Master thesis

Master of Science in Manufacturing Technology

Investigation of longitudinal distortion occurring in Acrylonitrile butadiene styrene copolymer (ABS) extrusion profiles

by

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Investigation of longitudinal distortion occurring in acrylonitrile-butadiene-styrene copolymer (ABS) extrusion profiles

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List of tasks

- Description of the problem in detail
- Reviewing the further works and their results
- Observation of extrusion process and post-processes
- Choosing the parameters to be investigated regarding banana problem for each process
- Making the test plans including these choosen parameters
- Conducting these tests producing samples and labeling them
- Making the banana measurements for each sample
- Analyzing the test datas statistically, obtaining the results showing the influence of each parameter on the banana problem
- According to these results, making standardisations, configurations and process change if need to minimize the banana problem
- Discussion of the results and recommendations for further works

Eidesstattliche Erklärung einsortieren

Summary

In this study, the longitudinal distortion of acrylonitrile-butadiene-styrene (ABS) extrusion profiles was investigated experimentally. The longitudinal distortion is a problem which is seen mostly in extrusion profiles. Since it causes deformed edge bands which look like a banana, this is known as banana problem. It creates undesired situation for customers and, consequently, for the producer. The aim of this work is to investigate this problem depending on chosen parameters by making tests and analyzing the results in order to find possible reasons, and then, to minimize or avoid the problem.

The general polymer classifications and characteristics of ABS which could be related to the longitudinal distortion problem were explained in detail. The extrusion process and its units were examined by focusing this problem. In experimental works, the entire extrusion line was observed, then, some processes were investigated by making cutting, winding and tensile tests. During observation, the parameters which could have an effect on banana shape were decided. With these parameters, test plans were created. Afterwards, these tests were conducted, then, the results were analyzed with the help of design of experiments (DOE). According to results, some causes were found. Some improvements such as alternating winding process were made in the extrusion line accordingly. Influences of studied parameters on the longitudinal distortion were shown and interpreted for further studies.

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1 Introduction

1.1 Definition of the problem

Extrusion is a basic plastic processing method in which a polymer material is melted. Then, this molten plastic is formed by pushing through a die with the help of high pressure created by the screw. Common polymers, such as high-density polyethylene (HDPE), low-density polyethylene (LDPE), polypropylene (PP), polystyrene (PS), polymerizing vinyl chloride (PVC) and acrylonitrile-butadiene-styrene (ABS) which is examined in this study, are used as raw material in the extrusion process. ABS is a widely used copolymer which is a combination of acrylonitrile, butadiene and styrene. Its important characteristics are hardness and rigid structure coming from Acrylonitrile-styrene copolymer, and ductility resulted by Butadiene polymer.

Longitudinal distortion is a commonly encountered problem in extrusion profiles with continuous cross-section. This problem will be later called 'banana problem' because of its resemblance, will be studied in detail.

Edge bandings, which are mostly demanded for furniture business, are used in home decoration and furniture. It is bonded to the sharp edges of chipboard or medium-density fibreboard (MDF) for safety and aesthetic concerns. They can be seen in the edge of tables and cabinets, as seen in Figure 1-1. This bonding process is done by gluing or laser bonding. Edge bandings, which consist of polymer materials, are manufactured in thickness ranging from 0,4 mm to 3,0 mm, in width ranging from 12 mm to 100 mm, by extrusion process. After the extrusion process, post-extrusion operations are done depending on use and material of the edge banding. For production of ABS polymer edge bandings which will be studied in detail later on, the post-extrusion processes in sequence are embossing, cooling, haul off, printing, primer, lacquer, in-line cutting in which 100 mm width extruded part is slit to 4 equal width edge bandings, and winding processes.

Figure 1-1: Sample of ABS edge band

It was observed that the dimensions of the edge bandings change both short after the production, as well as in long term. Especially in edge bandings from 0,8 mm to 1,0 mm in thickness, these changes were observed bowing to up or down as seen in Figure 1-2. Since it resembles the shape of banana, it is called 'banana shape effect'.

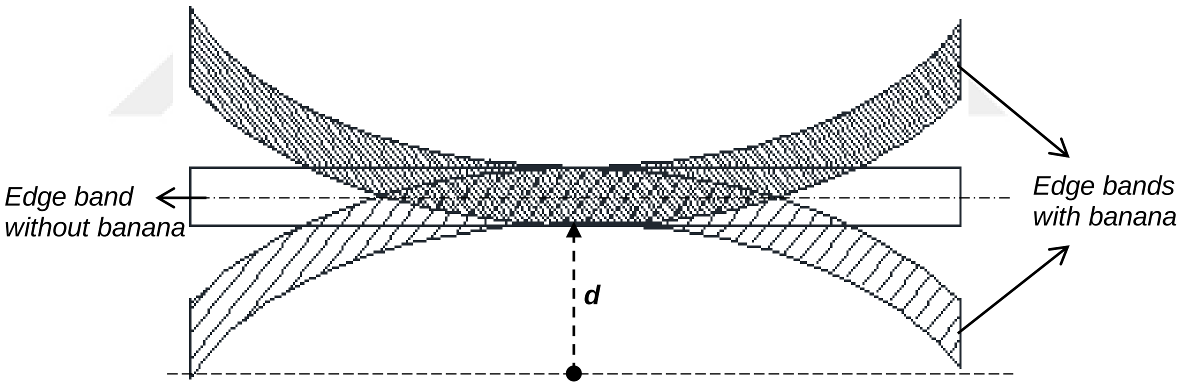


Figure 1-2: Top view of edge bandings with longitudinal distortion in both directions

As well as the decor of edge banding, its dimension has also visual significance on home decoration. For dimension control, edge bending sample with 2 meter length is taken from the product just after the production. After it is fixed from both ends in the same direction, the distance, ***d***, between the middle point of the sample and the point, where it is supposed to be in the same direction with fixed ends, is measured. Sample edge band on the measurement table can be seen in Figure 1-3. The important point here is that both ends of edge band have to be relaxed instead of being stretched during measurement.

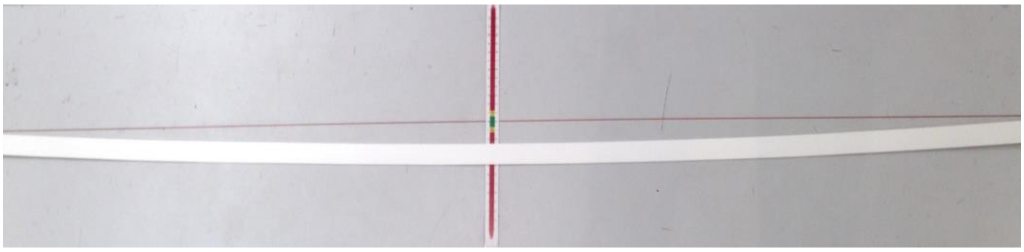


Figure 1-3: Banana-shaped 2m edge band sample and measurement table

As in all measurement techniques, there is a tolerance value which was decided by the customers here. While the edge bandings, which have ***d*** ≤12 mm dimensional deviation, are acceptable, those, which have bigger than 12 mm, are not acceptable. These edge bandings cause a big problem during bonding of edge bandings to the boards or furniture. Since the furnitures have straight edge, laser bonding or gluing, which are bonding techniques used by customers, can be only applied straight. However banana-shaped edge band can not be bonded to the straight edge of the furniture, because it is curved. So to say, this problem creates very undesired situation for furnishers and carpenters. In that case, they would be all scrap.

