Investigation and Multi-Response Optimization of Process Parameters in Stretch Blow Molding of PET Plastic Bottles to Minimize Defects

Henok Hailu Merga

A Thesis submitted to

The Department of Mechanical Design and Manufacturing Engineering

School of Mechanical, Chemical and Materials Engineering

Presented in Partial Fulfilment of the Requirement for the Degree of Master's in Manufacturing Engineering

Office of Graduate Studies

Adama science and Technology University

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February, 2022

Adama, Ethiopia

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Advisor:

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DECLARATION

I hereby declare that this Master Thesis entitled "Investigation and Multi-Response Optimization of Process Parameters in Stretch Blow Molding of PET Plastic Bottles to Minimize Defects" is my original work. That is, it has not been submitted for the award of any academic degree, diploma or certificate in any other university. All sources of materials that are used for this thesis have been dully acknowledged through citation.

Henok Hailu Merga	______________	______________
Candidate	Signature	Date

RECOMMENDATION

I, the advisor of this thesis, hereby certify that I have read the revised version of the thesis entitled "Investigation and Multi-Response Optimization of Process Parameters in Stretch Blow Molding of PET Plastic Bottles to Minimize Defects" prepared under my guidance by Henok Hailu Merga submitted in partial fulfillment of the requirements for the degree of Master's of Science in Manufacturing Engineering.

Therefore, I recommend the submission of revised version of the thesis to the department following the applicable procedures.

Dr. Devendra Kumar Sinha	________________	______________
Advisor	Signature	Date

APPROVAL SHEET

I, the advisor of the thesis entitled "Investigation and Multi-Response Optimization of Process Parameters in Stretch Blow Molding of PET Plastic Bottles to Minimize Defects" and developed by Henok Hailu Merga, hereby certify that the recommendation and suggestions made by the board of examiners are appropriately incorporated into the final version of the thesis.

Dr. Devendra Kumar Sinha	________________	______________
Advisor	Signature	Date

We, the undersigned, members of the Board of Examiners of the thesis by Henok Hailu Merga have read and evaluated the thesis entitled "Investigation and Multi-Response Optimization of Process Parameters in Stretch Blow Molding of PET Plastic Bottles to Minimize Defects" and examined the candidate during the open defense. This is, therefore, to certify that the thesis is accepted for partial fulfillment of the requirement of the degree of Master of Science in Manufacturing Engineering.

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Finally, approval and acceptance of the thesis is contingent upon submission of its final copy to the Office of Postgraduate Studies (OPGS) through the Department Graduate Council (DGC) and School Graduate Committee (SGC).

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Office of Postgraduate Studies, Dean	Signature	Date

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ACRONYMS

ANOVA= Analysis of Variance

ASTM= American Society of Testing and Materials

ASTU= Adama Science and Technology University

BPH= Bottle per Hour

COV= Covariance

DIC= Digital Image Correlation

DOE= Design of Experiments

GRA= Grey Relational Analysis

GRC= Grey Relational Code

HMI= Human Machine Interface

HSR= Hoop Stretch Ratio

HTGRA= Hybrid Taguchi-Grey Relational Analysis

IR= Infrared Radiation

ISBM= Injection Stretch Blow Molding

IV= Intrinsic Velocity

MFR= Mass Flow Rate

PET= Poly ethylene terephthalate

PLC= Private Limited Company

PSW= Plastic Solid Waste

SBM= Stretch Blow Molding

SEM= Scanning Electron Microscope

S/N= Signal to Noise ratio

Tg= Glass transition temperature

Tm= Melting temperature

TS= Tensile Strength

WT=Wall thickness

ABSTRACT

Plastic waste in (PET) Polyethylene Terephthalate bottles is posing new challenges, which in the current situation is a major concern in every industry. The defect in PET bottles mainly occurs due to improper selection of levels of process parameters during the production process. Therefore, optimizations of process parameters are very important to minimize defects produced due to improper stretch blow molding process parameter selections. The study is carried out on 2liter bottles since they have the highest demand and the highest defect rate in the PET bottling sector. In this research, the PET bottles have been developed from the preform at various blowing temperature, blowing speed and blowing angle on commercially available SBM setup. The design and plan of experiments have been done according to L9 orthogonal array of Taguchi method. The optimization of process parameters have been done through the hybrid Taguchi-Grey Relational Analysis (GRA) optimization technique on four factors namely: blowing temperature, first blow angle, second blow angle and blowing speed. The each value of parameter was taken at three levels in combination. The testing of all samples such as tensile test, wall thickness measurement and hoop stretch ratio measurement have been carried out as per ASTM standards. The morphology of the samples has been carried out through (SEM) Scanning Electron Microscope. A maximum tensile strength of 65 MPa, minimum hoop stretch ratio of 5.45 and a maximum wall thickness 0.24mm was found at varying process parameter combinations. Among the process parameters, it has been discovered that: blowing temperature was the most significant factor for minimizing defects while second blow angle was the least significant parameter. It was found that optimized values of the process parameters yielded 15% reduction in defects on PET bottles. The present study is expected to contribute significantly for the industries working in this field for carrying out production at optimum levels of process parameters for defect free products.

Keywords: Stretch Blow Molding, Hybrid Taguchi-Grey Relational Analysis, Process Parameter Optimization

CHAPTER ONE

INTRODUCTION

1.1. Background of the study

Bottled water is consumed all around the world as a necessity and a personal preference. People who needed bottled water lived in locations with poor water cleanliness, such as underdeveloped countries, despite the fact that vessels to bottle and transport water were part of the earliest human civilizations. People who choose bottled water despite its higher cost tend to reside in locations where clean water is already readily available, such as poor countries such as Ethiopia. These preferences for bottled water are partly based on flavor and convenience, but they are mostly influenced by bottled water companies' marketing activities.

Bottled water is more common today, which means more sales and more costs (Sevigny et al., 2017). Bottled water usage worldwide reached 3 billion hectoliters in 2014. According to estimates, the global rate of consumption increased by 7.6% in 2017. Per capita consumption increased by 3 liters to 50.1 liters, up from 47.1 liters in 2016 (Sinha et al., 2018).

Tap water and bottled water are the most popular water supply methods for human use. The former is provided through aqueduct and is available to consumers at the tap, while the latter includes drinking water sold in glass or PET bottles on the market. Over the last decade, lifestyle changes have fueled the rise of the bottled water market, with more and more glass packaging being replaced by plastic (Isabella et al., 2020). About 4% of the world's oil and gas production is utilized as a raw material for the manufacture of plastics, with the remaining 3–4% used to supply energy for their manufacturing (Hopewell et al., 2009). Furthermore, the majority of plastic generated each year is utilized to create short-life packaging that swiftly degrades in the environment, accumulating and damaging natural habitats around the world due to the resilience of polymers (Sinha et al., 2018).

Plastic bottles are becoming increasingly popular, and polyethylene terephthalate is one of the plastics that plays a vital role in everyday life. This well-known clear plastic can be found as a container for a water bottle or a soda bottle. PET is a polyester-based thermoplastic polymer that can be used for a variety of applications. Polyester resins are well-known for their exceptional mix of mechanical, thermal, chemical, and dimensional stability qualities. PET plastic bottles are extensively used for mineral water and carbonated soft drinks because it is an excellent water and moisture barrier material.

PET exists in three distinct states;

1. Preforms and melted plastic resin are amorphous, non-oriented, and clear.
2. Thermally crystallized (by temperature), such as resin pellets
3. Crystallized due to strain, such as bottle side walls

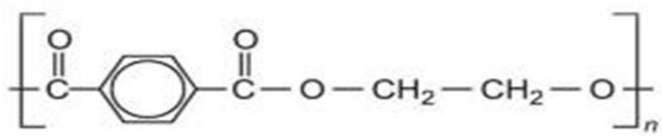


Figure 1.1. Molecular structure of PET (Kruszelnicka et al., 2018)

PET chemical formula: **$(C_{10}H_8O_4)$ n**

Preform, a semi-finished product, is used to make the PET bottle. PET preforms come in a variety of colors, shapes, and sizes. Parameters including thread weight, wall thickness, and length are used to define the PET preform. We can determine the volume and extent to which the preform bottle can be blown based on these factors (Kruszelnicka et al., 2018). A view of an exemplary PET preform is shown in Figure 1.2.

Figure 1.2. PET bottle preforms (Image courtesy of Roha pack PLC)

Transparent bottles are typically made via blow molding. Blow molding is a process for making glass containers such as bottles and jars that was developed thousands of years ago. The automated blow molding technique, as it is now known, has advanced rapidly over the previous century, expanding the variety of applications and material diversity. Despite the fact that blow molding has been around for a long time, producers are still having trouble optimizing and managing the process. (Groot et al., 2011).

Injection blow molding, extrusion blow molding, and stretch blow molding are the three primary blow molding techniques used in the production of polymer containers. In injection blow molding, a polymer preform is created by injecting a polymer melt into a tube-shaped mold, then transferring it to another mold where the finished container is blown by inflating the preform with air. Small or wide-mouthed containers are typically produced by injection blow molding. Before being blown into the container shape, the polymer melt is extruded into a preform shape. Extrusion blow molding can produce a wide range of container forms and has a high overall production rate. Finally, stretch blow molding is a prominent production method. Finally, stretch blow molding is a common industrial technique used to make PET (polyethylene terephthalate) bottles. (Groot et al., 2011).

Injection molding is used to create the bottles, which is then distorted radially by air pressure and axially by a stretch rod. Pre-blow and final-blow are the two stages of the air pressure load. The pre-blow shapes the majority of the bottle, while the final-blow applies more pressure to create the final detailed form. The final bottle quality is influenced by the processing circumstances and the PET qualities (Demirel et al., 2009).

The stretch blow process is seen schematically in Figure 1.3. The preform is first inserted into a mold from the stretch rod (Figure 1.3(a)). Injection molding of a polymer melt is commonly used to create the preform. The preform is then stretched with the stretch rod and inflated with pressured air at the same time (Figure 1.3(b) and (c)). After cooling, the resulting container is expelled from the mold (Groot et al., 2011).

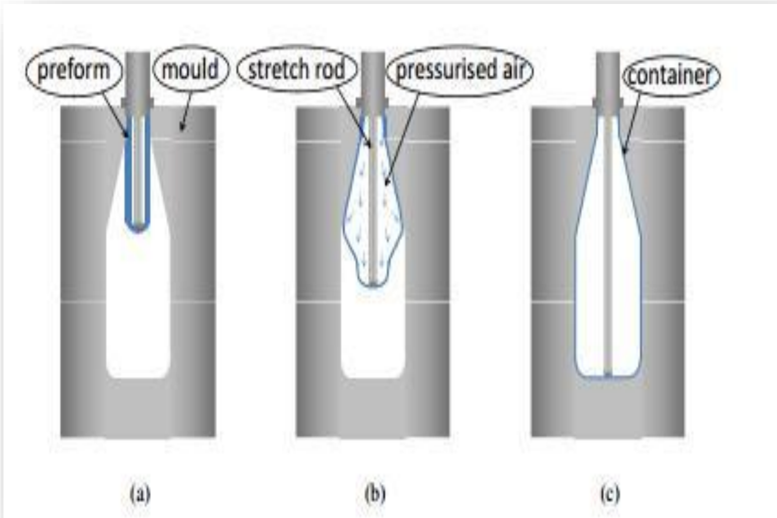


Figure 1. 3. Schematic Drawing of a stretch-blow molding process (Groot et al., 2011)

The primary goal of any manufacturing company is to provide high-quality items with a low rate of defective products. It is critical to eliminate these flaws in order to improve quality. Although the underlying principles of stretch blow molding PET bottles are straightforward, the actual mechanics of the process can be complicated. Major influences include the quality of the preform and its thermal profile right prior to blowing. The process parameters also have a significant impact on the procedure's final outcome.

Plastic products' potential and benefits include low manufacturing costs, excellent durability, and variety in application. A great number of favorable characteristics also represent well-known production issues that have negative consequences for the natural environment, climate, and human life and health (Kruszelnicka et al., 2018).

1.2. Statement of the problem

The demand for plastic bottles is steadily increasing. The blow molding process is used to make these plastic bottles. Defects are the most common problems encountered during the blow molding process for producing plastic bottles. These flaws can manifest themselves in a variety of ways, as stated below.

- Uneven wall thickness
- Burst bottles

- Small stretch ratios
- Pearlescence and haze
- Deformed bottles
- Bubbles on the surface of the bottles
- Formation of several layers of the bottle
- Not fully formed bottles

Among these defects, the major occurring ones in the industry are deformed bottles and burst bottles. These major defects are shown in figure 1.4.

Figure1.4. Major observed defects

These flaws develop as a result of a variety of circumstances in the SBM process. These issues can take many different forms, including incorrect process parameter selection, raw material quality, operator skill, machine failure, power outages, and maintenance failures, among others. However, the most significant contributor is the incorrect selection of the process parameters involved in the process.

The stretch blow molding process parameters have a significant impact on the product's quality and cost. Defects in PET bottle products are caused by incorrect process parameter selection. Trial and error procedures are used on SBM machines in the mineral water bottling business to achieve a better quality product. This strategy, however, is ineffective due to unnecessary trial runs, time spent, and the fact that it does not demonstrate the interaction between components (parameters).

To reduce flaws in SBM, main process parameters that affect end bottle quality, including as blowing temperature, blowing speed, and first and second pressure blow angles, must be optimized. For defect-free and high-quality products, the best selection of such factors is critical.

1.3. General objective of the study

The major goal of this thesis is investigate and perform multi-response optimization of process parameters in stretch blow moulding of PET plastic bottles to minimized defects.

1.4. Specific objectives of the study

To achieve the main objective of the thesis, the following specific objectives are designed;

1. To carry out the fabrication of plastic bottles on commercially available SBM machine as per the experimental design.
2. To carry out various tests such as tensile test, wall thickness measurement and hoop stretch ratio for the fabricated bottles as per ASTM standards.
3. To carry out the morphology of samples extracted out of developed products.
4. To carryout multi response optimization of process parameters using a Hybrid Taguchi-Grey Relational Analysis (HTGRA).
5. To predict and confirm the optimum levels of parameters at which defect free products occur.

1.5. Scope of the study

The study was focused on the multi-objective parametric optimization of the major product affecting parameters involved on SBM. This study involved the experimental investigation of PET bottles on SBM. From experience working as an operator of stretch blow moulding it is seen that the majority of defects are occurring on 2 liter bottles and hence this study is done specifically on 2L bottles. Any referenced PET bottle on this test refers to 2L bottles. Minitab software was used for optimization and also excel was used for graph generation and some minor calculations. Optimization and identification of optimum process parameter configuration for an ideal product was detailed in this study.

1.6. Significance of the study

The outcomes of this research will reach out to the numerous plastic mineral bottling companies in this country especially the startup companies which may suffer heavily due to lack of experience. Since waste reduction has become the main goal of any business oriented organization, the optimized process parameters of this study can be of great importance to achieve this goal. As a result of the waste reduction that will result from the optimized parameters, society will also be benefited from fewer landfills and high quality products.

1.7. Research motivation

The rising concern for plastic waste is becoming a major issue throughout the country. Plastic wastes are being produced and dumped daily around the country on a daily basis. Most factories give little to no attention on the rising concern of environmental pollution caused by plastics as result of these wastes as long as profits keep coming in. Plastic water bottling companies are one of these beneficiaries of the plastic waste. These wastes are being produced as a result of improper process parameters which lead to a high percentage of waste production. And since plastic cannot be recycled naturally and since it takes a very long time, it is a major concern for nature. This study provides a solution for this improper process parameter selection and, in turn, in the minimization of process defects and hence the motivation to carry out this study.

1.8. Organization of thesis

This thesis consists of five chapters;

Chapter One: The study begins with an introduction that includes a background on the study, a statement of the problem, the study's general and specific objectives, the study's scope, significance, and motivation.

Chapter Two: is concerned with the literature review, which is made up of several research publications linked to the SBM process and sheds light on the effects of the various parameters while analyzing the research gap. Finally, a summary of the many papers reviewed is displayed.

Chapter Three: The experimental details, such as the material utilized for the experiment, the machine used, the testing sets, the optimization techniques and software employed, and the methodology that achieved the study's aims, are briefly discussed in this chapter.

Chapter Four: The outcome and discussion of the experimental values are covered in this chapter. It examines the influence of process variables and demonstrates how improved outcomes contribute to defect reduction.

