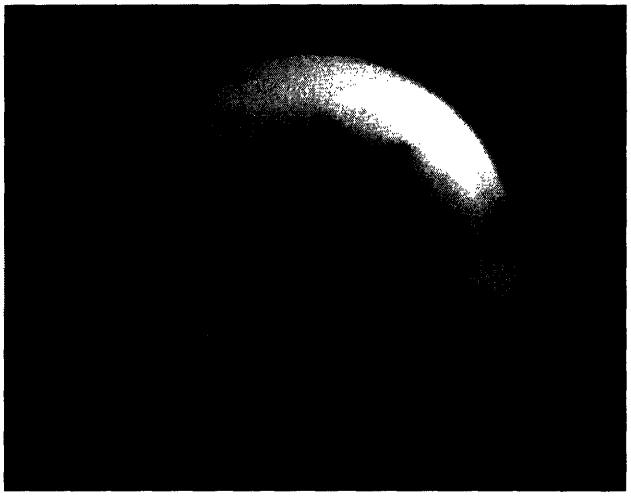

Figure 21: HDPE Second Test

After looking at this part there was not a clear improvement in the quality of the piece. It could also be seen that there were small abrasions on the surface of the material which show how the material formed while it was cooling.

The shrinkage increased dramatically as it moved to 2.7% as opposed to the previous value of 1.4% in the first trial. It was evident here, that the shrinkage in the part was result of the heat which was applied to the mold. Therefore slightly lower temperatures would be recommended for use in many applications Overall this type of plastic was able to produce a decent quality yo-yo part despite shrinkage and blemish issues. Its applications can be seen in plastic milk containers as shown below.

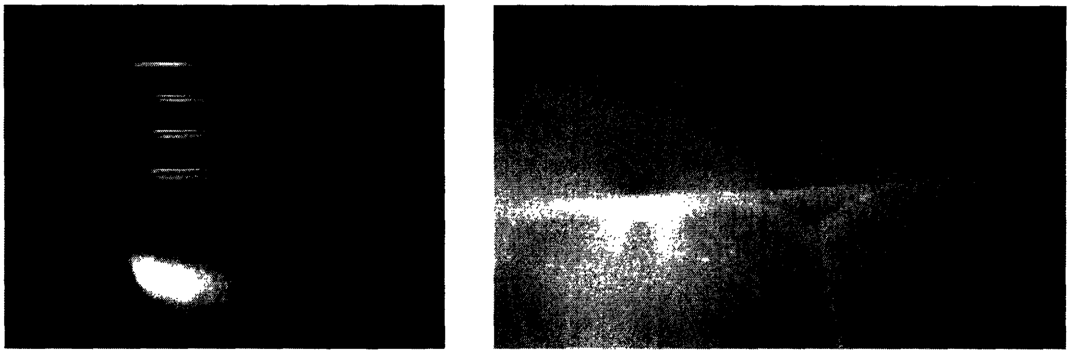

Figure 22: HDPE Applications in Milk Containers

LDPE

Low Density Polyethylene was the next plastic used in the experiment. It was used similarly to its high density form in HDPE. However, the temperature range for injection molding was slightly lower due to the structure of the plastic. Therefore, it was decided that LDPE should be run at a temperature range of 250°-450°F. This way melting or overheating the part could be avoided. The first test was then set at 300°F. As always, the cooling time was set to a standard of approximately 10 seconds. The first test appeared as follows (Figure 23).

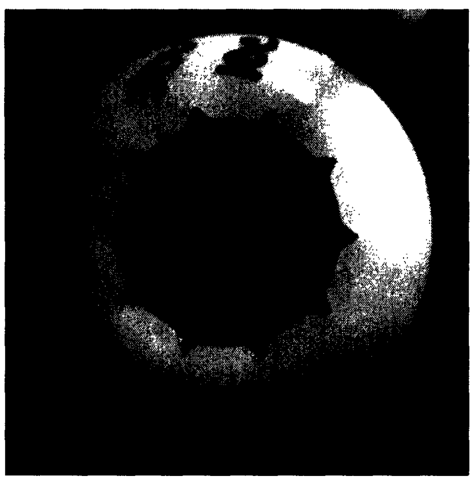

Figure 23: LDPE First Experimental Results

The yo-yo part appeared as expected in this case, despite LDPE being known for its film like applications and qualities. The part physically appeared to be clear and with no blemishes from molding. The weld lines in fact were not even visible on the part unlike PP and HDPE. Another major property was the fact that the parts were extremely flexible. A yo-yo piece could be held and deformed using one's hands unlike PP which was extremely rigid. The flexibility of the part showed why LDPE can be very useful with plastics which must undergo a significant amount of wear and tear.