1.2 Aim of the study

The purpose of this study is to understand this problem by investigating and analyzing the processes which can be a cause for this problem, then, to find possible reasons for minimizing or avoiding the problem. In this case, the company would get a knowledge about ABS polymer behaviour to take precautions by making improvements in order not to have it in the future.

Since the banana shaped edge bands can not be applied to the straight surfaces, they become scrap. When the scrap volume increases, consumption of plastic increases, use of production sources as well. The loss of company increases in total incrementally. Owing to avoiding or minimizing by keeping this problem in tolerance range, the company can minimize the scrap and loss.

1.3 Procedure of the study

Before starting, actual extrusion process is divided into three steps, Winding, Cutting and Extrusion steps to make the study easy searchable by going step-by-step. Then actual process conditions are firstly observed for each step. During observation, the parameters which could have an effect on banana shape are decided. With these parameters, test plans are created. Afterwards, these test plans are conducted. After the tests, the results are analyzed. Within this period, for creating test plan, making and analysing the tests, Design of experiments (DOE) is used with the use of Minitab software.

With the statistical analysis of results, the effects of parameters are seen numerically. After the test, the best result are chosen by comparing the effects of parameters. In the further tests, this best case is used to minimize the effect of that parameter. According to the results, optimum process conditions are implemented to minimize the banana effect.

2 Polymer Science

2.1 Introduction to polymer science

Polymers have been in the nature from the beginning of the universe, as a molecule form in animals, plants or any living organisms. However, they have being understood in last decades with improving science. As their nature has been understood, they have been developed by humans. Thus, new polymeric materials have been started to being used in human life, and their use is increasing day by day (Ebewele, 2000).

The first polymer found in natural products, like cotton, proteins and cellulose in trees have being used more in different areas, since they are advantageous compared to traditional materials, low cost, improvable in performance and safety, low weight, corrosion resistance and good insulation and conduction properties (Akay, 2012).

Polymer is a greek word meaning many (*poly*) units (*mere*). So basically, it is a large molecule which is called polymer molecule or macromolecule emerging from the repetition of small chemical units, called monomer that can be a single atom or a small group of atoms(Ghosh, 2006). As an example, the configuration of monomer (left) and polymer (right) can be seen in Figure 2-1.

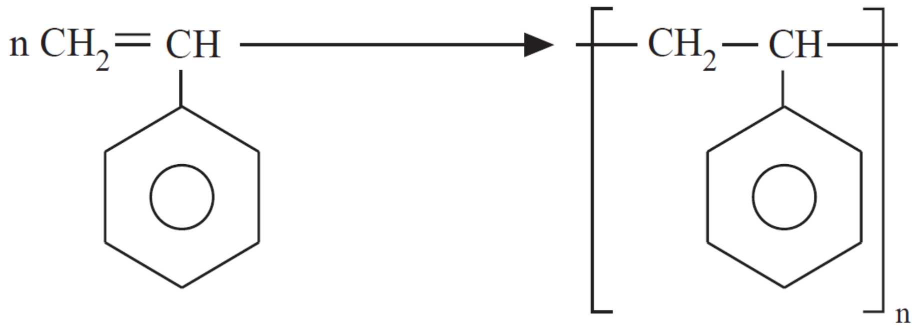


Figure 2-1: Styrene (monomer) and polystyrene (polymer) [Ebewele, 2000]

After opening the double bond of styrene, it becomes open to be linkable with other styrenes. Then *n*- number styrene are linked up each other by covalent bonding with the help of heat, light or a special catalyst as an initiator. As a result of bonding the repeat units, can be seen in above on right, the polystyrene which has degree of polymerization of n is obtained (Ghosh, 2006). This chain can be seen in Figure 2-2.

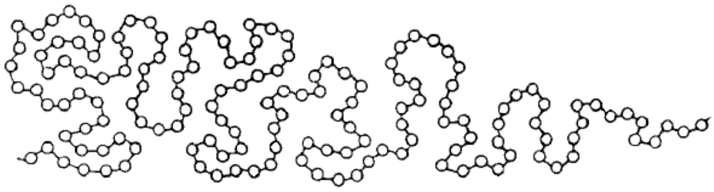


Figure 2-2: Polymer molecule model [Ghosh, 2006]

If we talk about chain, the length should be discussed. Here the term Length to Diameter (L/D) is used to specify the difference between polymers. This difference is in only physical and mechanical properties. Thermomechanical conditions determine the degree of entanglement. In case of melting temperature, the chain could be more straight and having more long length (Ghosh, 2006).

2.2 Polymer classifications

Polymers have been categorized in different ways. These categories are based on the origin of the polymer, the polymer structure, polymerization mechanism, molecular forces, the monomer type in the structure, thermal response and the composition.

There are three kinds of polymers based on the origin; natural, semisynthetic and synthetic polymers. Natural polymers are found naturally existing in plants or animals as proteins, cellulose, enzymes, natural rubber and starch etc. Semisynthetic polymers is obtained from natural sources but applied chemical treatment before use, like vulcanized rubber, some cellulosic polymers. The polymers which were produced in laboratories by humans due to needs are called synthetic polymers such as ABS (Ghosh, 2006).

According to the chain structure, polymers are classified into three groups, linear, branched and cross-linked structures, as in Figure 2-3. Linear structure is having long chain in which all monomers are linked to each other without branches. They have higher melting point and density. Branched structure is having linear chain with branches in which monomers are linked to each other in different length. Due to these branches, they have lower density and melting point. Cross linked structure is a complex structure in which monomers are linked to each other in three dimensional network structure. These polymers are hard and brittle (Ghosh, 2006).