Chapter Five: The study's experimental studies are summarized in the last chapter, along with recommendations for further research.

CHAPTER TWO

LITERATURE REVIEW

2.1. Introduction

In this chapter, previous studies that are relevant to this investigation are reviewed within the scope of the current investigation. The consequences of the SBM process are frequently mitigated by selecting the right procedure parameters. The optimization of process parameters is a critical issue for the SBM procedure to improve the nature of PET bottles, minimize errors, and enhance production rate. Numerous research have been conducted on the SBM process, as well as process optimization and testing, in order to achieve an ideal manufacturing process and a better knowledge of the various phases and elements involved.

2.2. Characteristics of PET

The average molecular weight, which is normally estimated by measuring the Intrinsic Viscosity, has a big impact on the PET polymer's properties (IV). The molecular weight increases as the IV increases. Depending on the size of the preform, the IVs utilized in preform injection molding range from 0.72 to 0.88. The density measurement of the preform determines its degree of crystallinity. At ambient temperature, amorphous PET has a density of 1.335 g/m3, but the predicted density of a perfect PET crystal is 1.455 g/m3. An increase in IV slows the process of crystallization, making it more difficult for a chain to form an ordered crystal by separating from other chains (Battini et al, 2020).

PET is thermally crystallized to a level of 50-70 percent as resin pellets. Spehrulites are enormous structures made up of thermally generated crystals that reflect light. As a result, PET appears white (Ottmar Brandau, 2012).

These crystals are melted during the injection process, resulting in an amorphous melt that is injected into the preform mold cavities. To avoid recrystallization, the preform is rapidly chilled. As a result, preforms lack a crystal structure. Amorphous describes this state. The molecular chains in the amorphous state have no direction or crystallinity, and their look has been compared to that of a dish of spaghetti. Because there is nothing to reflect light, the PET is clear. It also lacks the strength and barrier qualities of other materials (Bordival et al., 2009).

Stretch blow molding causes the amorphous chains in the preform to be stretched and orientated, resulting in a distinct type of crystallinity. The chains are oriented and imposed a linear ordered structure throughout the area where tension is applied by aligning them in the direction of stress. This "stretched chain" or stress-induced crystallinity is required for mechanical strength in the blow-molded container (Meen et al., 2018).

The completed bottle will include amorphous areas in the neck and gate where the bottle was not extended, orientated portions in the sidewalls, and occasionally thermally crystallized portions surrounding the gate, which is a frequent preform defect that cannot be remedied during blow molding (Ottmar Brandau, 2012).

2.3. Relevant Process Parameters

Bottles must meet a variety of performance parameters, including top load, thickness distribution, transparency, and barrier qualities, in order to meet the performance specifications set out by water, dairy, and juice makers. Blowing temperature, heat profile along the preform wall, blowing pressure, stretch ratios, wall thickness distribution, and air blow time are all parameters that influence the compromise between optimal bottle quality and cost considerations. Biaxial stretching and process heating conditions are the two key factors that influence the final qualities of a bottle. The temperature of the preform distribution regulates the blowing kinematics (stretching and blowing) and, as a result, the bottle's wall thickness distribution. In the last decade, numerical optimization approaches for SBM have gotten a lot of attention as a way to replace the costly, time-consuming, and inefficient trial-and-error method employed by operators and factories (Alzanki et al., 2019).

2.3.1. Blowing temperature

In SBM, temperature is one of the most critical variables. However, measuring and predicting it remains a sensitive undertaking, particularly in the direction of wall thickness. The orientation caused by biaxial stretching is affected by temperature, as are the mechanical, optical, and barrier properties of bottles (Alzanki et al., 2019).

The glass transition temperature (Tg) and the melt temperature are the temperature ranges for crystallization (Tm). Because the polymer chains' mobility is substantially restricted below Tg, the resin is regarded as "glassy," and they are basically held in place regardless of whether they are amorphous or crystalline. The polymer chains have too much energy above Tm to create stable ordered structures, resulting in amorphous molten resin. The polymer chains have enough energy between Tg and Tm to reorganize themselves into the most thermodynamically favorable configuration, causing the resin to crystallize. When the temperature rises above 65 degrees Celsius, PET begins to soften. PET has a glass transition temperature of roughly 80 degrees Celsius and a recrystallization temperature of over 115 degrees Celsius. As a result, the process temperature is maintained at roughly 100 degrees Celsius (Ottmar Brandau, 2012).

2.3.2. Blowing speed

The blowing speed is characterized by the amount of bottles a stretch blow molding machine can blow in an hour. It has a unit of Blt/Hr (bottle per hour) which may vary depending on the machine specification and the bottle size being produced. With a lightning speed, the stretch blow molding machines can blow thousands of bottles within minutes. For smaller size bottles (600ml PET bottles), the blowing speeds reach from 24,000 blt/hr – 48,000 blt/hr depending on the machine specification. For a larger bottle design (around 2 L), the blowing speed may reach around 18,000 blt/hr. Higher blowing speed doesn’t necessarily lead to a higher production rate. The faster the blowing speed the higher the temperature must also be and the more unstable the process may be also. So an optimum level of blowing speed must be used in order to utilize the raw material and to reduce energy costs that may incur.

2.3.3. Blowing Pressure angles

One of the most important components of a PET stretch blow molding machine is compressed air. It is what allows the customer's plastic bottle, container, or jar to expand and form. For one thing, incorrect pressure would prevent the product from stretching properly. As a result, you'd be wasting a lot of time, energy, and money creating inefficient products.

Another factor to consider is that if the pressure is too high, we may wind up paying more for the SBM procedure than is necessary. It all boils down to applying the proper amount of pressure to stretch the preform without wasting money or causing product problems. Installed air compressors for a high-volume stretch blow molder with PET material typically range from 2000 to 4000 horsepower.

A minimum blow air pressure of 35 bar is required for most bottles, with a maximum of 40 bar. Compressed air accounts for around half of the energy cost of bottle production, and increasing air pressure raises overall bottle costs. Recycling high-pressure air for pre-blow pressure is becoming a common practice to save energy and money.

A preform is blown in two stages as discussed in the first chapter. These stages are:

1. Pre-blow (first blow): the initial inflation of the bottle with a smaller pressure used to form majority of the bottle.
2. Final blow: the final blow exerts a higher pressure to produce the final detailed form of the PET bottle.

The pre-blow and the final blow are controlled by an angle of actuation on the blowing machine. On rotary blowing machines, the process inside the blow mould cavity runs its course on the bottle in 6 stages namely: Seal, stretch, first blow, second blow, recovery and finally exhaust. From these the first blow and the second blow stages are the most effective parameters in which the pressure is utilized. Optimization of these angles is a necessary stage of an ideal product quality.

2.4. Effects of process parameters in Stretch Blow Molding

In the plastic water bottling industry, there is a growing interest to optimize the use of raw materials in blow molded containers. With the rising concern of environmental pollution, optimization of products to reduce waste and defect has become a major research area in every aspect of manufacturing sector. Many scholars have carried out different optimization techniques in SBM process.

Wall thickness distributions are modeled using neural networks, and evolutionary multi-objective optimization techniques are employed to identify the best trade-offs between material utilization and mechanical attributes. To identify the optimal relationship between total mass and maximum strain when pressure is applied, the neuro-evolutionary approach method was effectively applied to an industrial bottle model. As a result, a collection of ideal thickness profiles has been discovered, which provide less strain under pressure while using less material (Pinto et al., 2020).

The influence of deformation rate on the final bottle thickness wall distribution was investigated numerically (Lontos et al., 2019);

- More material is transmitted to the bottom portion of the mold as the stretching velocity increases, resulting in a more uniform end product.
- The combination of high axial and radial strain rates is the key to good homogeneity along the whole length of a bottle.
- The higher the pre-blowing pressure, the more material accumulates along the bottle's middle distance, resulting in a final product with significantly thinner upper and lower sections.

The goal of the SBM manufacturing process is to achieve a uniform thickness of PET bottle. The temperature distribution on the preform's surface is largely responsible for the uniform thickness. Experimental and theoretical research on the infrared system and cooling system of the SBM machine CPSB-LSS12 to determine the best flow field in the heating box, which is the machine's main heating system, to improve temperature distribution. The results reveal that under the same fan operation conditions, a set of specified input angles provides the optimal temperature distribution. Two essential points are included in the impacts generated here for ideal flow sites. One of the points is that all of the preforms in the heating condition are processed in the same way. This is extremely helpful in ensuring product quality uniformity in mass manufacturing circumstances. Second, in the length direction of the preform, the temperature distribution induced by the flow field is highly consistent with the ideal temperature distribution (Hsieh et al., 2018).

The performance of PET bottles manufactured using the SBM method is determined by three primary factors: initial preform shape, initial preform temperature, and the balance of stretching and blowing rates. The thickness distribution in the final product has been shown to be influenced by process parameters such as the pre-blowing delay and the velocity of the stretch rod (Schmidt et al., 2007).

Using stereoscopic Digital image correlation (DIC), a unique experimental approach for obtaining the whole field strain map of a deforming bottle during the free stretch blow process has been devised. Experiments demonstrated that lowering the flow index lowered the effective deformation caused by pressure inflation when the air flow rate was reduced. As the temperature of the material grew, the magnitudes of the pressures also grew, highlighting the increase in preform deformability. Due to increasing deformability, the magnitudes of stretch-rod forces reduced as the material temperature increased. Due to dominant pressure inflation, increasing the flow index reduced the force magnitude, causing the preform to prematurely blow off the preform tip. The initial stiffness of the preform dropped considerably as the temperature of the material increased, with minimal effect from adjusting the flow index. Bottle shape and aspect ratio are determined by the degree of stretch-rod deformation relative to pressure inflation: stretch-rod dominance results in a more slender bottle shape, whereas pressure dominance results in a fatter bottle. This has an effect on the material distribution and performance of the finished production bottle (Nixon et al., 2017).

Mechanically, the mechanical and thermal reaction of the blown preforms affect the thermal stability of PET bottles created using the ISBM (injection stretch blow molding) process. The orientation and crystallization processes have the greatest impact on the mechanical and thermal properties of PET bottles at the microscopic level. The initial structure of the PET preform, the geometry and temperature distribution of the preform, the geometry of the blow mold, the temperature of the blow mold and its distribution in various parts of the mold, and technological parameters of the blow molding process determine the properties of PET bottles after manufacture by the stretch blow molding process (Wawrzyniak et al., 2020).

By examining the strain history and stress-strain relationship of PET, the effect of heating temperature and air mass flow rate on its deformation behavior was explored. The variability of the gradient in the strain hardening zone in the blowing scenario was not as large as in the biaxial stretching experiments, which was attributable to the interaction of temperature and strain rate effects. Furthermore, in the blowing situation, a sequential deformation was found, particularly in the 'low MFR (mass flow rate)' rate testing, which had a major impact on the stress-strain behavior (Yan et al., 2017).

Overall, the most important aspect of operating the SBM machine is understanding how to control the heating, cooling, and production speeds in order to maximize temperature distribution on the preform surface. The SBM machine's purpose is to ensure that the bottle has a uniform thickness. The cooling system is critical in assisting the SBM machine in optimizing the temperature distribution of the PET, as well as creating a temperature profile throughout the length of the preform, reducing heating time and reducing energy consumption by 10%. The temperature distribution for the PET will be developed by optimizing the cooling system and light heating (Bordival et al., 2009).

Increased preform length means less material concentration on the bottle neck and more material concentration on the bottom side walls, which is desired because it improves the stability of the filled bottle. One downside of the SBM process is that material accumulates in the center of the bottom section during stretching. This material concentration is useless in any way. As a result, lowering the material concentration in that location provides an optimization parameter for lowering the bottle's weight without compromising its mechanical performance. The concentration of material at the bottom of the preform decreases as the initial preform length increases, according to simulation data. 60.99 percent of the axial mold length is the best preform length (Lontos et al., 2019).

The mechanical and thermal properties of the bottle material are determined by the amounts of orientated and rigid amorphous phases. The intrinsic viscosity of the preform material, the power profile of the heating lamps in the heating oven, the heating time in the oven and the associated time of temperature-induced crystallization prior to the SBM process, the speed of the stretching rod, the pre-blow pressure, pre-blow duration, main blow pressure, main blow duration, temperature profile of the hot filling bottle are the main parameters of the hot mold SBM process that affect the properties of the hot filling bottle (there are two heat zones for the blow mold, the lateral surface of the bottles and the base zone), annealing time in the mold, bottle cooling air temperature in a blow mold fed by a stretching rod, and feed branch pressure for air cooling of a bottle in a blow mold supplied by a stretching rod (Wawrzyniak et al., 2020).

2.5. Plastic water bottling in Ethiopia

In Ethiopia, there are currently 67 water bottling firms, the bulk of which are located in the Oromia region, close to Addis Ababa, where they can reach the largest number of consumers. The water bottling plants generate almost 3.5 billion bottles of water each year, but only serve about 5% of Ethiopia's population.

According to the World Health Organization, a healthy person should drink two liters of water every day. Meanwhile, in Ethiopia, all of the country's bottle water manufacturers provide roughly 100 milliliters of water per person per day when their total production is divided by the country's population, which is close to 105 million birr. As a result of unclean tap water being distributed in many parts of Ethiopia, the number of water bottle companies is rapidly increasing. (Andualem sisay, 2018).

Ethiopia's plastic industry is rapidly expanding. Since 2011, the consumption of plastic products has increased by double digits each year, more than tripling in total. Packaging (58.4%), building (9.4%), and the automotive sector are the three most important business segments (6.6 percent).

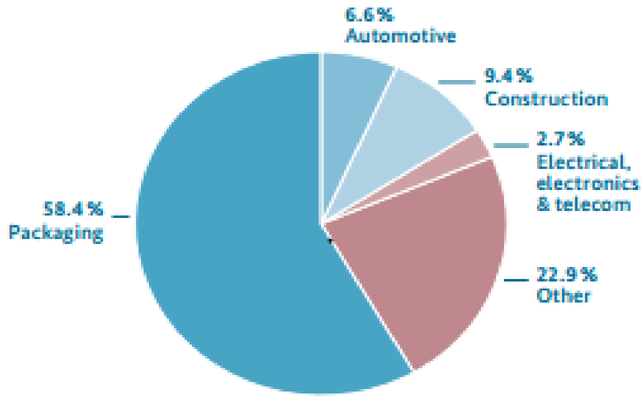


Figure 2. 1. Plastic consumption in Ethiopia in kilo tons (Linda Schramel, 2020)

2.6. Plastic Waste and Recycling trend in Ethiopia

Pollution has been a topic of discussion since the Industrial Revolution, and it has brought with it the benefits and drawbacks of industrial and technological advancement. The necessity to cope with materials in previously unknown forms has been thrown at the environment as a result of human activity (Linda Schramel, 2020). Historically, recycling in the plastics sector was done as part of the routine production process within manufacturing businesses. In extrusion, for example, in-house scrap is frequently reprocessed with fresh material to boost end material production yields where material and contamination limits allow. Plastic garbage, both commercial and post-consumer, is being disposed of in landfills (Vannessa et al., 2007).

Plastic solid waste (PSW) is a significant contributor to waste generation on a global scale. Because of the growing production and consumption of polymer materials, polymer disposal is becoming a global issue. The varied levels of waste output in many countries based on their socioeconomic levels has become a severe concern for PSW disposal and management. Garbage management is a complicated process that necessitates a variety of data from diverse sources, such as influencing variables in waste generation, large-scale projections, and dependable data. Each year, at least 93 million tons of garbage are generated throughout Eastern and Central Asia. The amount of garbage generated per person per day ranges from 0.29 to 2.1 kilograms, with an average of 1.1 kg/capita/day (Singh et al., 2017).

Plastic bags and bottles are among the most polluting items in the environment, according to reports. Plastic bottles used for bottling water and other beverages take hundreds of years to degrade. The plastics industry understands the importance of recycling post-consumer plastic packaging to reduce environmental impact (Singh et al., 2018).