In reference to its ability to make a part which had sharp and detailed corners, LDPE was also a very good product for use. The part was also viewed in the comparator for closer analysis. (Figure 24)

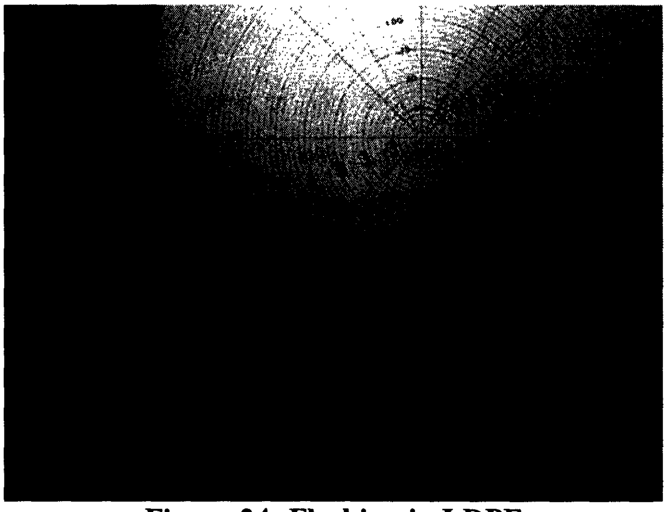

Figure 24: Flashing in LDPE

The picture above shows that the low density polyethylene was capable of being molded into the desired part but there was some flashing which had occurred. When placed in the comparator, approximately one bar or 0.125mm of flash could be seen within the part. This was less significant than the flash which was observed in the Polypropylene runs mentioned earlier.

The shrinkage of the part was an improvement over that of HDPE due to the fact that the percentage of shrinkage was measured to be only about 1%. Such a value was very acceptable in this case especially for a product which could be deformed so easily. Generally, the shrinkage for LDPE is generally ranged from 0.007-0.025mm which is quite small. In this particular application it was found that there was minimum shrinkage, thereby being placing it in the expected range.

Once again the temperature was also varied in order to show contrast with parts or if there would be any visible changes. As a result, the temperature was increased to about 350°F. Figure 25 shows the results of this second trial

Figure 25: 350°F Test Results for LDPE

Here you can see no difference between this and the first part, in terms of overall quality. The shrinkage, however, did vary as it was a value of 0.5%. This was a very drastic result as the parts were able to hold a better mold diameter given an increase in temperature. It is definitely clear that the plastic can be shaped into any type of mold which is desired. Therefore the applications for LPDE are quite broad. This can be used in products like plastic bags Figure 26 or simply blended with other plastics to help make a different plastic with similar material properties.

Figure 26: LDPE Plastic Bag Sample

PS and Other

Finally, PS is the last type of plastic which could be analyzed in its recycled state. This plastic can be molded in many different types of shapes and sizes. It also seems to hold several geometers very well. PS is also very clear as it can be used in medical applications such as medicine cups (Figure 17) below.

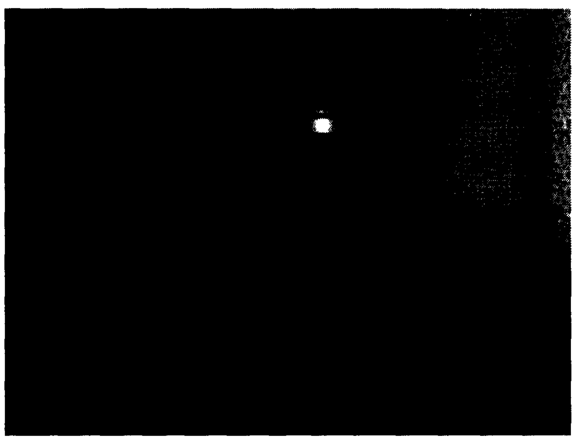

Figure 27: PS Medicine Cup

PS like LDPE did not show any blemishes but it does seem like it is easy to scratch when under a little bit of pressure. Likewise in the shrinkage area, PS is known to be almost as low as PVC ranging from 0.004-0.006mm meaning that small and precise parts can be made. Despite these effects, it seems as thought PS would be better if it is blended to help make better plastic properties.