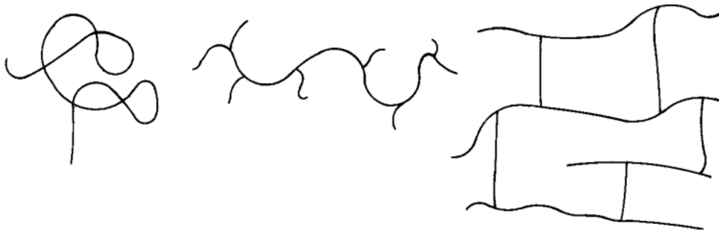


Figure 2-3: Linear (left), branched (middle), cross linked (right) [Ebewele, 2000]

Intermolecular forces which pull the molecules to each other are determined by chemical bonds between molecules. These chemical bonds are divided into two bonds depending on valence electrons. In primary valence bonding, because the atoms are kept together to create molecules by using their valence electrons, they are strong bonds which are ionic, metallic and covalent bonds. The atoms in polymers use mostly covalent bonds. In secondary bonding, the valence electrons are not used, because all electrons were used to form molecules. However, these molecules pull to each other because of cohesive aggregation. These are called secondary valence forces, known as van der Waals, dipole and hydrogen bonds which are weaker than primary bonds. Both are created in molecule formation. To have maximum strength of these bonds, the effect of secondary bonds must be increased by coming all molecules close to each other (Ebewele, 2000). These intermolecular forces contribute defining the mechanical properties of plastics, such as tensile strength, stretchability and tension (Ghosh, 2006).

There are two polymers when they are heated giving different response. Thermoplastics are softening and melting, and can be easily molded. When they are cooled, they become hardened. They are reusable and recyclable. Heating and cooling can be applied many times reversibly. However, thermosettings soften, then change chemically irreversibly when they are heated. Thermoplastics are mostly linear and branched polymers which are soluble and fusible, such as ABS, while thermosettings are cross-linked polymers which are insoluble and infusible (Ghosh, 2006).

According to their composition, polymers are divided into two groups, homopolymer and copolymer. Homopolymers are having same repeating units in their molecules. Copolymers are created by adding different repeating units. ABS is a copolymer which is combined of three monomers. They are having more than one repeating unit in their molecule. Copolymers have four subgroups, random copolymer which the repeating units are found randomly on the chain, alternating copolymer that the repeating units are found ordered, block copolymer that has repeating units ordered blocks, graft copolymer which one repeating unit is branched onto other repeating unit (Ebewele, 2000).

Molecules are existing in nature as a form of solid, liquid and gas. This differs in polymers, because of strong intermolecular forces and complex chains, they decompose before vaporizing. Also, the length of polymer chains restraint formation of crystals found in solid phase of polymers. Thus crystallinity is a term used to describe the degree of structural form in polymer solids (Ebewele, 2000). This classifies the polymers into three groups; crystalline, semi-crystalline and amorphous. Crystalline polymers have long chains arranged orderly by forming plate-like structure, known also as lamellar crystals. Amorphous polymers have more disordered short range repeating units instead of ordered long chains, such as ABS. Semi-crystalline polymers contain both structures in their volume (Ghosh, 2006). In Figure 2-4, amorphous and crystalline structures can be seen.

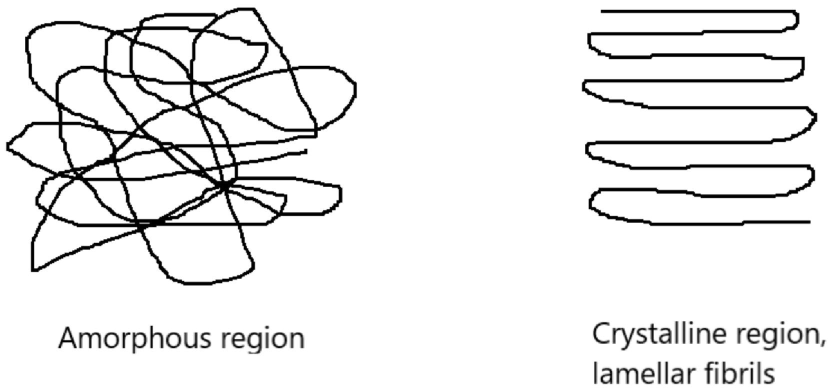


Figure 2-4: Amorphous and crystalline regions of a polymer

2.3 Acrylonitrile-butadiene-styrene (ABS)

Acrylonitrile-butadiene-styrene (ABS) is a synthetic polymer was discovered to improve both polystyrene and styrene-acrylonitrile properties. It is a synthetic amorphous thermoplastic. It can be found with branched or linear structure. It is a alternating copolymer.

ABS is a copolymer, known also as terpolymer, which is derived from combining of three different monomers, acrylonitrile, butadiene and styrene, as seen in Figure 2-5.

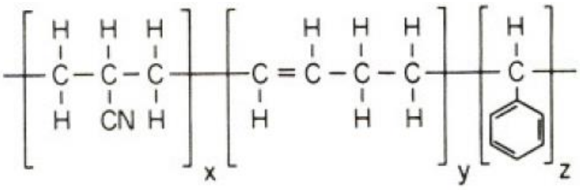


Figure 2-5: Configuration of ABS, acrylonitrile(left), butadiene(middle), styrene(right) [Rutkowski and Levin, 1986]

ABS can be generated by two methods. In the first method, styrene-acrylonitrile copolymer resin is blended with butadiene-acrylonitrile elastomer mechanically. In the second method, styrene and acrylonitrile are grafted onto polybutadiene. The volume fractions of these monomers are important for the physical properties of ABS. The constituents are varying from 15-30% acrylonitrile, 40-60% butadiene and 5-30% styrene. While acrylonitrile gives chemical resistance and heat stability, butadiene contributes toughness and impact strength, styrene delivers rigidity and processability to ABS polymer. In overall, ABS plastic shows good strength, rigidity, toughness, durability as well as good electrical and thermal properties. These properties can be changed by modifying volume fractions of these monomers (Ebewele, 2000).

It is used in home appliance products, pipe, fittings and housing of fridge and TV etc. Commercial ABS is found as a granule and filament. Nowadays, it is becoming popular in Additive manufacturing technology, specially in 3D Printing technology as a filament. Its general properties can be seen in Table.2-1.

Properties	Results
Density, g/cm^3	0,99-1,10
Ultimate strength, MPa	18-63
Glass transition temperature T_g, ˚C	107
Elongation, %	10-140
Modulus of Elasticity, MPa	700-2870
Notched impact resistance, N-m/cm	0,37-6,4
Heat deflection temperature, ˚C (ASTM D648)	75-107
Dielectric constant, 10^3 cycle	2,7-4,8
Dielectric loss, 10^3 cycle	0,002-0,012
Water absorption 24h, % (ASTM D570)	0,1-0,3
Speed of burning	Slow
Sunlight effect	Yellowing
Acid/base effect	Influenceable
Transparency	Opaque

Table 2-1: ABS general properties [Savasci et al., 2008]

2.4 Characteristics of ABS

Above, ABS copolymer was introduced and told about its general properties. In this chapter, properties of ABS are studied in detail, and some properties which is thought that it could has any effect on banana problem is investigated. Morphological structure of polymers is studied to understand the behaviour of polymers. Since ABS is an amorphous polymer, amorphous structure properties are focused.