The recycling sector is important in Ethiopia for two reasons: on the one hand, there is a scarcity of raw materials, and on the other side, an informal recycling system exists. Ethiopia suffers from a general shortage of raw materials such as plastic, metal, and paper, owing to a lack of resources within the country (for example, Ethiopia only recently began crude oil production) and a pervasive technological deficit. Because to the strong reliance on raw material imports, as well as the foreign exchange crisis and high transportation expenses, prices are two to three times higher than on the worldwide market. As a result, reuse and recycling as a source of local raw material is extremely important. In addition, an informal recycling system exists, with one of the highest recycling rates in East and Central Africa, comparable to that of certain European countries (Linda Schramel, 2020).

Municipal rubbish is collected and transported to landfills by municipal waste management corporations in practice. It is mostly made up of organic trash, with little bits of plastic, paper, and metal thrown in for good measure. The informal sector is in charge of municipal garbage recycling: street collectors and so-called "korales" collect all types of recyclables from streets and landfills. Because of the high demand for these raw materials, recycled materials include biomass, textiles, rubber, ash, dust, and waste oil, in addition to plastic. Recycling legislation, collection, and technology, on the other hand, remain an issue. The majority of PET is collected from hotels and restaurants.

Other than these plastic wastes is generated from defects of PET bottles and preforms from plastic water bottling companies. More than 3 percent of produce product results in defects as result of improper process parameter settings. From this 3 percent more than 75 percent consists of burst bottles and uneven distributed wall thickness in bottles. The other 15 percent includes preforms which are burned as a result of power outages and 10 percent of wastage is a combination of polybags used for packaging and labels.

2.7. Summary of literature review

According to the literature reviewed regarding the SBM process and its related optimization problem, with respect to the governing parameters, were addressed. SBM is one of the widely used manufacturing processes in the plastic industry. However, when the process is not optimized or when the process parameters are not properly selected, the production process is not effective and the raw materials are not being utilized efficiently.

The majority of researchers agree that blowing temperature, heat profile along the preform wall, blowing pressure, stretch rations, and wall thickness distribution are all important factors in SBM. From this, most of them agree that the blowing temperature has the most significant effect on the final outcome of a product. Most of the researchers used the Finite Element Method as their tool to optimize these parameters.

Finally, from the reviewed books, journals, magazines and other sources, the gap observed from these led to this study to be carried out on the SBM process to minimize defects occurring in the process.

2.8. Research Gap

Even though numerous researchers have done a number of researches on the stretch blow molding process, there is still a gap in the area of process parameters optimization and identification of major process defects that arise in SBM process. Since the output of the SBM process is heavily affected by the aforementioned process parameters, it is one area of research that must be done in detail clearly. From the reviewed literature, it is evident that there is a lack of research on the optimization of the process parameters. A multi objective optimization technique can be applied to simultaneously get an optimum values for the process parameters involved in the SBM process to achieve high quality defect free products.

CHAPTER THREE

RESEARCH MATERIALS AND METHODOLOGY

3.1. Material

The SBM process of PET, whose chemical makeup is Carbon, Hydrogen, and Oxygen, was the subject of this research. PET is a colorless, semi-crystalline resin in its native state. PET can be semi-rigid to rigid depending on how it is produced, and it is extremely lightweight. It works effectively as a gas and moisture barrier, as well as an alcohol and solvent barrier. Unreinforced to glass reinforced, flame retardant, and high flow PET grades are commercially available for diverse engineering applications that often require better strength and/or heat resistance. Table 3.1 lists the physical and thermal properties of PET.

Table 3.1. Physical and thermal properties of PET (Firas Awaja, 2005)

Property	Test method	Value (unit)
Molecular weight (of repeating unit)	-	192 (g mol $^{-1}$)
Mark-Houwink parameters	-	K= 3.72 x 10 $^{-2}$ (ml g $^{-1}$) a=0.73
Weight-average MW	-	30000-80000 (g mol $^{-1}$)
Density	-	1.41 (g cm $^{-3}$)
Glass transition temperature	DSC	69-115 (^{0}c)
Melting temperature	DSC	265 (^{0}c)
Heat of fusion	DSC	166 (J/g)
Breaking strength	Tensile	50 (MPa)
Tensile strength (Young's modulus)		1700 (MPa)
Yield strain	Tensile	4 (%)
Impact strength	ASTM D256-86	90 (J m^{-1})
Water absorption (after 24 h)	-	0.5 (%)

3.2. Process parameters

The process parameters are the factors that are varying in this process and are selected based on literature review. Blowing temperature and blowing angles are the factors that affect the strength of the PET bottles while blowing speed affects the mechanical property (Ottmar Brandau, 2012).. In this experiment, all of the parameters were used to evaluate the effect of each parameter on the end product quality and to choose the best process parameter from the factors that were chosen.

3.2.1. Blowing temperature

Temperature has a major influence on the final product quality. The reviewed literatures revealed that higher amount of temperature reduce the properties of the bottle. Improper selection of temperature can affect the orientation of the PET monomers and can cause defects like

- Poor transparency of PET bottles (if the heating temperature is too high).
- The pearl gloss appears in the PET bottle (if the heating temperature is too low).
- The upper part of the bottle is too thick (if the upper temperature is too low).
- The bottle's bottom is too thin (if the temperature at the bottom is too high).
- Stretching the bottom of the bottle (if the temperature is not enough and not penetrated the bottle).
- Blasting at the bottle's bottom (if the temperature at the bottom is too high).

For this research, the temperature was selected in three levels for each layers of infrared oven lamp by adjusting it on the human machine interface.

3.2.2. Blowing angles

As explained on previous sections, PET bottle is blown in two stages namely: first blow and second blow. The application of pressure that forms the bottle is done by high pressure compressors. The first blow forms most of the shape for the bottle, while the final blow gives the bottle the shape of the mold cavity.

- Seal angle = preform insertion into mould cavity= 0^0

- Stretch angle = application of stretch rod to stretch the bottle axially= 15^0-180^0
- First blow angle = application of lower pressure to form most of the bottle = {55-60^0}-70^0
- Second blow angle = application of higher pressure to form final shape of bottle = {70^0-73^0}-190^0
- Recover angle = recycling of air throughout the system = 191^0-259^0
- Exhaust angle = removal of air from the mold cavity =260^0-360^0

The mold angles can be seen in figure 3.1.

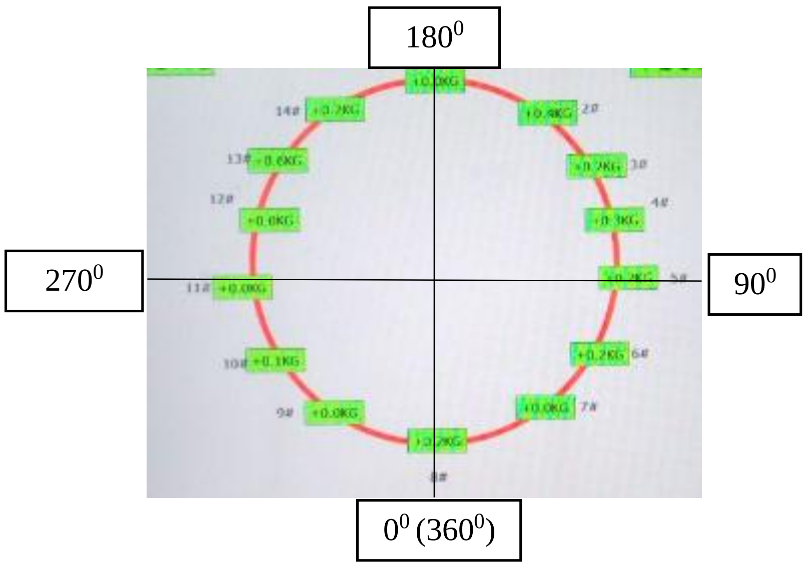


Figure 3.1 Mold angle illustration diagram

Improper selection of these parameters can have defects like;

- Uneven wall thickness of PET bottles
- The position of the bottom of the PET bottle is offset
- Blasting at the bottom of the bottle
- Thin sidewalls
- Top load failure
- Localized surface imperfection

For this research, both of the blowing angles (pre-blow and second blow) were selected in three levels.

3.2.3. Blowing speed

The blowing speed is characterized by the amount of bottles a stretch blow molding machine can blow in an hour and has a unit of Blt/Hr (bottle per hour). This parameter is one of the major quality influencers in the SBM process. Arbitrary selection of speed can cause defects like;

- Neck constriction
- Hard and thin shoulder
- Opalescence
- Choked body

For this study, the blowing speed was selected in three levels.

3.3. Experimental procedure

Figure 3.2 depicts a common procedure for studying multi-objective parametric optimization of PET preform process parameters in the SBM process to reduce faults.

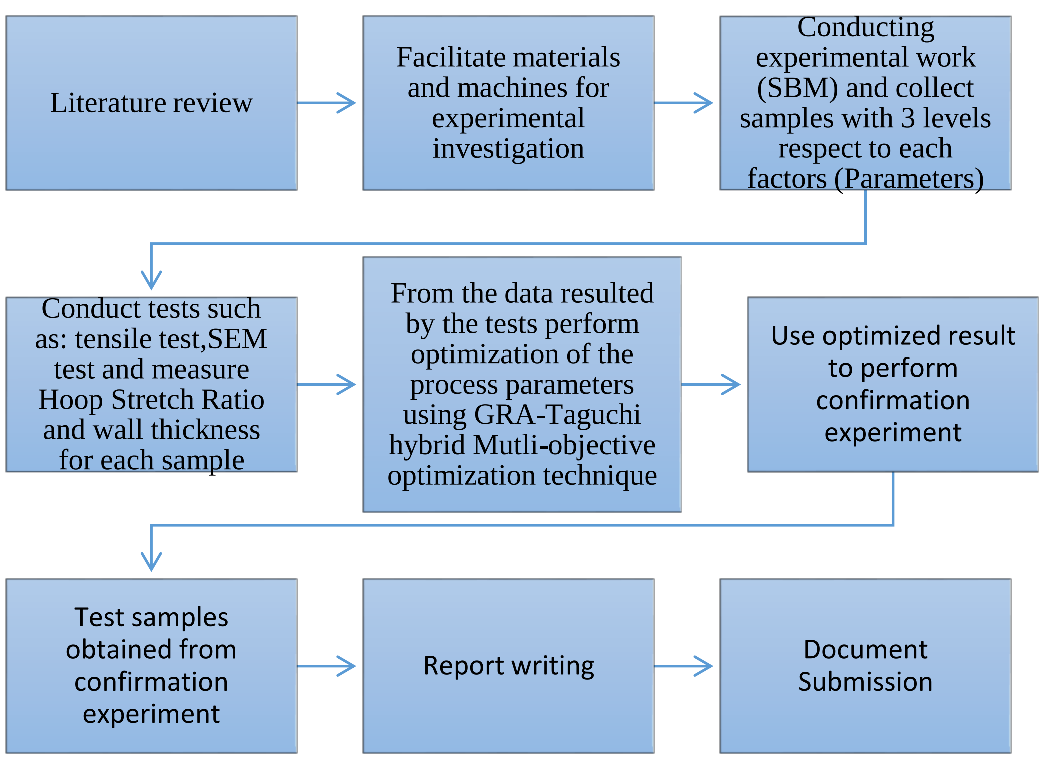


Figure 3.2. Flow chart of experimental work

3.4. Stretch blow molding machine

The machine used to carry out the experiment is called Xilinear 14 Cavity Semi-automatic Rotary PET plastic bottle blowing machine. It can be used to produce water bottles, juice bottles, carbonated drink bottles, etc. Some of the specifications can be seen in table 3.2. The machine has great features like: high automation, high intelligence, HMI (human machine interface) touch screen, steady infrared heating system, highly precise blow-mold closing system, high speed production, no contamination, self-lubricating system, low consumption of electricity, air and water, High transparency, easy maintenance, low noise and detection system using sensors. Any problem can be indicated by an alarm on the HMI so the operator can take the necessary steps and precautions.

Table 3.2. SBM machine details

Application	**Bottle**
Plastic Processed	PET
Blow Molding Type	Rotary Blow Molding machine series
Automatic	Semi-automatic
Voltage	380v/3PH/50HZ
Power (W)	188KW
Air Source	Recommended air compressor of 10m^3/min 30Kg
Cooling water	Recommended water chiller with 10HP
Dimension (L*W*H)	4120mm*3080mm*3630mm
Weight	1380kg
Product Description	14 Cavity Semi-Automatic PET bottle blowing machine
Raw Material	PET preform
Cavity number	14 cavity
Bottle sizes	0.6-2L
Bottle neck size	Φ10--20Φ
Theoretical Output	25000-28000 BPH (bottle per hour)
PLC	Siemens.ect
Machine type	Blowing Plastic Machine

Figure 3.3 shows the SBM machine used to carry out the experiments for this study.

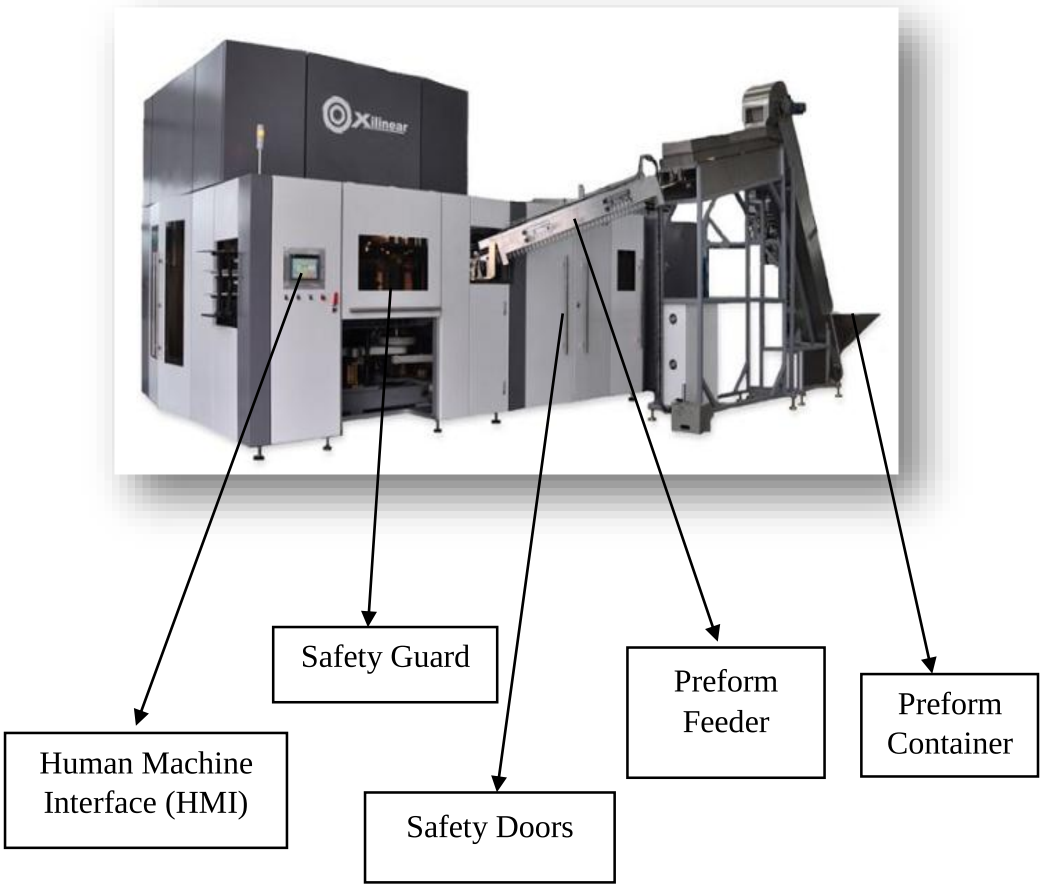


Figure 3.3. Semi-automatic 14 cavity SBM machine

3.5. Samples and Sampling

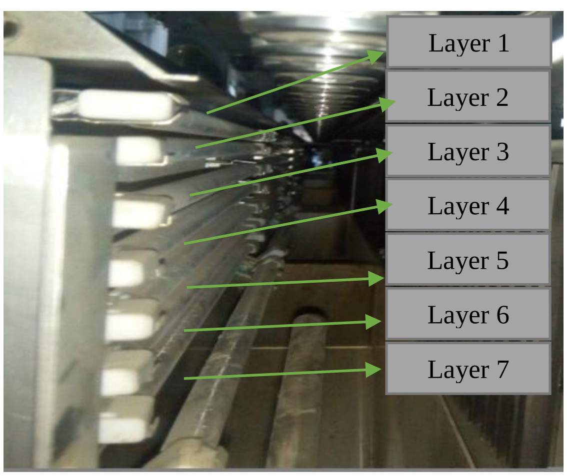
The samples were taken with a combination of blowing parameters like: Speed (Blt/Hr), blowing temperature, first blow angle and final blow angle. For the experimentation L9 experimental design was used and 2 samples for each design (18 in total) samples were taken. There are three levels for each process parameters. The experimental design can be seen in table 3.3.