The last part of the experiment was to test how plastics can be mixed in order to make other types of products. This is very relevant as all recycled plastics have another plastic or additive placed in it for the resin to regain its initial material properties. Therefore, special care must be made when mixing or regrinding plastic so that a quality product can be made. Such an effect can be seen when PS was mixed with PP and one other polymer that might be classified in category # 7. The results of the experiment yielded the part shown in Figure 18.

Figure 28: PS Blend Results

If one looks closely, one can notice a major difference in this part in relation to the part made out of PP. Here by using the comparator one can see that this plastic does not have trouble in terms of having flashing. It appears as though there is more shearing in this product. The PS blend is not able to make the sharp corners properly and instead shreds (Figure19).

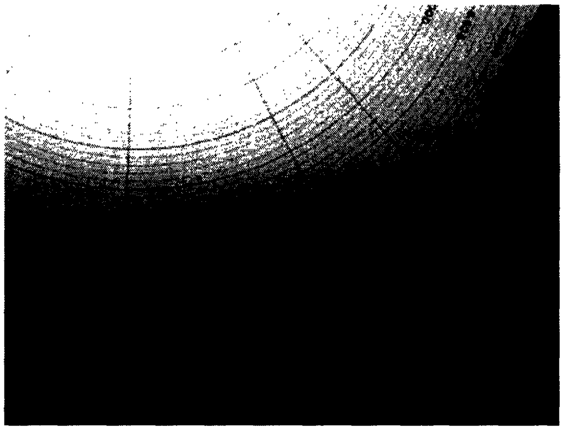

Figure 29: Shearing in the Part

Another noticeable feature was the weld lines. Several of the weld lines were cracked and falling apart. This could be attributed to the material properties of the product were now much more brittle (Figure 20).

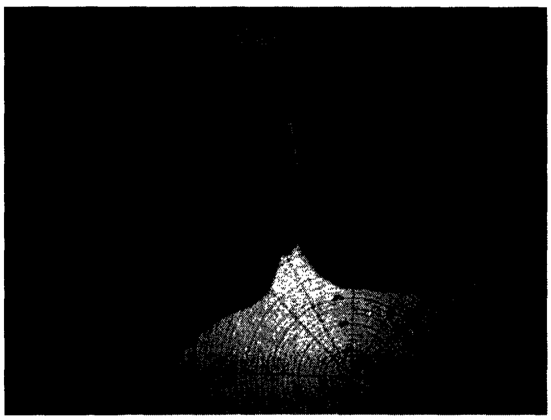

Figure 30: Defects in PS Blend

Further analysis leads to the possibility that the wrong temperatures were used during the experiment. However, lower temperatures were investigated and weld line imperfections still existed.

The results from this part would not be good for many applications as the blend does not have any special properties. That type of behavior is very typical of a blend due to the fact that the quality of the material properties decreases every time a certain part is recycled. The blend also shows how some of the qualities of the PP which was evident in the blend still exist. The part had the milky white appearance of normal PS but it could be seen through close inspection that there were swirls showing where the PP was situated.

A second type of blend was made to make those swirls much more clear. Figure 21 shows a blend where Polypropylene is the more dominant of the two plastics which were being placed together.

Figure 31: PP Dominated Blend with PS

Afterwards, a test was made simply to look at that shrinkage that affects the blend. The initial part was tested for shrinkage and it was determined to be 1.4%. This means that the part can be made for small details but may crack under any other conditions. The blend which had the higher traces of PP had a shrinkage of 1.3% which was the lowest of the shrinkages that have been found thus far. Therefore the blend had very specific properties that were undermined by being too brittle to be properly applied to other applications.

Mixed Plastics

The experiment showed how plastics can be suited for several applications based on their material properties. Quality was based on how well they could produce one of the yo-yos or how well plastics handled their general home applications. One of the most interesting points is to note that plastics can be mixed or reground in order to make certain blends with special characteristics. This fact is very important within the recycling realm as it is needed to remake parts. The initial step in preparing these plastics is to be aware of what types of plastics can be mixed together. A simple way to do this is to look at the melting temperatures of the given plastic and use that as a marker for the plastics that can be pared together (Table 2 below).