2.4.1 Glass transition temperature

Normally, molecules have 3 different physical phases; solid, liquid and gas. The transitions between these phases are apparent stable, happens at certain temperatures. However, the transitions for polymers are partially different and more complex. In most polymers, decomposition happens before boiling, in cross-linked polymers, decomposition happens before melting. Transitions between liquid and solid phase are more dispersed and hard to pinpoint (N.N., 2004).

There are two temperature points to understand the thermal behaviour of polymers. In crystalline polymers, crystalline structure melts above the crystalline melting point (T_m). In amorphous polymers, there is no melting, but transition happens. This transition takes place in the temperature point called the glass transition temperature (T_g). In this area, the phenomena passing from liquid-like phase to glass-like phase in amorphous polymers occurs and known as the glass transition (Jadhav et al., 2009).

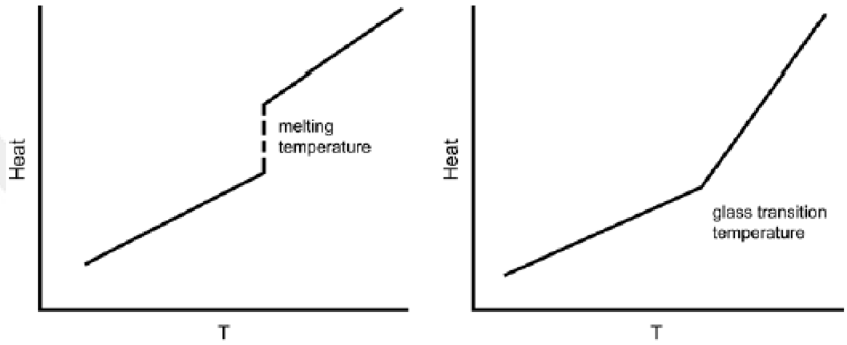


Figure 2-6: Heat-Temperature plot; a)melting point(left), b)glass transition point(right) [Jadhav et al., 2009]

Figure 2-6 exhibits the measure of heat applied to the polymer on y-axis and the related temperature on x-axis. In Fig.2-6a for fully crystalline structures, non-continuous line is showing break at melting point. The solid takes a huge amount of heat without any temperature change at this zone, known as latent heat of melting. Slope of upper line of plot is equal to heat capacity. In Fig.2-6b for fully amorphous structures, there is no break or latent heat in heated polymer, but the only change at the glass transition is unstable temperature with increasing heat. This increase in slop exhibits the increase in heat capacity (Jadhav et al., 2009).

Figure 2-7 shows the specific volume change with temperature in both amorphous (ABCD) and crystalline (ABEF) polymers.

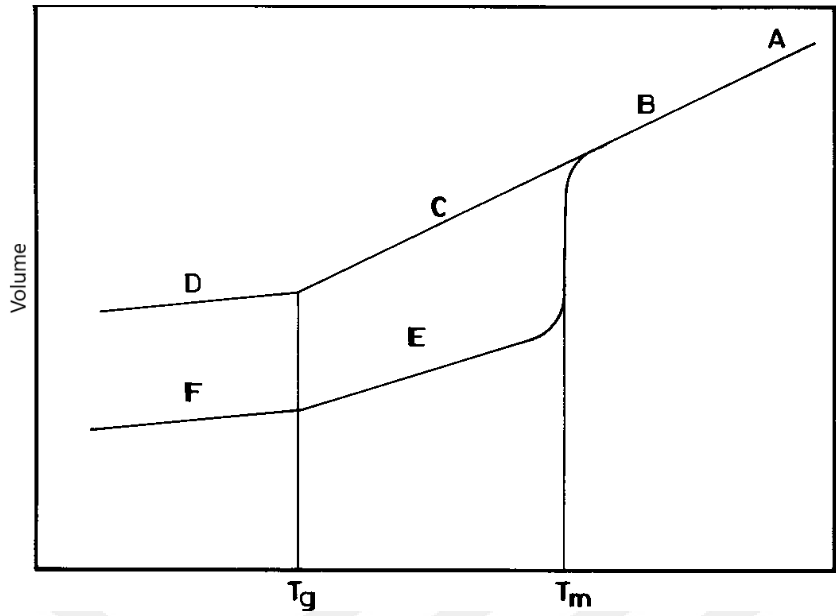


Figure 2-7: Specific volume-Temperature plot; (A)Liquid zone; (B)viscous liquid with some elastic response; (C)rubbery zone; (D)glassy zone; (E)crystallites in a rubbery matrix; (F)crystallites in a glassy matrix [Ebewele, 2000]

If the amorphous one is heated, the volume increases with constant rate until T_g. Beginning from T_g, volume starts to increase with higher constant rate, and hard, brittle and glassy state (zone D) transform to soft, rubbery state (zone C) above T_g. When still keep heated, it changes to viscous liquid state (zone B) from the rubbery state. Viscosity decreases with increasing temperature until thermal degradation (zone A). In crystalline polymers, the changes at T_g are less, since the changes takes place only in small amorphous areas, while crystalline areas are not affected. Between T_g and T_m, the polymer becomes composing of rigid crystallites dispersed in a rubbery amorphous matrix (zone E). This structure is rigid, flexible and tough when compared to zone C. At T_m, crystallites melt resulting in viscous liquid as in amorphous polymers.

As expressed above, some changes in properties of amorphous polymers are seen at T_g, like hardness, volume, percent elongation to break and Young modulus. Polymers are hard, brittle and glassy below T_g. Above T_g, they become soft and rubbery. While some polymers are used below their T_g which is higher than room temperature, some, e.g. rubbers, are used above their T_g that is lower than room temperature (Jadhav et al., 2009). That is why the glass transition temperature must be known for the use of polymers.

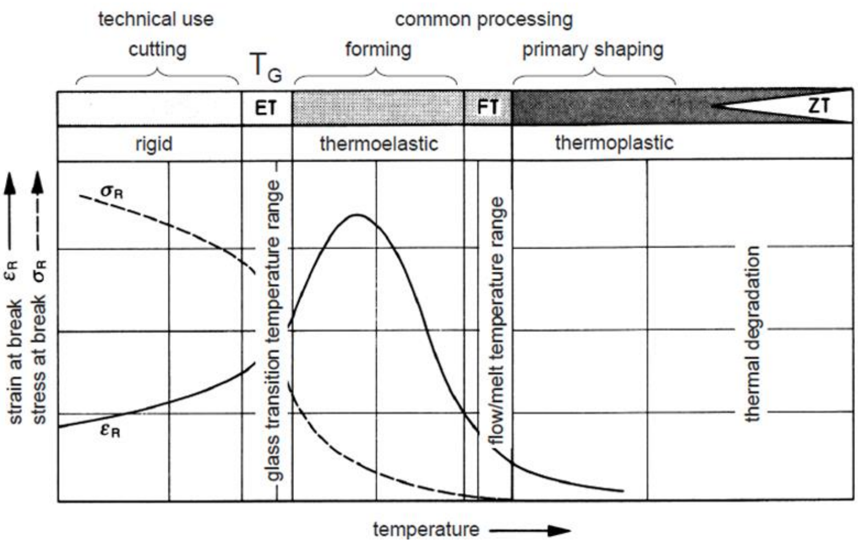


Figure 2-8: State plot of amorphous polymers depending on temperature [Stommel, 2016]

In Fig.2-8, ABS state diagram can be seen. At temperatures below T_g which is used for technical use like cutting, stress at break is higher than strain at break, above T_g used for forming, stress decreases, while strain increases because of viscous concept until processing temperature. Exceeding processing temperature used for primary shaping, thermal degradation happens. For ABS, T_g is around 105ºC, while processing temperature is around 230ºC (Flynt, 2017).