Table3.3. Process parameters and their levels as per L9 OA

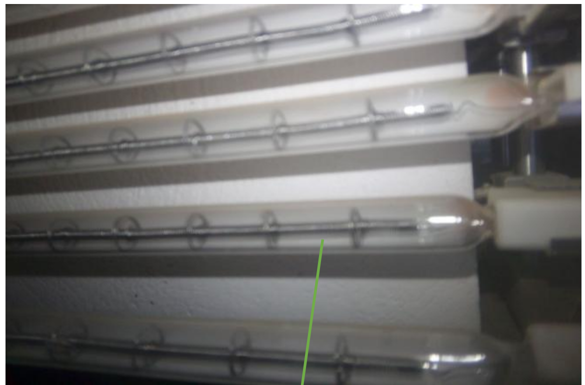
No	**Blowing temperature layers (%)**							**First blow angle**	**Second blow angle**	**Blowing speed**
	Layer 1	*Layer 2*	*Layer 3*	*Layer 4*	*Layer 5*	*Layer 6*	*Layer 7*			

1	96	47	OFF	24	55	53	33	57	71	11,000
2	96	47	OFF	24	55	53	33	56	70	10,000
3	96	47	OFF	24	55	53	33	58	72	12,000
4	95	46	OFF	23	54	52	32	57	70	12,000
5	95	46	OFF	23	54	52	32	56	72	11,000
6	95	46	OFF	23	54	52	32	58	71	10,000
7	97	48	OFF	25	56	54	34	57	72	10,000
8	97	48	OFF	25	56	54	34	56	71	12,000
9	97	48	OFF	25	56	54	34	58	70	11,000

The layers for the temperature (layer 1-layer 7) in table 3.3 indicate the temperature for the infrared radiation oven lamp. There are 7 layers of which one is turned off and these layers are distributed over the entire length of the 2L preform bottle. The layers are represented %. The percentage is taken from the preset machine working temperature which is set by the operator on the HMI. This temperature ranges from 130-165 ^{0}c. The layers are the percentage of this temperature respectively. This percentage is also called operating percentage. The oven lamps can be seen in figure 3.4.



(a)



(b)

Tungsten filaments encapsulated in quartz tubes are used in infrared oven lamps. Quartz is infrared-transparent and can endure the high temperatures generated by the lamp. The wavelength emitted is determined by the filament temperature. (Image courtesy of (Ottomar Brandau).

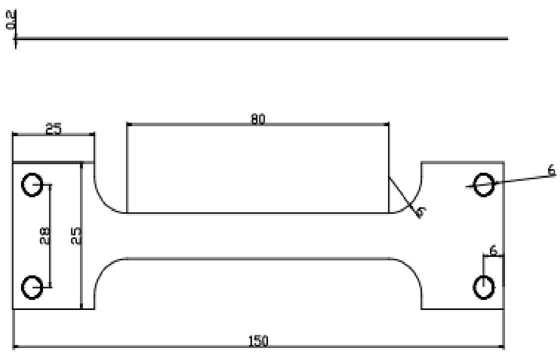
Figure 3.4. Infrared radiation oven lamp a) layers b) feature

3.6. Testing conditions and preparation

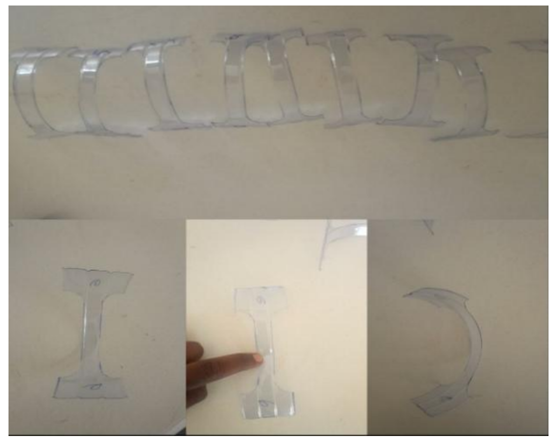
3.6.1. Tensile test

The tensile test was carried out at room temperature with a constant strain rate in a quasi-static state. It was carried out in the ASTU Mechanical Department theory of machines lab with an Electro-Hydraulic Universal testing machine. During this test, a constant load from the dynamometer load cell is applied to all specimens until they fail owing to plasticity. The test specimens were cut as per ASTM standards using simple blades and scissors due to the material smoothness. The tensile strength was determined as per ASTM specimen standard D882. The specimen is extracted from the area between the label panel and the base of the PET bottle horizontally along the bottle wall as shown in figure 3.5 (c).

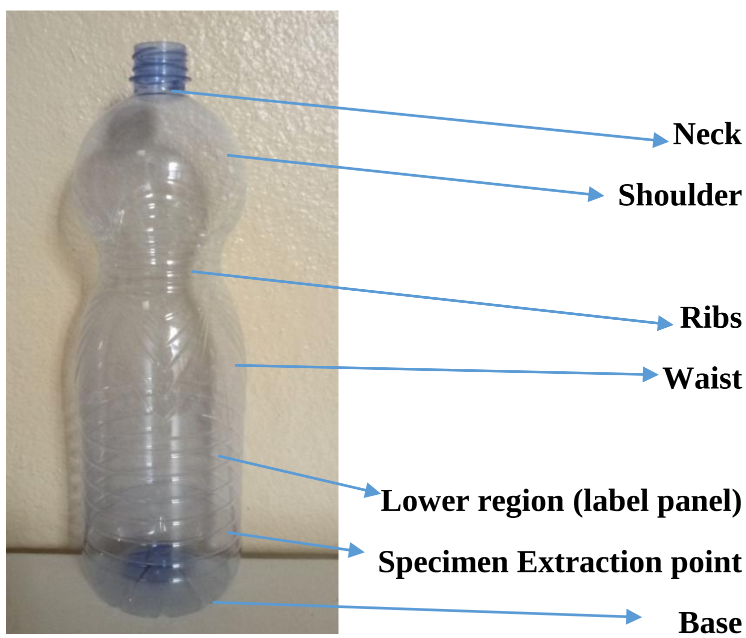
Specimens are pushed in tension until they fail in ASTM D882 testing. The initial strain rate is determined by the specimen's maximal elongation at break. Higher crosshead speeds are frequently necessary due to the high elasticity of plastic sheets and sheeting. The use of a suitable preload is one of the most important aspects of ASTM D882 testing. When thin film specimens are put into grips for testing, they are frequently relaxed rather than taut. A preload, which may be easily set, removes any slack in the specimen before recording data during testing, assuring accurate and reliable findings. The determination of tensile characteristics of plastics in the form of thin sheets and films is covered by this standard (less than 1.0 mm in thickness in which it is 0.2mm for this specimen). Figure 3.5 depicts the specimen specification diagram.



(a)



(b)



(c)

Figure 3.5. a) ASTM D882 specimen specification (all dimensions are in mm), b) samples extracted as per the standard and c) Bottle feature and extraction point

(Callister W. et al., 2010) shows the formulas for calculating tensile strength and percent elongation (strain rate) are

$$Tensile\ Strength = \frac{Breaking\ force(N)}{orginal\ Crossectional\ Area(m^2)}$$

$$percent\ elongation = \frac{(elongation\ at\ rupture) \times 100}{initilal\ gage\ length}$$

The mechanical behaviors of the PET samples were prepared with blades and scissors and were tested in the Universal Testing machine. The experiments were conducted at room temperature. During tensile testing the samples were placed vertically in the grip appropriately to prevent slipping. The experiment was conducted at room temperature.

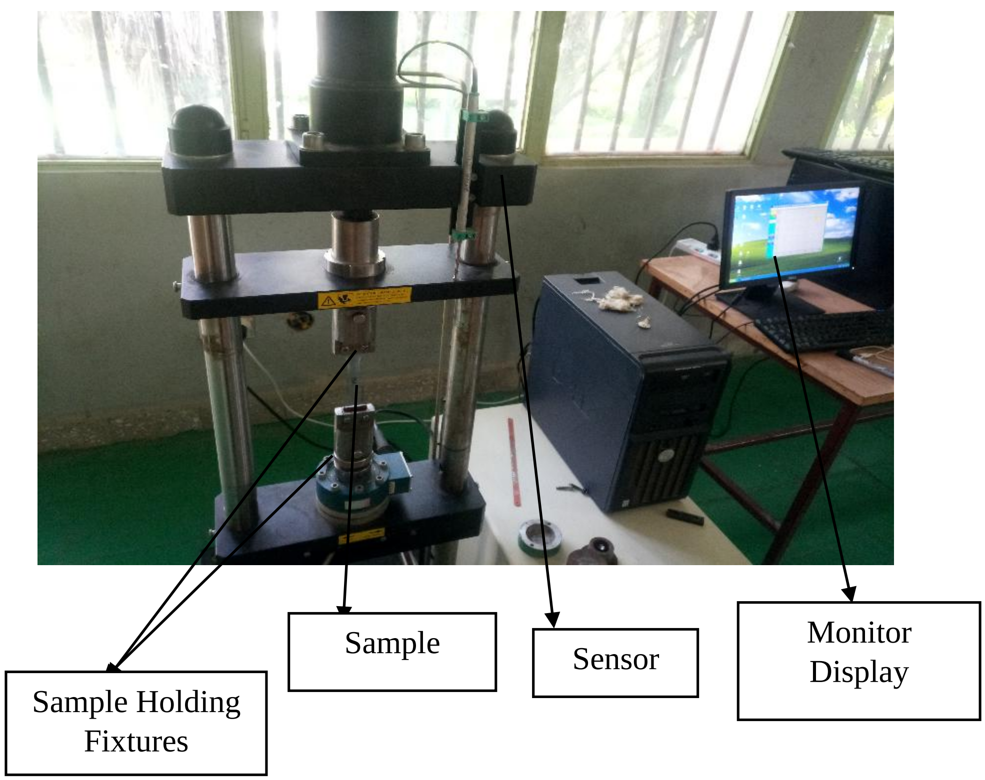
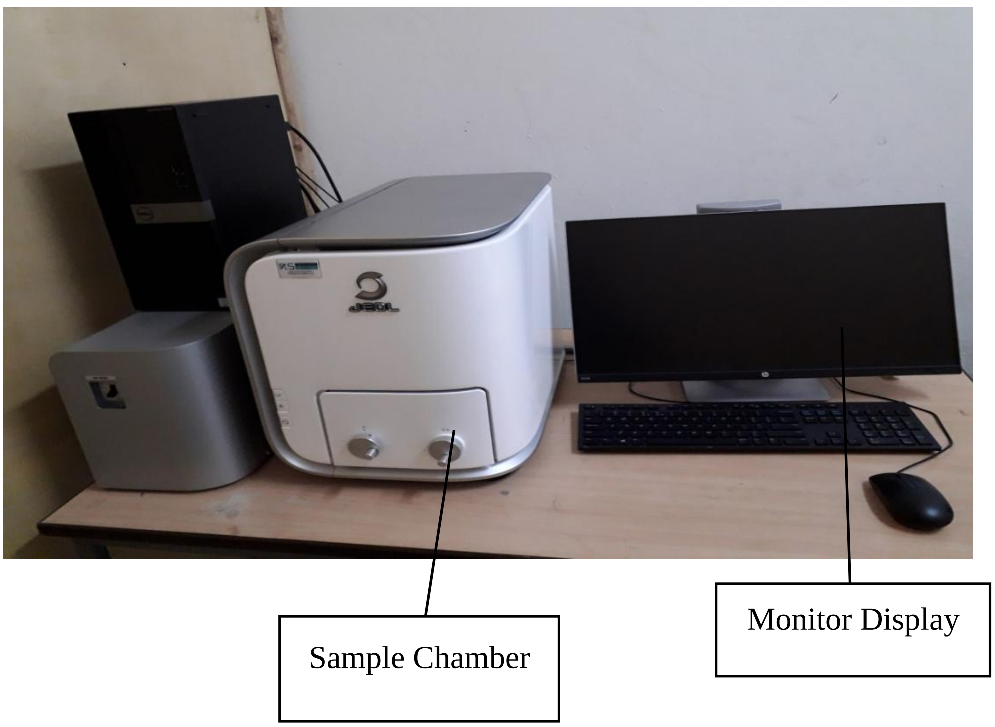


Figure 3.6. Universal testing machine with tensile testing setup

3.6.2. Scanning Electron Microscope (SEM) test

SEM is a test method that uses an electron beam to scan a sample and produce a magnified image for analysis. It's also known as SEM microscopy and SEM analysis. The observation was carried out in order to explore the microstructure of the PET surface and to determine the type of surface change caused by the process parameters on the PET bottle. The test was carried out at ASTU applied biology lab that is located at the skill center. Due to the limitation of multiple tests, only two samples were tested. The sample was cut with a size of 15 mm by 15 mm.

a)



b)

Figure 3.7. a) SEM test specimen and b) SEM testing machine

3.6.3. Hoop Stretch Ratio and wall thickness

The hoop stretch ratio and wall thickness were to check how the parameter differences affected the preform wall distribution. The ideal range for the hoop stretch ratio is from 4.3 to 5.5. Due to the lower weight standard for preform in Ethiopia being lower than 43grams for 2L bottles the stretch ratio is somewhat higher than this range for the samples. There is no one standard range for the wall thickness since the preform weight and process parameters can affect the average thickness of the bottle. Both hoop stretch ratio and wall thickness were measured by Vernier caliper.

An average reading from multiple measures was taken for both measures of the hoop stretch ratio and the wall thickness along the bottle wall.

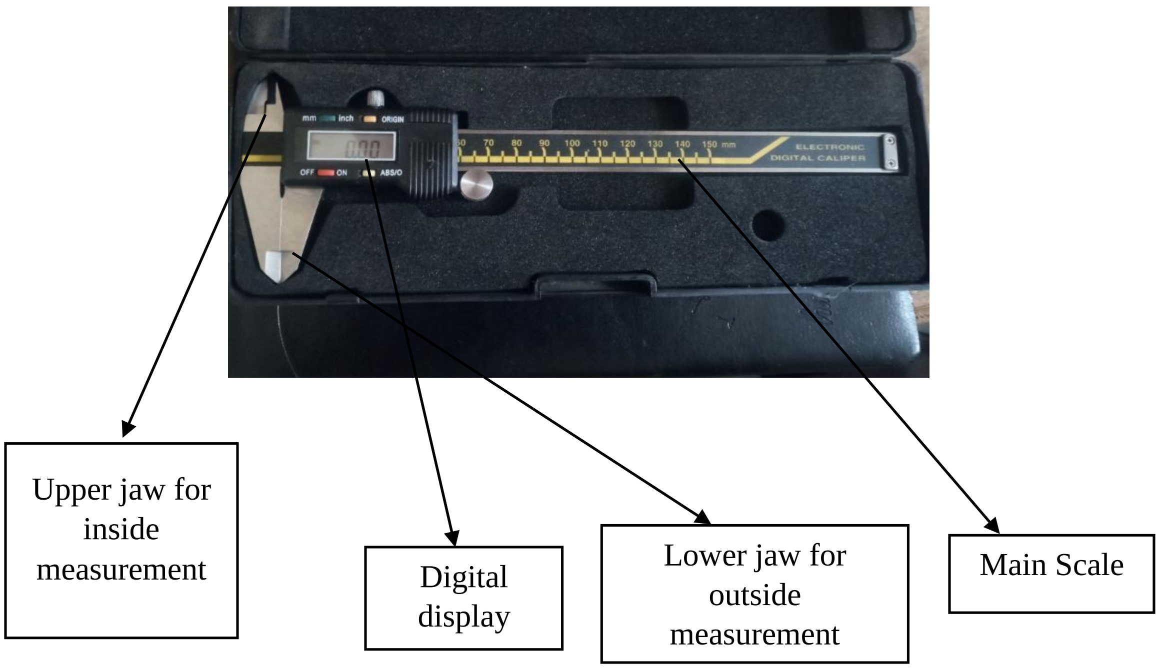


Figure 3. 8. Digital Vernier Caliper

3.7. Hybrid Taguchi-Grey Relational Analysis (HTGRA) Multi-optimization technique

As stated before, defect reduction is one of the main goals of any industrial plant. And with the current demand for high quality products, the help of optimization methods has become an important section. To identify an ideal setting for one of a process's output parameters, a variety of optimization approaches are available. These solutions, however, do not work for many output parameters. The identical optima setting determined for one output element is obviously not applicable for many output factors because their natures may differ. As a result, obtaining a single optimal blowing condition for all answers becomes critical in order to achieve all objectives at the same time. A multi-objective optimization strategy can help with this. To achieve the preferred multi-quality aspects of the multi replies, it is critical to transform all of the objectives into a corresponding single objective function. Specialized multi-objective optimizations, such as HTGRA, should be useful for this.