Table 2: Melting Temperatures for Plastics 1-7

Recycled Plastics	Melting Temperatures $^{\circ}C$
PET	212-265
HDPE	122-124
PVC	75-105/ 150-220 *
LDPE	98-115
PP	160-175
PS	100-120/210-249*

One of the most used plastics in the mixed plastics segment is PP. This particular plastic is missed with others like HDPE, LDPE, PS, PVC, ABS, and other PP copolymers which have a different make up from normal polypropylene plastics. This relates to such applications like PP & PS which are used to make yogurt cups, HDPE & PP which are used to make the plastic flower pots. Other popular blends are with PC & PP which are utilized in car bumpers. One of the most important aspects to note is the fact that no recycled plastic actually has an affinity for another plastic. Often when these plastics are mixed they do not go well together due to the fact that they combine in different phases. Consequently, stabilizers need to be added to the plastics in order for bonding to occur. It is only in the presence of these stabilizers that these plastics are actually able to hold themselves together. The additives which are placed in the material after recycling show just how unreliable some forms of mixing parts are. Special care must be used when selecting the plastics so that a high quality product can actually be produced.

Currently there are several mixes which do help improve the usage of other plastics. This can be seen in blends with Polycarbonate which help make the material easier to machine and ductile in general. These benefits, however, come at a price as once they are created

* Varies depending on state of plastic

it is very difficult to recycle the product due to the fact that having several different types of compounds present would lead to having impurities and instabilities in the plastic. Overall this would lead to a lower quality product in the long run.

Further Research

After completing the experiment other issues are still left unanswered. One of the central problems that come to mind is why there is not a greater move towards recycling in the corporate industry if it is actually possible to recycle most of the 6 different types of plastic. Although a significant amount of plastic can be recycled, practicality of recycling should also be considered in the decision of what products should actually undergo treatment. Factors such as economics play a huge role in what types of plastics make sense to recycle. The companies which actually manufacture plastic products rather spend time working with virgin material rather than using recycled materials. This occurs due to the fact that the lower price of recycled plastics is usually a result of a lower quality product. Earlier in the plastics section it was clear that recycling products takes a large amount of effort because it is difficult to get the exact same material properties from reused plastic. Therefore the appeal of recycling is lessened due to a possible loss in quality. Manufacturers would rather deal with a resin which they know is brand new can be trusted in terms of reliability.

The other reason which can be investigated goes into the actual cost to recycle these products. The process of recycling requires collection and sorting. Nonetheless, sorting can be very difficult if certain plastics like PP or PVC are not completely purified before the recycling process begins. For that reason, more time and money must be placed in making sure that the plastic is safe and durable in some applications. Here, money is also lost in the reclaiming cost as it would cost extra money to convert the raw material to the plastic product. As a result, most plastics are just not economically smart to recycle at the present moment. Currently, the main plastics which are recycled are PET and HDPE. These plastics earn their value as a result of the fact that they can reproduce a similar quality product over a long product life.

Conclusion

In conclusion, the research and experiment show that it is possible to actually reuse a lot of the products which we do see in the seven categories of products being produced today. However, this process is not completed due to the fact that companies and other industries will lose money if more time and effort is placed into recycling products. Clearly one of the most important factors which affect this decision pertains to the quality of the plastic versus. the cost of the plastic. In this case, it is clear that the price may be lower but after plastics are recycled they have been known to be lacking in some material properties. Companies would place themselves at greater risk if they purchase plastic that might fail or not be as durable as it is in its virgin form. As a result, some plastics are mixed with others in order to gain better attributes for product applications. These new types of plastic, however, still cannot measure up to the performance that some plastics give in their virgin form. Currently a larger recycling scale may work or products of PET and HDPE but the other categories namely, numbers 3-7 are recycled in moderation. The current technologies for recycling do in some cases validate the push to increase recycling to many other plastics. However this effort is counteracted from an economics perspective as a more significant recycling program will not be in the best interests of any companies looking to lower their costs and make more money. Therefore recycling other plastics would not be sensible due to the higher costs needed to ensure better quality products.

Appendix A

Table 3: Market Prices for Virgin & Recycled Plastic

Plastic	Virgin Pellets cents per/lb	Recycled Pellets cents per/lb
PET	54-64	42-51
HDPE	39-55	34-49
PVC	DNE in this form	20-29
LDPE	40-47	25-30
PP	41-51	29-37
PS	34-39	22-27

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