2.4.1.1 Glass transition on a molecular scale

As mentioned above, intramolecular forces are caused by primary bonding, intermolecular forces are provided by secondary bonding. Heating process effects the intermolecular bonding by causing vibration, rotation and translation movements of a molecular system. Vibrations are always existing at every temperature range. Durability of molecular system is determined by the vibration energy of the bonds. Therefore, thermal degradation happens after exceeding the vibration energy of the bonds. Other movements, rotational and translational, are related to the transitional phenomena and the deformations, happening at T_g and T_m (Ebewele, 2000).

In amorphous polymers at low temperatures, chain segments are inactive except atomic vibrations. When the temperature is increased, the magnitude of these vibrations rise, secondary bonding forces become weaker. At T_g, chain ends and segments obtain enough energy to get rid of intermolecular restraints and get long range segmental motion, which is a motion to make the polymer pliable, consequently, cause an increase in free volume (Sperling, 2006). With increasing temperature, thermal energy and magnitude of molecular motions increase as well. Even translation or slip of molecules becomes possible, elasticity gets lost. When decreased the temperature to below T_g, this segmental motion stops, moving chains become extended chains which have minimum energy causing decrease in free volume, lastly, the glass transition happens.

Theories of glass transition should be also known to understand the complex nature of glass transition including equilibrium, thermodynamic and kinetic factors. In free-volume theory, molecular motions are caused by the existing holes, vacancies or voids where the atoms could be settled (Sperling, 2006). In kinetic theory, glass transition must be considered as a dynamic response because it is dependent upon the rate of heating or cooling, namely, time scale. In thermodynamic theory, glass transition is considered as a result of a change in entropy in changing temperature.

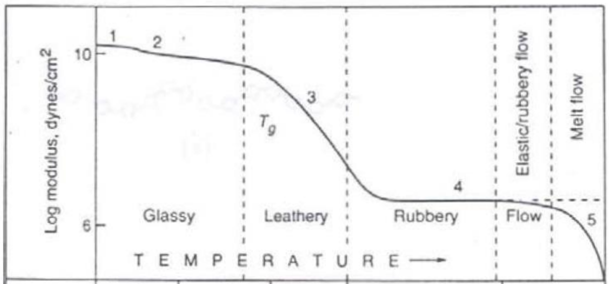
2.4.1.2 Factors influencing the glass transition

When chain length decreases, chain ends increase per unit volume, consequently, free volume increases. T_g becomes lower. Polymers which are with backbone having higher flexibility, meaning need lower activation energy, have lower T_g. Side groups increase the chain stiffness, lower the flexibility, increases T_g. Branched structure have more chain end, so have more free volume which means lower T_g. However, branches act like side groups which lower rotations and increase T_g. Cross-linking decreases the mobility of chain, so T_g will increase. Small molecules and plasticisers causing plastic flow, increase the chain mobility by leaving gap, so T_g decreases. Higher crystallinity increases T_g. Other effect changing T_g is time. Short times do not give enough time to chains to move, so the polymer is still glassy. Intermediate times may be enough to be rubbery. Lastly, the chains move easily on each other at longer times, so the polymer becomes a viscous liquid (N.N., 2004).

2.4.2 Viscoelasticity

The behaviour of materials depending on the deformation characteristics divides the ideal materials into two groups, the elastic solid and the viscous liquid. The elastic solid which has a certain form deforms applying external forces into changed shape, after removing of these forces, it reverts back to its original shape. During the deformation, it keeps the energy coming from the external forces, then, uses this energy to get back the original shape after removal of these forces. On the contrary of elastic solid, viscous liquid has no certain shape and flows irrecoverably under the external forces (Ward and Sweeney, 2004).

Unlike elastic solid and viscous liquid, polymers exhibit intermediate characteristics of both elastic solid and viscous liquid which are depending on temperature and experimentally chosen time. The material response showing liquid and solid like properties involving complicated relation of temperature, time and stress is called viscoelasticity. Five regions of viscoelastic behavior in amorphous polymer can be seen in Fig.2-9.



	1	2	3	4	5
Defor-mation	Hookian glassy	Secondary transition	Primary transition	Highly elastic rubbery	Flow
Molecular motion	Bend & stretch of bonds	Excitation of internal rotation			
		Side groups	Main chain, gradual	Main chain (segmental) large-scale mobility	Chain slippage

Figure 2-9: Regions of viscoelastic behavior of amorphous polymers [Ghosh, 2006]

Amorphous polymer shows glassy and brittle elastic behavior in glassy state where it is stiff below T_g because of impossibility of large molecules to form crystalline structure. In glass transition state, some viscous molecular relocations take place because of the free volume at T_g. In rubbery states just above T_g, viscous molecular motion continues and elastomeric behavior which is nonlinear elastic occurs, as a viscoelastic result. In flow state, the polymer starts to behave like non-newtonian viscous liquid because of shear rate of flow (Roeder, 2013).

Viscoelasticity is an important plastic behaviour to understand long-term or short-term properties depending on desired application area. It is affected by chemical structure, molecular weight, crosslinking and molecular orientation. There is two basic features seen in polymers as a result of viscoelasticity; creep and stress relaxation.

2.4.2.1 Creep

When a constant load is applied to an amorphous polymer, polymer starts to deform continuously. The first strain value is known from its stress-strain modulus, like in elastic solids, then, its strain increases slowly depending on time for viscous liquids (Cerrada, 2005). This deformation that has time dependent increasing strain under constant stress is called creep. It is enabled by intermolecular motions in amorphous polymers. Strain plot concerned with stress can be seen in Figure 2-10 where ε_1 is instant elastic strain as in elastic solids, while ε_2 is time dependent strain which has non-constant increase.