The HTGRA method consists of the following optimization steps that were applied;

1. Determine the process parameters and their levels.
2. Choosing an orthogonal array that is adequate.
3. Run trial trail runs and assess the results.
4. Compiling and normalizing response data.
5. Calculate Grey Relational Grade using Grey Relational Coefficient (GRC) (GRD).
6. Using the main effects table, determine the best level of parameter setting.
7. Using Analysis of Variance, determine the most influential parameters.
8. Optimal process parameter prediction.

As far as the theory of Taguchi methodology is concerned, it can be applied for the optimization and prediction of optimum levels of input parameters for optimum values of each output parameters. So, using conventional method of Taguchi, for each response variable there is optimum levels of input parameters. But GRA (Grey Relational Analysis) is such a method that common optimum levels of input parameters are achieved for all output responses at a time. But though other methods, the common optimum levels cannot be achieved. In the present thesis, the GRA without entropy method has been applied. GRA relational was chosen since it allows to study the interaction between governing parameters while Taguchi allows to run fewer experimental runs while getting the same results on the final optimization.

3.8. Minitab Software

Minitab is a robust statistical software tool used in math, statistics, economics, sports, and engineering. It is a highly interactive software that simplifies numerical computations and allows optimization techniques like as regression analysis, ANOVA analysis, DOE, Taguchi analysis, and producing time series graphs to be performed quickly while saving time. It is the most effective tool for quality improvement projects based on data. It was utilized in this study to generate the Taguchi's L9 design, as well as to calculate the SN ratio and plot mean results.

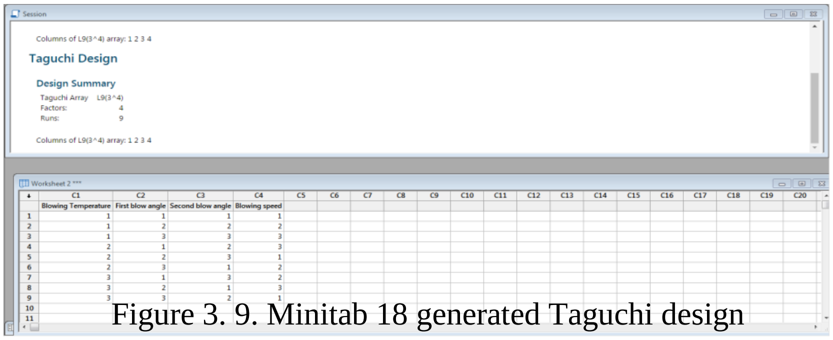


Figure 3. 9. Minitab 18 generated Taguchi design

To assess process resilience and divergence from desired values, the signal to noise ratio was used. The noise is caused by uncontrollable factors in the experiment that must be addressed in order to lower the noise and hence the variation in the experimental or actual process variables.

3.9. Process Parameters Level designations

Based on Taguchi method, 3 levels is taken for each of the parameters in this study.

- *Level 1 for lower level of each parameter*
- *Level 2 for medium level (which was the operating condition at work then) of each parameter and*
- *Level 3 for higher value taken for each parameter*

These level can be seen in table below

Table 3. 4. Parameter Level designation

Levels	**Parameters**			
	Blowing Temperature	Pre-blow angle	Final blow angle	Blowing speed
1	A1 (95)	B1 (56)	C1 (70)	D1 (10000)
2	A2 (96)	B2 (57)	C2 (71)	D2 (11000)
3	A3 (97)	B3 (58)	C3 (72)	D3 (12000)

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1. Introduction

The findings of the experimental works have been discussed in depth in this chapter. In different sections the result from tensile test, SEM test, wall thickness measure and hoop stretch ratio measurements are discussed. The HTGRA optimization method was applied and the results are also discussed. Finally, the conduction of confirmation experiment and result are discussed.

4.2. Tensile test

PET has high tensile strength compared with its close plastic relatives. The tensile tests have been performed on the PET film at room temperature. For tensile strength evaluation, nine specimens were tested. This means one specimen for each combination of process parameters was tested by the universal testing machine. The findings of this test are summarized in Table 4.1.

Table 4.1. Tensile strength result

EXPERIMENT RUN	TENSILE STRENGTH (MPA)	ELONGATION AT BREAK (%)
1	65	9.33
2	60	5.65
3	45	10.74
4	62.5	10.07
5	58	4.58
6	50	8.67

7	48	4.81
8	55	5.88
9	63	7.24

Figure 4. 1. Samples after plastic failure on UTM during tensile testing

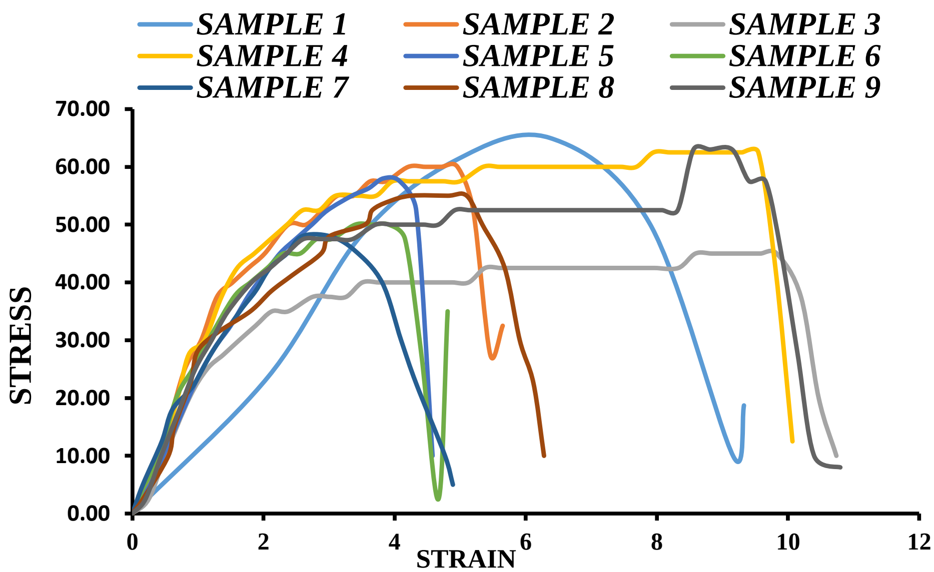


Figure 4.2. Stress-strain diagram for all the 9 samples

Axial load was applied for the entire specimen and this in turns leads to elongation of specimen until failure occurs shown in figure 4.1. The failure exhibits a ductile nature of the PET material.

Figure 4.2 shows the tensile strength results for the nine specimens. The link between stress and strain is depicted in the graph. It was calculated by progressively adding force to the test samples and detecting deformation, from which stress and strain were calculated. The graphs depict the attributes of PET materials in each sample, such as Young's modulus, yield strength, and ultimate tensile strength. The graphs depict the attributes of PET materials in each sample, such as Young's modulus, yield strength, and ultimate tensile strength.

Because the material is ductile, the graph shows a relatively linear stress-strain relationship for each sample up to a well-defined yield point. The elastic region is indicated by the linear component of the curves, and the slope is the modulus of elasticity, also known as Young's modulus. At room temperature, the stress-strain behavior of PET samples shows an initial linear increase in the first region, followed by an increase in strain and a very sluggish increase in stress, which is typical of plastic deformation. With increased tension, the plastic in this location showed irreversible plastic deformation. The tension in the plastic deformation zone was lower than the yield strength and varied little with the strain.

The greatest stress obtained during the stress-strain test is the tensile strength of the samples, whereas the yield strength is the point where the stress-strain curve deviates from linearity or the strain value when the sample breaks. Sample one has the maximum tensile strength of 65 MPa. Sample 3 has the minimum observed tensile strength of 45 MPa. From the graph it can be seen that samples subjected to the increase in both speed and temperature exhibit a lower tensile strength. This indicates that temperature and speed in SBM process are directly proportional and an increase in both parameters results in a weaker bottle strength. Similarly an increase in the pre-blow angle and the final blow angle also exhibit same properties as that of the blowing speed and blowing temperature. Samples with higher tensile strength are the ones subjected to at least two parameters with lower levels of numbers.

In conclusion the main parameter that has main effect on the tensile strength of the bottle is the blowing temperature and the least effective is the final blow angle.

4.2.1. Analysis of main effect plot of tensile strength

Minitab calculated the signal-to-noise ratio (S/N ratio) to determine the robustness, which can be used to find control factor settings that minimize the effect of noise on the response. For each combination of control factor levels in the design, Minitab was used to calculate a separate signal-to-noise ratio.

The primary influence map for tensile strength S/N ratios is shown in Figure 4.3. The numerical value at the maximum point in each graph represents the parameter's best value at that level of tensile strength. They also show the ideal conditions within the experimental conditions' range. According to the graph, the best condition (level) for increasing tensile strength is:

- Level 1 for blowing temperature (95,46,OFF,23,54,52,32)
- Level 2 for first blow angle (57)
- Level 1 for final blow angle (70)
- Level 2 for blowing speed (11000)

These levels imply 1 being the minimum, 2 for middle and 3 for maximum according to the experimental design rule of Taguchi.

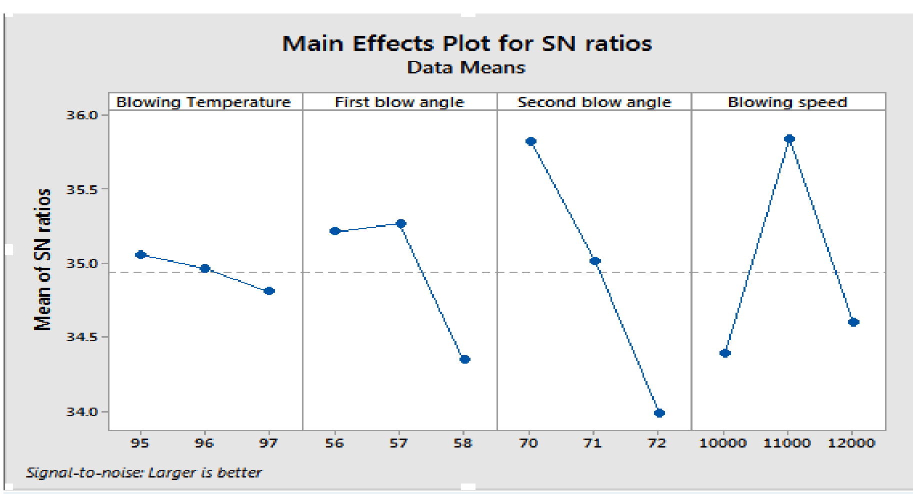


Figure 4. 3. Main effect plot of S/N ratio of tensile strength

4.2.2. Response table for S/N ratios of tensile strength

With a delta value of 1.84, the response table for tensile strength shows that blowing temperature had the greatest impact on enhancing the tensile strength of PET bottles. With a delta value of 1.45, blowing speed is the second most important element in improving tensile strength. Table 4.2 below summarizes the findings.

Table 4. 2. Response for S/N ratios of tensile strength

level	blowing temperature	first blow angle	second blow angle	blowing speed
1	35.82	35.21	35.06	34.39
2	35.01	35.27	34.96	35.84
3	33.99	34.34	34.81	34.60
DELTA	1.84	0.92	0.25	1.45
RANK	1	3	4	2

4.3. Hoop Stretch ratio

We must investigate how stretch ratios between bottle and preform are computed and how temperature changes in the preform wall affect them, as described in the literature review, in order to better understand what the process must achieve in order to reduce faults. Hoop stretch ratio is calculated by dividing the internal diameter of the PET bottle with its corresponding internal diameter of the preform to see how much the preform has stretched during heating and blowing. The inner preform walls were chosen for these tests as a reaction because they must extend more. Because the temperature inside the wall is higher, the inner preform walls stretch longer.

The internal diameter of the bottle and preform were measured by a digital Vernier caliper. From these measurements the hoop stretch ratio was calculated by using equation 4.1 (Ottmar Brandau, 2012).

$$\text{Hoop stretch ratio} = \frac{internal\ diameter\ of\ PET\ bottle}{internal\ diameter\ of\ preform} \ldots\ldots \text{(Equation 4.1)}$$

Table 4.3. Hoop stretch ratio calculated (from equation 4.1)

SAMPLE NO	STRETCH RATIO
1	5.75
2	5.67
3	5.81
4	5.45
5	5.5
6	5.6
7	6.15
8	5.95
9	5.88

4.3.1. Analysis of main effect plot of Hoop stretch ratio

The primary effect plot for S/N ratios of hoop stretch ratio is shown in Figure 4.4. The numerical value of the minimum point in each graph is the best value for that parameter at that hoop stretch ratio level. They also show the ideal conditions within the experimental conditions' range. According to the graph, the best conditions for lowering the hoop stretch ratio are:

- Level 3 for blowing temperature (97,48,OFF,25,56,54,34)
- Level 2 for first blow angle (57)
- Level 3 for final blow angle (72)
- Level 1 for blowing speed (10000)

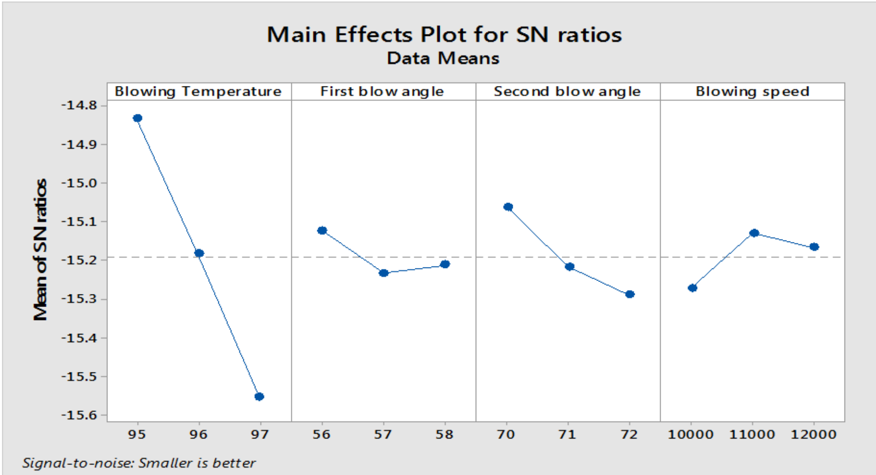


Figure 4.4. Main effect plot of S/N ratio of tensile strength

4.3.2. Response table for S/N ratios of Hoop stretch ratio

The response table for Hoop stretch ratio indicates that blowing temperature had the highest contribution in decreasing the hoop stretch ratio of the PET bottles with delta number of 0.72 whereas first blow angle has the lowest effect with delta number 0.11. The results are summarized in table 4.4 below.

Table 4.4. Response for S/N ratios of Hoop stretch ratio

level	blowing temperature	first blow angle	second blow angle	blowing speed
1	-14.83	-15.12	-15.06	-15.27
2	-15.18	-15.23	-15.22	-15.13
3	-15.55	-15.21	-15.29	-15.17
DELTA	0.71	0.11	0.23	0.14
RANK	1	4	2	3

4.4. Wall thickness measurement

The ability of PET to self-level is one of its most fundamental qualities. This means that when one section of a prototype stretches first, the act of stretching causes strain-hardening, making stretching more difficult. This causes nearby areas that were perhaps a little cooler to expand, and the preform develops into a bottle with as small as a 0.0254 mm difference in wall thickness around the circle of the bottle as a result of this back-and-forth stretching and halting. Many bottles, however, display even greater variations. There are a number of conditions that must be met in order to obtain the desired output, as with any plastic process. Table 4.4 shows the average measure of wall thickness measured by a digital Vernier caliper.

Table 4.5. Wall thickness ratio measurement

SAMPLE NO.	WALL THICKNESS (in mm)
1	0.22
2	0.195
3	0.24
4	0.235
5	0.225
6	0.1825
7	0.2
8	0.23
9	0.18

From the results, it was observed that a raise in temperature results in a small wall thickness which can result in unstable and defected bottles. Besides that an increase in pre-blow angle can also result in thinner bottle surfaces. Sample 3 showed the highest wall thickness of 0.24mm and sample 9 the smallest wall thickness of 0.18mm. These results are shown in figure 4.5. It is to be noted that a proper selection of SBM process parameter combination is vital to avoid defects that arise with uneven wall thickness.

Figure 4.5 shows wall thickness vs samples measurement for the wall thickness of the PET bottles.

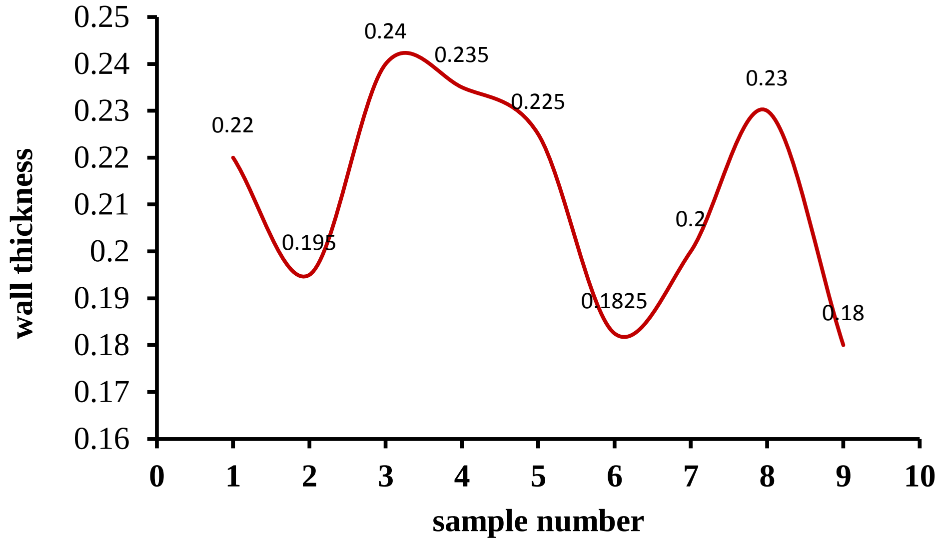


Figure 4.5. Wall thickness Vs. Sample number

4.4.1. Analysis of main effect plot of wall thickness

The primary effect plot for S/N ratios of wall thickness is shown in Figure 4.6. The numerical value at the maximum point in each graph represents the parameter's best value at that level of wall thickness. They also show the ideal conditions within the experimental conditions' range. According to the graph, the best conditions for lowering the hoop stretch ratio are:

- Level 2 for blowing temperature (96,47,OFF,24,55,53,33)
- Level 2 for first blow angle (57)
- Level 3 for final blow angle (72)
- Level 3 for blowing speed (12000)

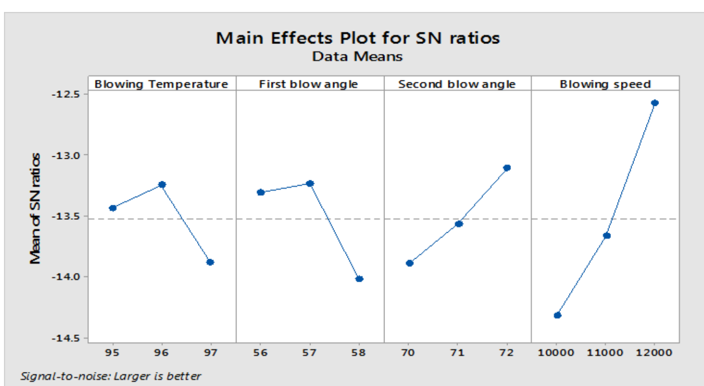


Figure 4.6 Main effect plot for S/N ratio of wall thickness

4.4.2. Response table for S/N ratio of wall thickness

The response table for wall thickness measure indicates that blowing speed has the highest contribution in increasing the wall thickness of the PET bottles with delta number of 1.74 whereas second blow angle has the lowest effect with delta number 0.63. The results are summarized in table 4.5 below.

Table 4. 6 Response for S/N ratios of wall thickness

level	blowing temperature	first blow angle	second blow angle	blowing speed
1	-13.31	-13.89	-13.44	-14.32
2	-13.24	-13.56	-13.25	-13.67
3	-14.02	-13.11	-13.88	-12.58
DELTA	0.79	0.78	0.63	1.74
RANK	2	3	4	1

4.5. Morphological analysis

The morphological analysis of the PET bottles undertook at different magnification. Figure 4.7 shows a 500 micrometer SEM generated surface. The SEM experiment took on two samples namely sample 1 (normal working condition) and sample 6. From the image at the same resolution and zooming, it can be seen on the sample 6, visible white with black boundary surface which indicated a cluster of material due to uneven wall distribution and hence causing defect on the final PET bottle. This feature is distributed along the PET wall. Here on the fig below it can be seen in comparison with the normal condition (sample 1) surface. The dark spots on the sample (figure 4.7 b) indicate a material aggregation due to improper process parameter conditions that cause defected bottle products. The samples are selected for comparison between the samples with the most visible defective features and the least visible feature on the PET bottles.

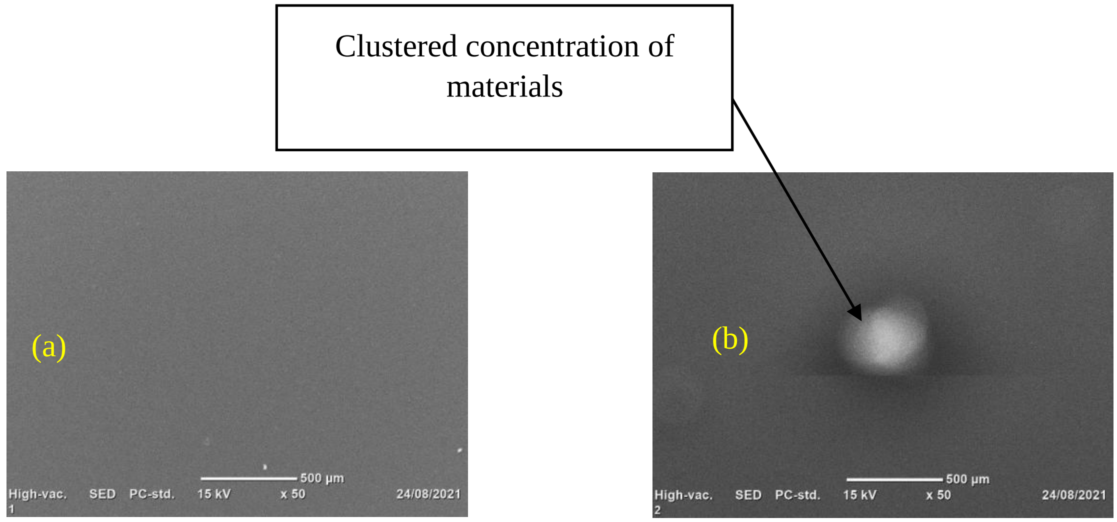


Figure 4.7 SEM generated surfaces (a) Sample 1 and (b) Sample 2

4.6. Hybrid Taguchi-Grey Relational Analysis (HTGRA)

The numerical data obtained from tensile strength, hoop stretch ratio and wall thickness measure were used to predict the optimal parameter combination for the best product with ideal mechanical and physical property yielding PET bottle. The step by step optimization technique applied is shown as follows.

For predicting the optimum response, four factors were selected with three levels each and these are;

A. Blowing temperature (factor A)
B. Pre-blow angle (factor B)
C. Final blow angle (factor C)
D. Blowing speed (factor D)

For these factors the responses are;

- Tensile Strength
- Hoop Stretch ratio and
- Wall thickness measure

Table 4.7 shows the experimental design with the responses.

Table 4.7 L9 experimental design

Trial Number	**Factors**				**Tensile Strength (MPa)**	**Wall thickness measure (mm)**	**Hoop Stretch Ratio**
	A	B	C	D			
1	1	1	1	1	65	0.22	5.75
2	1	2	2	2	60	0.195	5.67
3	1	3	3	3	45	0.24	5.81
4	2	1	2	3	62.5	0.235	5.45
5	2	2	3	1	58	0.225	5.5
6	2	3	1	2	50	0.1825	5.6
7	3	1	3	2	48	0.20	6.15
8	3	2	1	3	55	0.23	5.95
9	3	3	2	1	63	0.18	5.88

Step 1; Transformation of response values into S/N ratios

For Tensile Strength and wall thickness larger is better formula is used for optimization since larger number of this values means a stronger bottle is yielded.

S/N ratio= $-10\log \frac{1}{n}\sum_{i=1}^{n}\left(\frac{1}{Yij\text{^}2}\right)$ (4.2**, Krishnajah K. et al., 2012**)

For Hoop Stretch ratio smaller is better for optimization. This means lower stretch ratio means less deformation which occurred with good wall distribution without defect incurring.

$$\text{S/N ratio}= -10\log \frac{1}{n}\sum_{i=1}^{n} Yij^2$$ (4.3**, Krishnajah K. et al., 2012**)

Table 4.8. S/N ratio (from equation 4.2& 4.3)

Trial Number	***S/N ratio for tensile strength***	***S/N ratio for Wall thickness ratio***	***S/N ratio for Hoop Stretch Ratio***
1	36.2583	-13.1515	-15.1934
2	35.5630	-14.1993	-15.0717
3	33.0643	-12.3958	-15.2835
4	35.9176	-12.5786	-14.7279
5	35.2686	-12.9563	-14.8073
6	33.9794	-14.7747	-14.9638
7	33.6248	-13.9794	-15.7775
8	34.8073	-12.7654	-15.4903
9	35.9868	-14.8945	-15.3875

Step 2; Normalization of S/N ratio

For larger the better (for tensile strength and wall thickness measure)

$$Zij= \frac{Yij - \min Yij}{Max\ Yij - \min Yij}$$ (4.4**, Krishnajah K. et al., 2012**)

For smaller the better (for hoop stretch ratio)

$$Zij= \frac{Max\ Yij - Yij}{Max\ Yij - \min Yij}$$ (4.5**, Krishnajah K. et al., 2012**)

Table 4. 9. Normalized values of S/N ratio (from equation 4.4 & 4.5)

Trial Number	***Normalized S/N ratio for tensile strength***	***Normalized S/N ratio for Wall thickness measure***	***Normalized S/N ratio for Hoop Stretch Ratio***
1	1	0.698	0.443
2	0.782	0.278	0.328
3	0	1	0.529
4	0.893	0.927	0
5	0.690	0.776	0.00756
6	0.287	0.0479	0.225
7	0.175	0.366	1
8	0.546	0.852	0.726
9	0.915	0	0.628

Step 3; Calculation of quality loss

ΔT.S (quality loss for Tensile strength) = Yoj – Yij, where Yoj=1 (highest value of quality and the maximum amount of quality loss can be 100% if the deviation of any quality characteristics was found to be 100% from its observed value.) …… (Equation 4.6**, Krishnajah K. et al., 2012**)

ΔW.T (quality loss for wall thickness) = Yoj – Yij (4.7**, Krishnajah K. et al., 2012**)

ΔH**.**S.R (quality loss for Hoop stretch ratio) = Yoj – Yij(4.8**, Krishnajah K. et al., 2012**)

Table 4. 10. Quality loss

Trial Number	**ΔT.S**	**ΔW.T**	**ΔH.S.R**
1	0	0.302	0.557
2	0.218	0.722	0.672
3	1	0	0.471
4	0.107	0.073	1
5	0.31	0.224	0.924
6	0.713	0.952	0.775
7	0.825	0.634	0
8	0.454	0.148	0.274
9	0.085	1	0.372

Step 4; Determination of Grey relational coefficients for each response

GCij = $\frac{\Delta min+\lambda\Delta max}{\Delta ij+\lambda\Delta max}$ **,** assuming $\lambda = 1$ (4.9**, Krishnajah K. et al., 2012**)

$\Delta min = 0$ And $\Delta max = 1$

GCij = $\frac{1}{\Delta ij+1}$

Table 4. 11. Grey relational coefficients

Trial Number	**$GC_{T.S}$**	**$GC_{W.T.}$**	**$GC_{H.S.R}$**
1	1	0.768	0.642
2	0.821	0.581	0.598
3	0.5	1	0.68
4	0.904	0.932	0.5

5	0.763	0.817	0.52
6	0.584	0.512	0.563
7	0.548	0.612	1
8	0.688	0.871	0.785
9	0.922	0.5	0.729

Step 5; Calculation of GR code or Gr grade

GRG= $\frac{1}{m}\sum_{i=1}^{m} GCij$ (4.10**, Krishnajah K. et al., 2012**)

Where m=number of responses in the experiment (=3)

GRG= $\frac{GCT.S+GCW.T+GCH.S.R}{3}$ (4.11**, Krishnajah K. et al., 2012**)

Table 4. 12. Grey relational code

Trial number	GRC
1	0.803
2	0.667
3	0.727
4	0.778
5	0.7
6	0.553
7	0.72
8	0.781
9	0.717

Step 6; calculation of optimum values for each factor (Highest number is selected)

The optimum levels for each parameter is calculated as shown in table 4.13.

Table 4. 13. Optimum levels **(Krishnajah K. et al., 2012)**

Factors	**Level 1**	**Level 2**	**Level 3**
A	$\frac{0.72+0.781+0.717}{3}$ ***=0.7393***	$\frac{0.803+0.667+0.727}{3}$ *=0.7323*	$\frac{0.778+0.7+0.553}{3}$ *=0.677*
B	$\frac{0..667+0.7+0.781}{3}$ *=0.716*	$\frac{0.803+0.778+0.72}{3}$ ***=0.767***	$\frac{0.727+0.553+0.717}{3}$ *=0.666*
C	$\frac{0.803+0.553+0.781}{3}$ *=0.712*	$\frac{0.667+0.7+0.781}{3}$ *=0.721*	$\frac{0.727+0.778+0.72}{3}$ ***=0.7417***
D	$\frac{0.803+0.7+0.717}{3}$ *=0.74*	$\frac{0.727+0.778+0.781}{3}$ ***=0.762***	$\frac{0.667+0.553+0.72}{3}$ *=0.645*

Optimum values are **A1, B2, C3 and D2** for each factor.

4.7. Confirmation experiment

The optimized findings were further studied by conducting a confirmation experiment to validate the accuracy and reliability of the optimization results achieved by the integration of the Taguchi technique and GRA with the use of Minitab and Excel software for numerical calculations. The confirmation experiment was conducted based on the experimental result shown in table 4.13.

Table 4.13. Confirmation experiment experimental design

S.No.	**Blowing temperature layers (%)**							**First blow angle**	**Second blow angle**	**Blowing speed**
	Layer 1	*Layer 2*	*Layer 3*	*Layer 4*	*Layer 5*	*Layer 6*	*Layer 7*			
1	95	46	OFF	23	54	52	32	57	72	11,000

Based on this experimental design, confirmation experiment for the predicted values of input process variables have been carried out on SBM followed by the testing of samples as per ASTM standards. Then this sample was then tested for tensile strength, wall thickness measurement and hoop stretch ratio and the results are shown in table 4.14.

Table 4.14. Optimized sample tests

S.No.	Tensile Strength (MPa)	Wall thickness (mm)	Hoop Stretch Ratio
1	66.5	0.23	**5.47**

After confirmation experiment with the optimized values, the data collected shows an increase in the PET bottles tensile strength and wall thickness with a reduction in the hoop stretch ratio. The following conclusion can be drawn from the confirmation experiment:

- The highest recorded tensile strength is 66.5 MPa.
- The highest recorded wall thickness measure is 0.23mm.
- The highest recorded hoop stretch ratio is 5.47.

Therefore, it can be observed that the tensile strength and wall thickness to be maximum and hoop stretch ratio to be minimum at the predicted optimum levels of process parameters through HTGRA. Hence, the predicted levels have been validated experimentally and the values of validated output characteristics are shown in Table 4.14.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATION

5.1. Introduction

In this section conclusions from results and recommendation and future work for better productivity is presented.