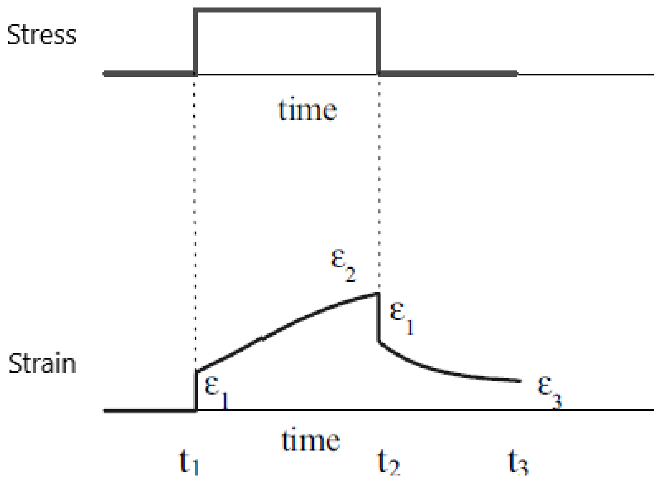


Figure 2-10: Viscoelastic creep strain and stress plots [Cerrada, 2005]

After removal of applied stress, the elastic strain, $\varepsilon_{1,}$ is recovered as in elastic solids. Then, the creep recovery, which is a recovery of some creep deformations, takes place with diminishing rate until remnant permanent strain, ε_3. Although, most polymers have a large portion of permanent strain, some polymers are full recoverable in case of enough time for recovery (Papanicolaou and Zaoutsos, 2011).

2.4.2.2 Stress relaxation

Under deformation, amorphous polymer has a strain. If this strain is kept constant by applying stress, it is seen that this needed stress to keep the viscoelastic polymer at the constant strain reduces with time. This response due to a re-arrangement of molecules in the polymer is called stress relaxation as can be seen in Figure 2-11.

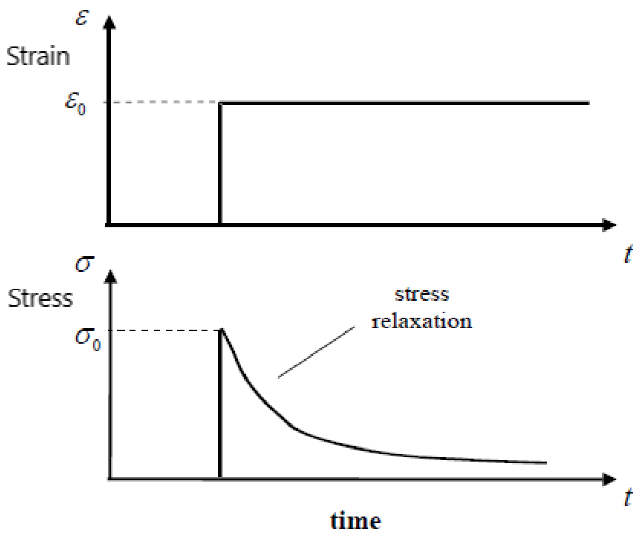


Figure 2-11: Stress relaxation [Cerrada, 2005]

2.4.3 Shape memory effect

Basically, shape memory effect is a feature of a material which can regain its original shape when stimulated under proper conditions. The stimulus which activates this effect is mostly heat, but other stimuli have been also observed such as electric current, humidity, light or alternating magnetic fields (Lendlein, 2013). This effect is caused by the change in the molecular mobility of the chains during the glass transition in amorphous polymers. This occurs in two steps, programming and recovery. The original shape is memorized by the equilibrium state of the cross-links in the structure. In programming step, the change in the molecular mobility during the glass transition causes deformation which brings non-equilibrium state of the chains in temporary form. In recovery step, permanent shape is regained under heating in order to get back equilibrium state before loading (Xiao and Nguyen, 2014).

To understand this behavior in detail, thermodynamic principles of shape memory polymers and basic working mechanism have been discussed below.

2.4.3.1 Molecular mechanism of SME

Amorphous polymers have polymer chains the most random conformation with the same internal energy. In glassy state, all molecular motions are frozen, while, in transition to rubber state under heating, molecular motions become unhindered. The polymer chains obtain the energetically equivalent conformation without any disentanglement as much as possible. Therefore, polymer chains prefer forming random coils than stretched conformations due to entropy. In this state, the polymer can be elongated in the direction of applied force. If this force is implemented for short time, the entanglement of the chains with adjacents will block the permanent motions and the polymer gains back to its original shape, called also as memory effect. If the force is implemented for longer time, the plastic deformation happens due to disentangling of chains from each other. These released chains provide segments to have relaxation and to shape entropically possible random coils. Above T_g, the temperature causes more segment mobility and a decline in the mechanical stress of elastic state being elongated by an external force (Lendlein and Kelch, 2002).

The disentangling of chains under loading can be prevented completely through the cross-linking which have physical netpoints. These netpoints determine also the highest transition temperature. In addition to these, network of molecules have flexible amorphous chain segments. Above T_g, the network becomes elastic, where exhibits entropy elasticity. In case of entropy loss, they can be elongated and oriented by pulling netpoints away from each other. After removal of external forces, the polymer gains back the entropy lost before and the original shape. So, the network is able to keep the mechanical stress in equilibrium (Lendlein and Kelch, 2002).

After cooling the polymer which has been elongated above the transition temperature, strain-induced crystallization of the chain segments takes place. Due to existing of amorphous region, the crystallization can not be complete. However, formed crystallites hinder the chain segments from instantly reshaping the random coils and from recovering the permanent shape which is determined by the netpoints. These netpoints which have highest transition temperature, stabilize the permanent shape of networks (Lendlein and Kelch, 2002).

2.4.3.2 Working mechanisms of SME

Apart from molecular mechanism of SME, they have some basic working mechanisms which include programming and recovery steps. Some of them are depending on application and size, while, others are more generic which can be suitable for wide range of polymers. These are dual state, dual component and partial transition mechanisms.

Dual state mechanism is more seen in the glass transition of polymers. After removal of the force, the deformed shape will sustain at below $T_{g.}$

Above T_g, original shape is regained with the help of cross-links which keep energy in the programming step and use it for recovery step.

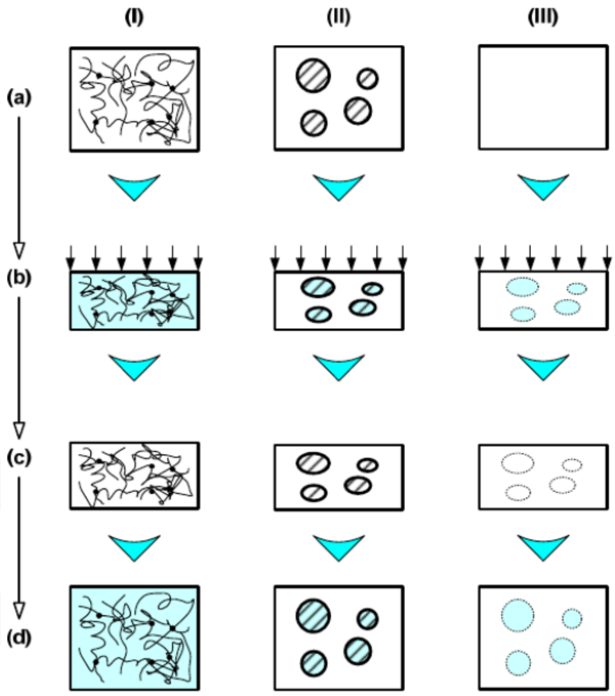


Figure 2-12: Basic working mechanisms for polymers; I)dual-state, II)dual component, III)partial transition, a)original shape, b)during heating and deformation c)after cooling and removing forces, d)re-heating for shape recovery [Wu et al., 2013]

In dual component mechanism, seen in Fig.2-12(II), there are two components, hard segment, which keeps the elastic energy in programming step, and soft segment that determines the toughness during heating. After cooling the polymer and removing the force, deformed shape is maintained except elastic recovery. After heating, the soft segment initializes the shape recovery. The elastic energy kept in hard segment is used as an impulse for recovery (Zhou and Huang, 2014).