5.2. Conclusions

In this study, optimization of process parameters in stretch blow molding process on 2liter bottles is done to minimize defects and increase the productivity. Experimental investigation was conducted and optimization using HTGRA multi-optimization technique was applied to optimize the process parameters like blowing temperature, blowing speed and blowing angles.

Determining the optimum parameters for SBM process is vital for the excess amount of plastic waste being produced and deposited carelessly in the environment. This waste includes not just scrap, rework, and rejection, but also financial costs associated with incompatible products, maintenance costs, failure costs, and excessive production costs. Most businesses in this industry rely on trial & error to find the best (usually temporary) combinations of SBM process parameters. This method, on the other hand, does not illustrate the interaction of components and necessitates the expenditure of time, money, and energy. The multi-objective optimization technique used in this work, on the other hand, is capable of selecting the ideal combination of SBM machine process parameters with the fewest number of experiments and the lowest defect production. The main objective of this project is to provide the best optimum parameter levels to get the best product with the least possible defects.

The best process parameters were studied in three stages in this study.

1. To use failure mode analysis to identify the significant faults in the SBM process. It investigates the main flaws in the SBM process and determines the control elements and their levels in order to choose the best orthogonal array.
2. The aim of the second stage was to conduct analysis and experimentation. GRA-Taguchi hybrid was used to optimize the process parameters after the experimentation was conducted and the significant factors were determined.
3. The significant factors were optimized in the last stage, and the optimized data was used to conduct a successful confirmation experiment.

From this research, the following conclusions are drawn:

1. The most important parameter which affects the final product quality is the blowing temperature.
2. The best level for each factors is A1, B2 (57^0), C3 (72^0) and D2 (11000 Blt/Hr) for blowing temperature, pre-blow angle, final blow angle and blowing speed respectively.
3. As the blowing temperature and speed increase, the tensile strength drops.
4. The tensile strength showed an increase from average tensile strength of 56.28 MPa to 66 MPa.
5. The hoop stretch ratio showed a decrease from average of 5.75 to 5.47.
6. The wall thickness didn’t show any major difference other than no outliers existing between the confirmation experimental PET bottles.
7. Based on the optimized values the company reported a daily decrease of defected waste 2L PET bottles by 15%. This 15% reduction may seem small due to the scope of the study being limited only on the 4 process parameters.

5.2. Recommendations

The best settings for the SBM process on a Xilinear 14 cavity semi-automated rotary blowing machine were determined in this study. The process parameters are chosen using the machine manual, a literature review, optimization approaches, and experimental research. Due to limitation on the scope of the study this research did not consider the following;

- Other machine types
- Preform material quality used
- Other bottle types (below and above 2litres)
- Other process parameters involved in SBM process

Even though the machine differ from this study the literatures reviewed indicated that blowing temperature is the most significant parameter to be altered in order to minimize defects and this study has shown that reducing the blowing temperature with the given combination of the other parameters yields a better product quality. It is recommended to reduce the blowing temperature.

5.3. Future works

The following proposals for future research are provided from several angles, as well as the scope and limitations of the study:

- ❖ To apply the methods used in this research in other plastic industries other than water bottling companies. This is due to the unchecked and uncared for plastic wastes that occur in multiple industries due to improper parameters selections.
- ❖ The computational tool can be used to predict the various characteristics of PET bottles.
- ❖ To carry out this type of study in other types of SBM machines with different combinations of process parameters and for different bottle types also.
- ❖ Further researches can be done by adding other parameters and by carrying out multiple tests which have not been included in this study due to limitation of availability.
- ❖ Creating awareness on the plastic wastes that are harming the environment as a result of poor production techniques applied by the plastic bottling industry.
- ❖ "Less waste means less pollution" slogan for improving quality of PET products and creating a better environment for the next generation.

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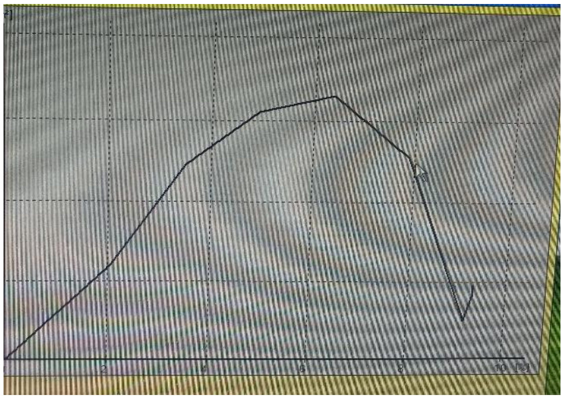
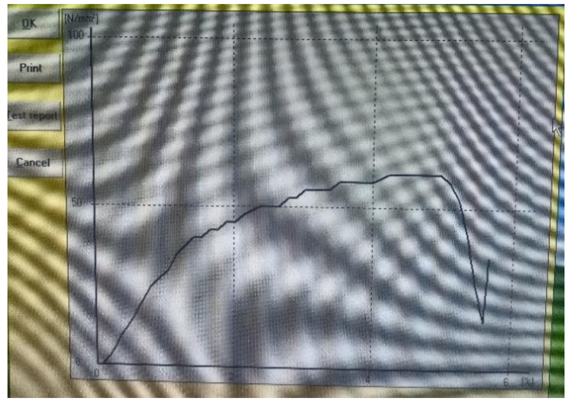
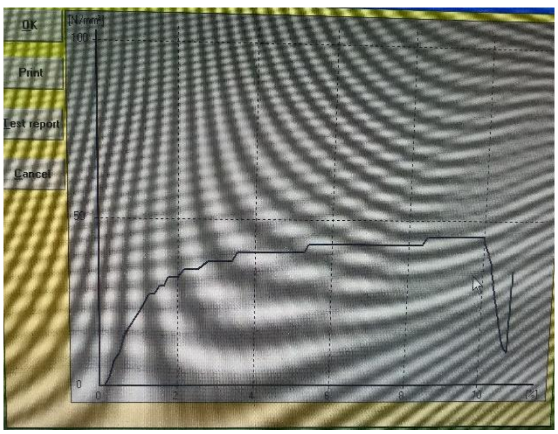
APPENDIX