There is no cross-link or elastic hard segment in partial transition mechanism, seen in Fig.2-12(III). When the polymer is heated to middle point of a transition, some part of the polymer softens acting as a soft segment in dual component mechanism, while, the rest is still hard. After applying forces and cooling, softened part becomes hard again for avoiding elastic recovery of the deformed matrix. When it is heated, it softens again to previous state which leads to shape recovery.

2.4.4 Molecular orientation

Before using polymers, they are mostly processed by some technologies such as injection molding, extrusion, in which they are stretched under some stress, temperature and speed conditions depending on their use. They are elongated in one direction by forces because of the nature of these technologies. The polymer chains are oriented in this direction, called flow direction. This process in which amorphous polymer molecules are oriented by applying forces above T_g for their application are called molecular orientation, as seen in Figure 2-13.

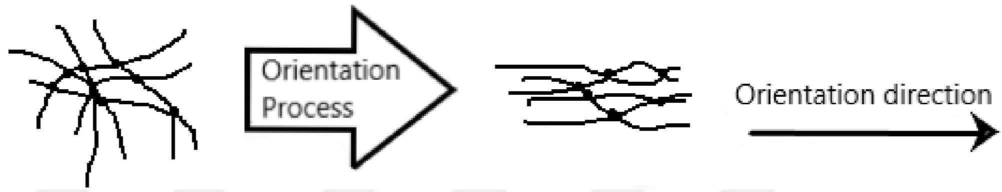


Figure 2-13: Molecular orientation

Polymers become anisotropic materials which their mechanical and physical properties are strongly dependent on flow direction, when they are processed. In crystalline structures, their morphological properties are affected by the molecular orientation, while, the tensile modulus is directly related to the molecular direction in amorphous polymers. The tensile modulus in the direction of the orientation is the highest value and greater than the unoriented polymer modulus, as seen in Figure 2-14. Ductility is also affected by the orientation which causes decreases micro defects and gaps at intermolecular level due to its packing effect (Patel and Bogue, 1981).

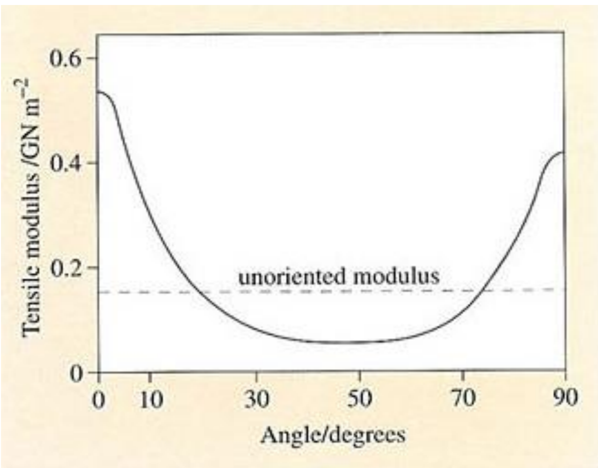


Figure 2-14: Tensile modulus with angle to the orientation direction [N.N., N.D.]

In addition to improving the tensile strength as in Figure 2-14, this is used to increase hoop strength for blow molded bottles and tear strength for films. However, this causes post-extrusion problems due to non-uniform shrinkage and warpage for many extruded parts. During shaping of the polymer in the die as in Figure 2-15, molecular orientation takes place because of the strain introduced to the long chain molecules. The undesired orientation mostly happens while the polymer is pulled by haul-off after the exit of the die. At first, the polymer is at the temperature at which orientation influences are maximum, with promptly cooling. Setting neck-in in the die gap and the speed of flow are usually tried to avoid this problem (Frankland, 2016).

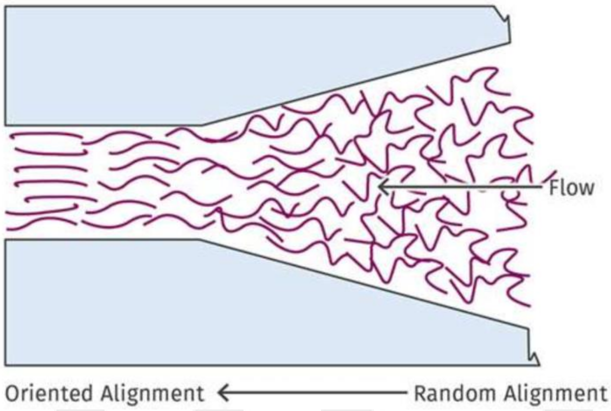


Figure 2-15: Molecular orientation by cross-sectional view of the die [Frankland, 2016]

For transparent polymers, orientation can be measured by birefringence and infrared spectroscopy. In another simple test, called Chrysler test, samples are cut from the extruded part, measured and, then, reheated to near the processing temperature. Afterwards, they are cooled and measured again to detect the shrinkage in shape. This dimensional change shows the degree of orientation in that area (Frankland, 2016).

The tendency of polymer for these post-process problems from orientation is mostly related to T_g, because the glass transition is the temperature at which the polymer transforms from a rubber to a solid. Under the T_g, the movement of molecular chain is mostly limited, that is, any orientation retains. At the T_g, the molecules become free to move and order themselves into relaxed structure to relieve the orientation. Above the T_g, the rate for reaching the relaxed state increases with increasing temperature (Frankland, 2016).

During the aligned deformation, molecular segments which consist of junction points of molecules have rotational rearrangement. These local shear transformations along the chain conclude molecular orientation. Since the molten amorphous polymer is described as a network with junctions or temporary crosslinks being created and chain segments being relocated, it is complex to measure the degree of orientation. Therefore, birefringence is used to know an average of orientation instead of calculation of displacement vectors of each junction (Vrentas et al., 1984).

After removing the deforming forces, the molecules become curled up again if the polymer is still above T_g. In this case, this process do not go to equilibrium. While the molecules start to form random coils, the polymer becomes hard below T_g on the other hand. It possibly causes residual orientation, called as frozen-in strain, and residual stresses, known also as frozen-in stresses (Brydson, 1995).