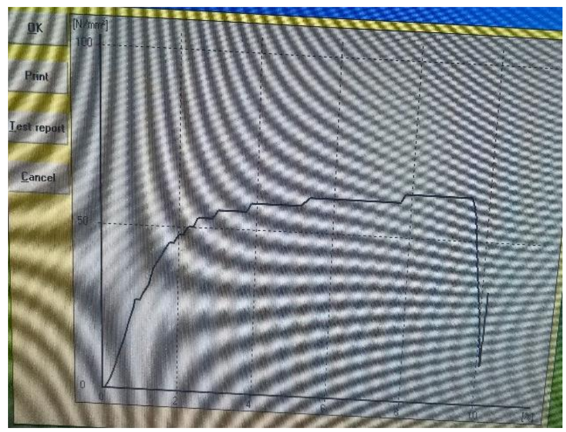
Appendix A

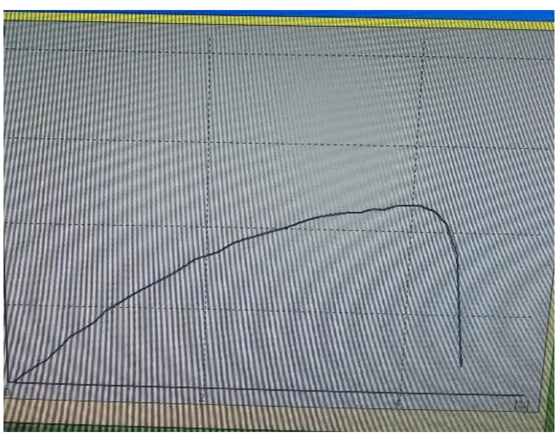
Tensile test

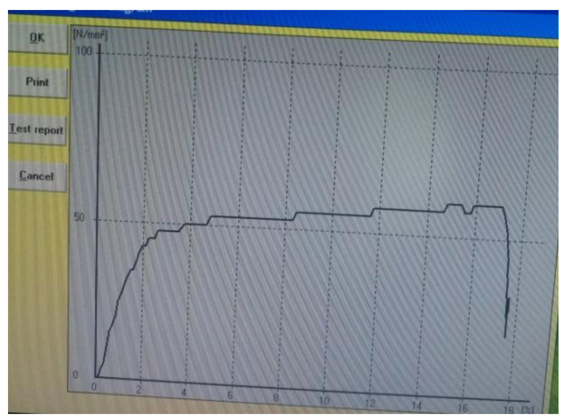


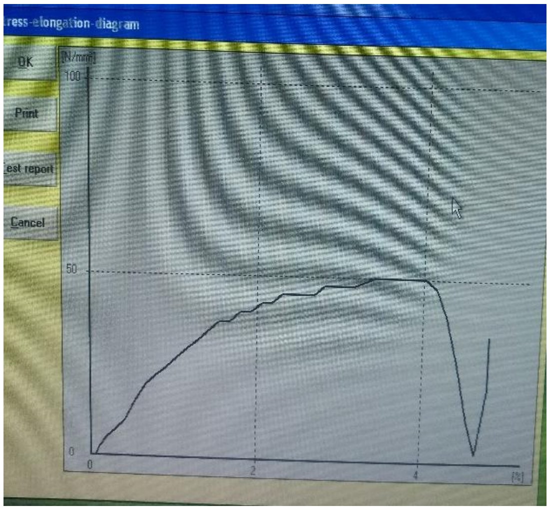


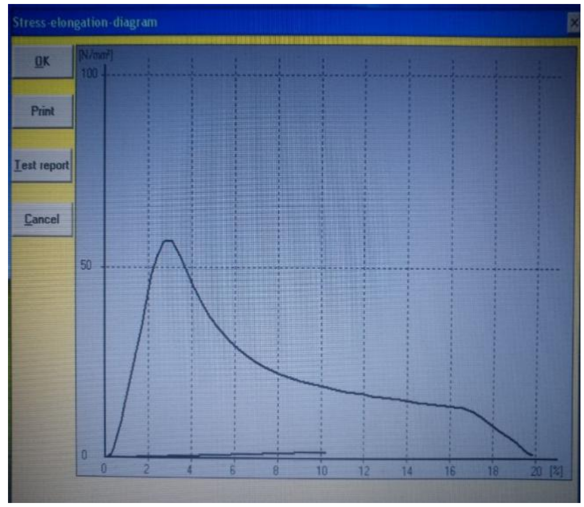


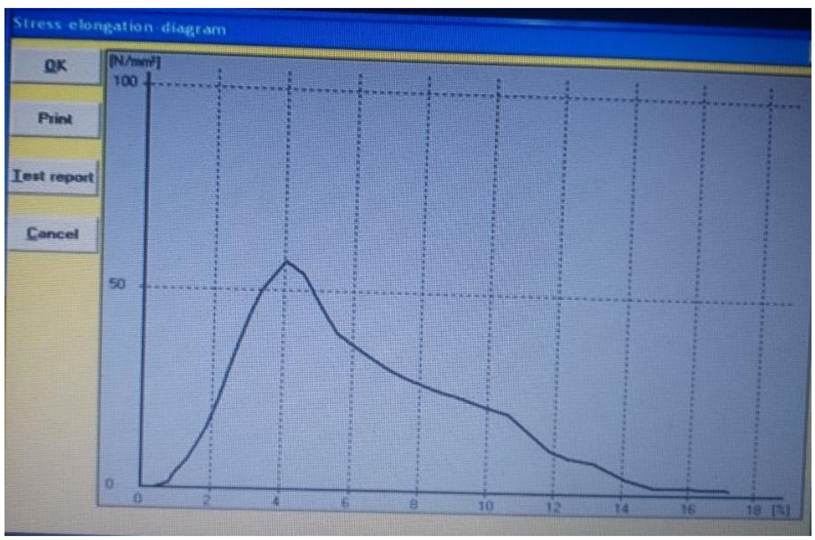






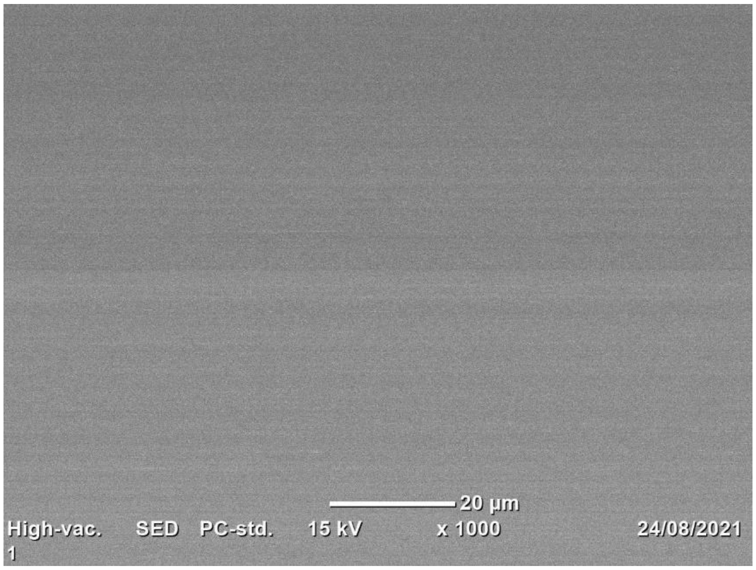


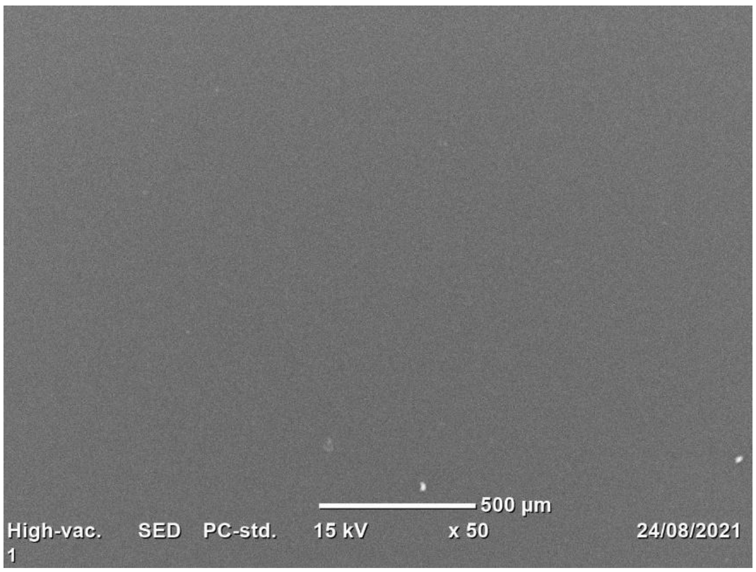


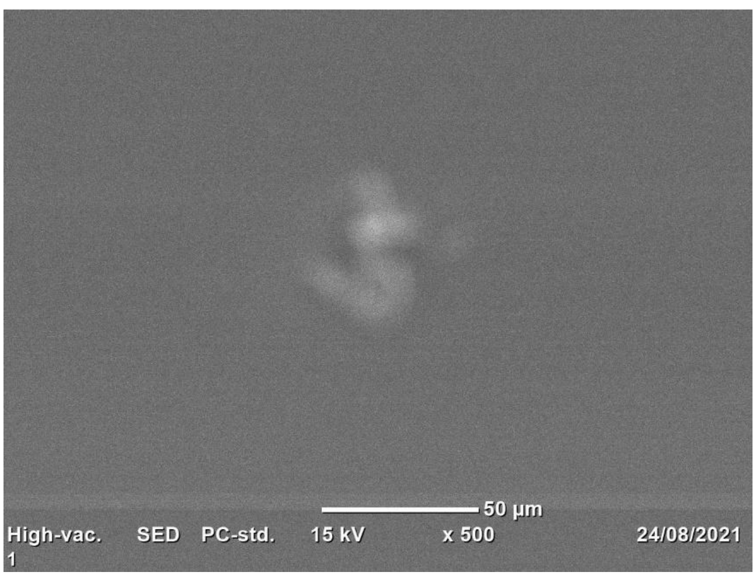


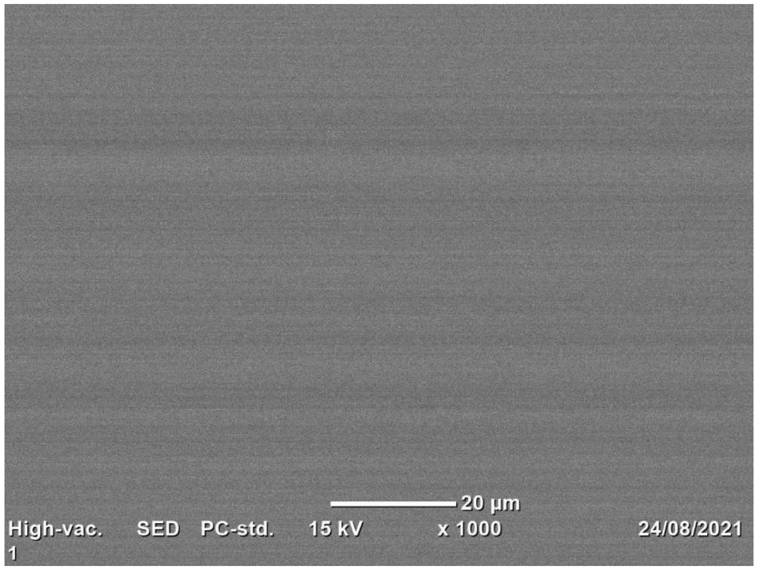
Appendix B

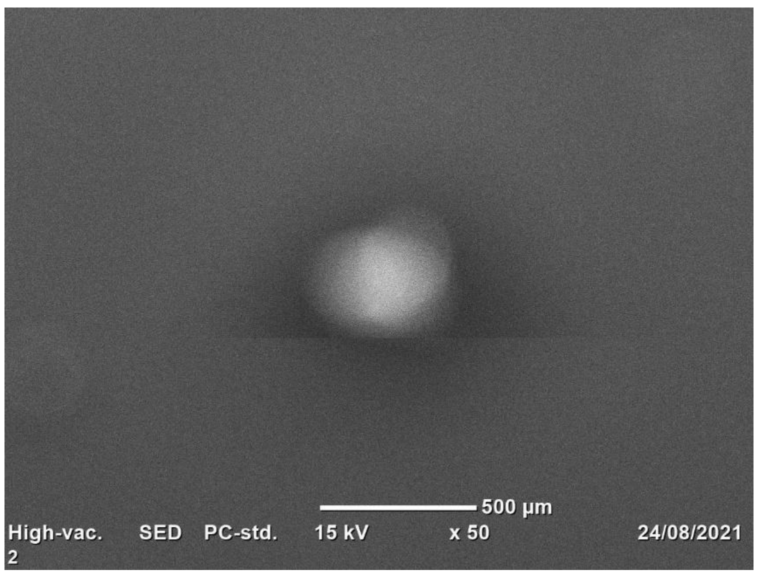
SEM test

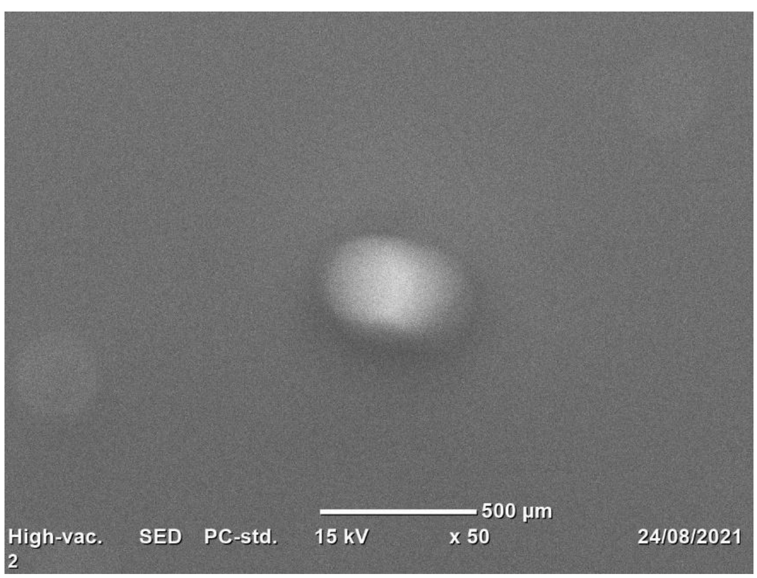

20 µm
High-vac. SED PC-std. 15 kV x 1000 24/08/2021
1

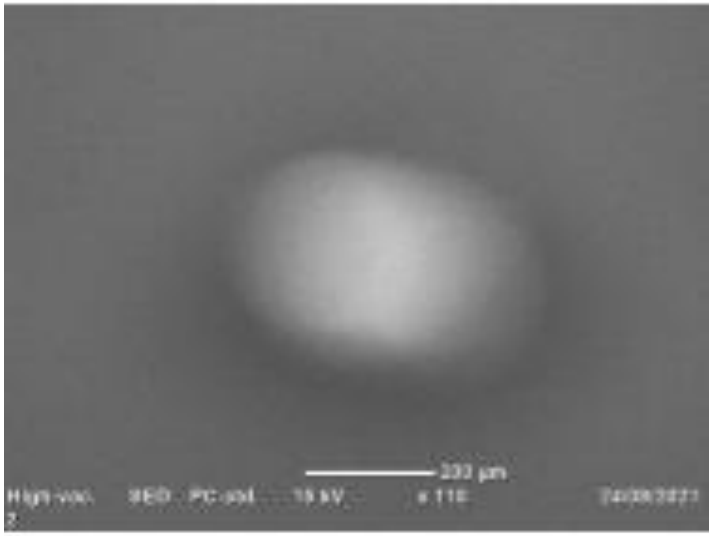

500 µm
High-vac. SED PC-std. 15 kV x 50 24/08/2021
1

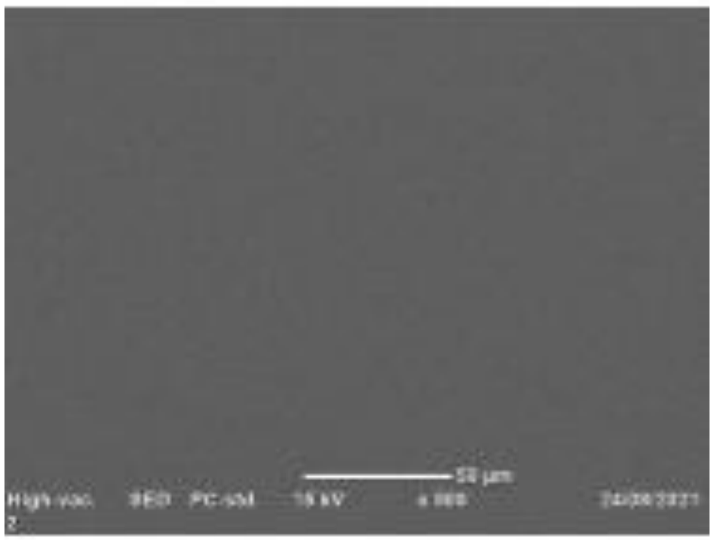

50 µm
High-vac. SED PC-std. 15 kV x 500 24/08/2021
1

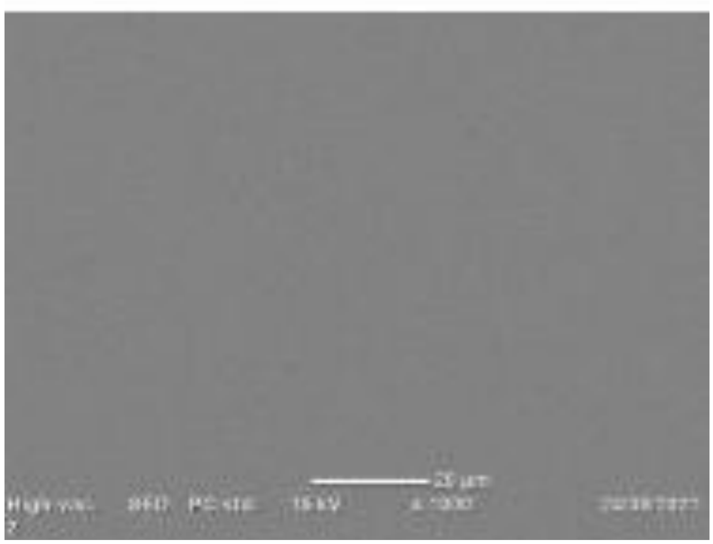

20 µm
High-vac. SED PC-std. 15 kV x 1000 24/08/2021
1


500 µm
High-vac. SED PC-std. 15 kV x 50 24/08/2021
2


500 µm
High-vac. SED PC-std. 15 kV x 50 24/08/2021
2


High-vac.
PC-std.


High-vac.
PC-std.


High-vac.
PC-std.

Appendix C

Minitab 18

↓	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12
	Blowing Temperature	First blow angle	Second blow angle	Blowing speed	Tensile Strength	Wall thickness ratio	Hoop Stretch Ratio	SNRA1	MEAN1	SNRA2	SNRA3	SNRA4
1	96	57	71	11000	65.0	0.2200	5.75	36.2583	65.0	36.2583	-15.1934	-13.1515
2	96	56	70	10000	60.0	0.1950	5.67	35.5630	60.0	35.5630	-15.0717	-14.1993
3	96	58	72	12000	45.0	0.2400	5.81	33.0643	45.0	33.0643	-15.2835	-12.3958
4	95	57	70	12000	62.5	0.2350	5.45	35.9176	62.5	35.9176	-14.7279	-12.5786
5	95	56	72	11000	58.0	0.2250	5.50	35.2686	58.0	35.2686	-14.8073	-12.9563
6	95	58	71	10000	50.0	0.1825	5.60	33.9794	50.0	33.9794	-14.9638	-14.7747
7	97	57	72	10000	48.0	0.2000	6.15	33.6248	48.0	33.6248	-15.7775	-13.9794
8	97	56	71	12000	55.0	0.2300	5.95	34.8073	55.0	34.8073	-15.4903	-12.7654
9	97	58	70	11000	63.0	0.1800	5.88	35.9868	63.0	35.9868	-15.3875	-14.8945

Taguchi Design

Design Summary

Taguchi Array	L9(3^4)
Factors:	4
Runs:	9

Columns of L9(3^4) array: 1 2 3 4

Taguchi Analysis: Tensile Strength versus Blowing ... le, Blowing speed

* NOTE * Unable to perform linear model analysis.

The following terms cannot be estimated and were removed:

Blowing Temperature*First blow angle
Blowing Temperature*Second blow angle
Blowing Temperature*Blowing speed
First blow angle*Second blow angle
First blow angle*Blowing speed
Second blow angle*Blowing speed

Response Table for Signal to Noise Ratios

Larger is better

Level	Blowing Temperature	First blow angle	Second blow angle	Blowing speed
1	35.06	35.21	35.82	34.39
2	34.96	35.27	35.01	35.84
3	34.81	34.34	33.99	34.60
Delta	0.25	0.92	1.84	1.45
Rank	4	3	1	2

Response Table for Means

Level	Blowing Temperature	First blow angle	Second blow angle	Blowing speed
1	56.83	57.67	61.83	52.67
2	56.67	58.50	56.67	62.00
3	55.33	52.67	50.33	54.17
Delta	1.50	5.83	11.50	9.33
Rank	4	3	1	2

Response Table for Standard Deviations

Level	Blowing Temperature	First blow angle	Second blow angle	Blowing speed
1	*	*	*	*
2	*	*	*	*
3	*	*	*	*
Delta	*	*	*	*
Rank	2.5	2.5	2.5	2.5

* ERROR * No graphs will be plotted for StDevs. All values are missing.

* NOTE * Could not graph the specified residual type because MSE = 0 or the degrees of freedom for error = 0.

Taguchi Analysis: Tensile Strength versus Blowing ... le, Blowing speed

* NOTE * Unable to perform linear model analysis.

The following terms cannot be estimated and were removed:

Blowing Temperature*First blow angle
Blowing Temperature*Second blow angle
Blowing Temperature*Blowing speed
First blow angle*Second blow angle
First blow angle*Blowing speed
Second blow angle*Blowing speed

Response Table for Signal to Noise Ratios

Larger is better

Level	Blowing Temperature	First blow angle	Second blow angle	Blowing speed
1	35.06	35.21	35.82	34.39
2	34.96	35.27	35.01	35.84
3	34.81	34.34	33.99	34.60
Delta	0.25	0.92	1.84	1.45
Rank	4	3	1	2

Response Table for Means

Level	Blowing Temperature	First blow angle	Second blow angle	Blowing speed
1	56.83	57.67	61.83	52.67
2	56.67	58.50	56.67	62.00
3	55.33	52.67	50.33	54.17
Delta	1.50	5.83	11.50	9.33
Rank	4	3	1	2

Response Table for Standard Deviations

Level	Blowing Temperature	First blow angle	Second blow angle	Blowing speed
1	*	*	*	*
2	*	*	*	*
3	*	*	*	*
Delta	*	*	*	*
Rank	2.5	2.5	2.5	2.5

Main Effects Plot for Means

* ERROR * No graphs will be plotted for StDevs. All values are missing.

Main Effects Plot for SN ratios

* NOTE * Could not graph the specified residual type because MSE = 0 or the degrees of freedom for error = 0.

Taguchi Analysis: Hoop Stretch Ratio versus Blowing ... Blowing speed

* NOTE * Unable to perform linear model analysis.

The following terms cannot be estimated and were removed:

Blowing Temperature*First blow angle
Blowing Temperature*Second blow angle
Blowing Temperature*Blowing speed
First blow angle*Second blow angle
First blow angle*Blowing speed
Second blow angle*Blowing speed

Response Table for Signal to Noise Ratios

Smaller is better

Level	Blowing Temperature	First blow angle	Second blow angle	Blowing speed
1	-14.83	-15.12	-15.06	-15.27
2	-15.18	-15.23	-15.22	-15.13
3	-15.55	-15.21	-15.29	-15.17
Delta	0.72	0.11	0.23	0.14
Rank	1	4	2	3

Response Table for Means

Level	Blowing Temperature	First blow angle	Second blow angle	Blowing speed
1	5.517	5.707	5.667	5.807
2	5.743	5.783	5.767	5.710
3	5.993	5.763	5.820	5.737
Delta	0.477	0.077	0.153	0.097
Rank	1	4	2	3

Response Table for Standard Deviations

Level	Blowing Temperature	First blow angle	Second blow angle	Blowing speed
1	*	*	*	*
2	*	*	*	*
3	*	*	*	*
Delta	*	*	*	*
Rank	2.5	2.5	2.5	2.5

Main Effects Plot for Means

* ERROR * No graphs will be plotted for StDevs. All values are missing.

Main Effects Plot for SN ratios

* NOTE * Could not graph the specified residual type because MSE = 0 or the degrees of freedom for error = 0.

Taguchi Analysis: Wall thickness ratio versus Blowing ... lowing speed

* NOTE * Unable to perform linear model analysis.

The following terms cannot be estimated and were removed:

Blowing Temperature*First blow angle
Blowing Temperature*Second blow angle
Blowing Temperature*Blowing speed
First blow angle*Second blow angle
First blow angle*Blowing speed
Second blow angle*Blowing speed

Response Table for Signal to Noise Ratios

Larger is better

Level	Blowing Temperature	First blow angle	Second blow angle	Blowing speed
1	-13.44	-13.31	-13.89	-14.32
2	-13.25	-13.24	-13.56	-13.67
3	-13.88	-14.02	-13.11	-12.58
Delta	0.63	0.79	0.78	1.74
Rank	4	2	3	1

Response Table for Means

Level	Blowing Temperature	First blow angle	Second blow angle	Blowing speed
1	0.2142	0.2167	0.2033	0.1925
2	0.2183	0.2183	0.2108	0.2083
3	0.2033	0.2008	0.2217	0.2350
Delta	0.0150	0.0175	0.0183	0.0425
Rank	4	3	2	1

Response Table for Standard Deviations

Level	Blowing Temperature	First blow angle	Second blow angle	Blowing speed
1	*	*	*	*
2	*	*	*	*
3	*	*	*	*
Delta	*	*	*	*
Rank	2.5	2.5	2.5	2.5

Main Effects Plot for Means

* ERROR * No graphs will be plotted for StDevs. All values are missing.

Main Effects Plot for SN ratios

* NOTE * Could not graph the specified residual type because MSE = 0 or the degrees of freedom for error = 0.