2.4.5 Residual stress formation

In the end of any manufacturing process, after all forces causing deformation have been removed, some internal stresses are locked within the part, consequently, they decrease the strength capacity of the part. These stresses are called residual stresses which sustain within the deformed solid material. It considerably affects the mechanical and physical properties of the material such as a decrease in ultimate strength and change in dimensions. It is three dimensional stresses that have tensile and compressive stresses components.

When viewed the banana problem as a geometric difference, it could be said that right-curved banana has longer right edge than left edge. In case of opposite, left-curved banana happens if the left edge is longer than right edge. This length difference may take place from different strains resulting in different tensile and compressive stresses. Therefore, residual stresses formation in polymers have been studied.

The residual stresses may have many causes, such as thermal-elastic stresses which are coming from fastly inhomogeneous cooling from the melt, shear stresses which are generated from nonisothermal flow of the polymer through the mold or die, entropy stresses due to molecular orientation of the polymer chains and pressure-induced stresses in injection molding (Turnbull et al., 1999). These stresses can cause unequal free strains due to thermal and phase change which are the root causes of residual stress formation. Zobeiry and Poursartip categorize the formation of residual stresses into 4 scales; micro-level, affected by elastic, viscoelastic properties and thermal properties, molecular orientation, macro-level, resulted in thickness and temperature change through thickness, coupon-level, affected by thermal and surface properties of tools and component-level, including process and post-process parameters (Zobeiry and Poursartip, 2015).

2.4.5.1 Types of residual stresses

Amorphous polymers are processed in the molten state or rubbery state, the part is cooled below T_g fastly in order to make the final shape permanent as desired. Here, some internal stresses can be induced through different ways as clarified below.

Through molecular orientation, the amorphous polymers are deformed. During cooling, the orientation become frozen in including internal stresses which are respond of the material to the deformation process. This causes anisotropy in some mechanical properties and instabilities in dimension or shape. The degree of molecular orientation is directly proportionate to the cross-linking density. Even in thermoplastics, cross-links increase physically with decreasing temperature and increasing rate of deformation. As said above, the most imporant result of molecular orientation is anisotropy. Anisotropy effects, frozen-in entropy stresses, thermal twisting, thermal torsional stresses and thermal shearing, have important role in residual stress formation (Struik, 1978).

In the molten state, molecules are random coils due to the equilibrium state without any stress. When processed, the polymer is sheared and stretched by aligning the molecules in the flow direction. Molecular orientation is locked inside the part, when the solidification happens before molecules are fully relaxed in the equilibrium state. This kind of frozen-in stress is called flow-induced stress, resulting in anisotropy and dimensional instability such as warpage and shrinkage (Zhang et al., 2002).

Another stress is thermal-induced stresses that take place due to shrinking the polymer during the cooling, known also as cooling stresses. Cooling rates of polymer change in width. During cooling, external edges cool and shrink faster than the center which is still hot. Then, the center of the polymer starts to cool and shrink while the edges are already rigid. In this case, contraction of center is restricted by external edges. This results in tensile stress in the center and compressive stress in edges. In case of asymmetric stress distribution, internal stresses are induced as in Figure 2-16 (Zhang et al., 2002).

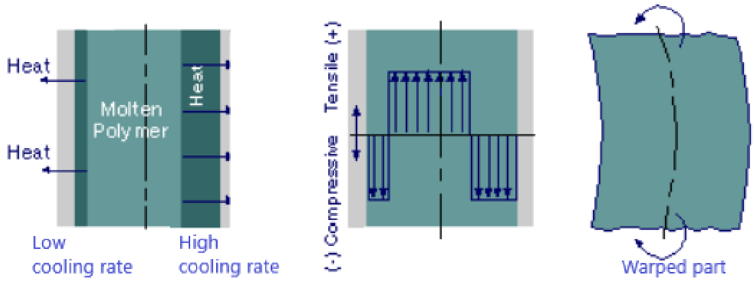


Figure 2-16: Cooling stress induced in a part [N.N., 2006]

Process-induced stresses occur after the deformation, releasing the constraints from the finished part. The part goes to equilibrium state with the stress left inside the part, called residual stresses depending on process. These process-induced stresses can be flow or thermal induced stresses which one of them is the dominant, as seen in Figure 2-17.

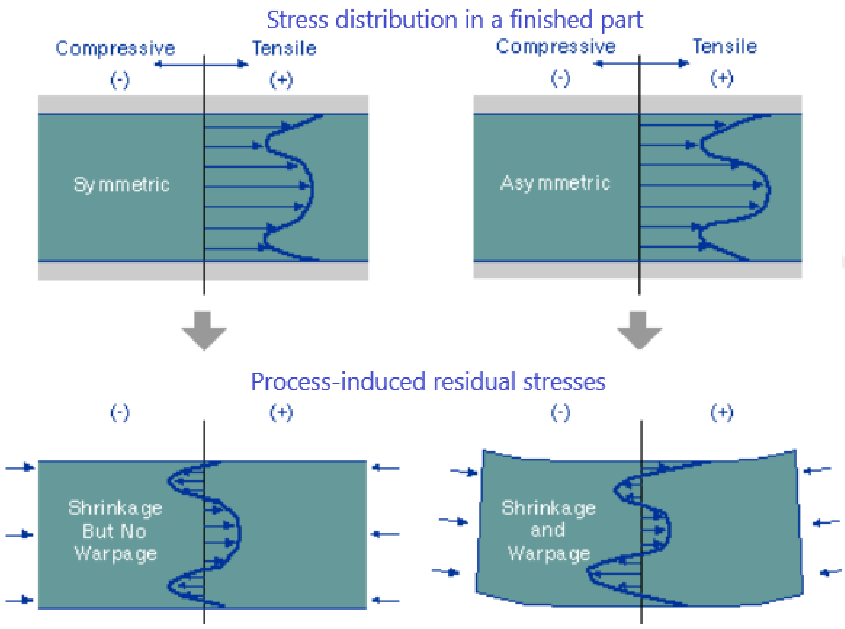


Figure 2-17: Residual stresses in a finished part [N.N., 2006]

3 Extrusion: Polymer Processing Technology

3.1 Fundamentals of extrusion technology

Polymer processing technology consists of two processes. At the first one, polymer is formed into powder or granules. At the second process, polymer is converted into products which have desired shapes from powder or granules. The second kind of polymer processing has many methods depending on use such as injection molding, extrusion, thermoforming, blow molding etc. However the extrusion has been focused below, since this project is about the extruded product.

Extrusion is a technology where granular or powder thermoplastic materials are processed to continuous melt which is then formed into products with uniform cross-sectional area through the die (Ebewele, 2000). This melting process is realized with the help of temperature and pressure. Extrusion line is basically seen in Figure 3-1.

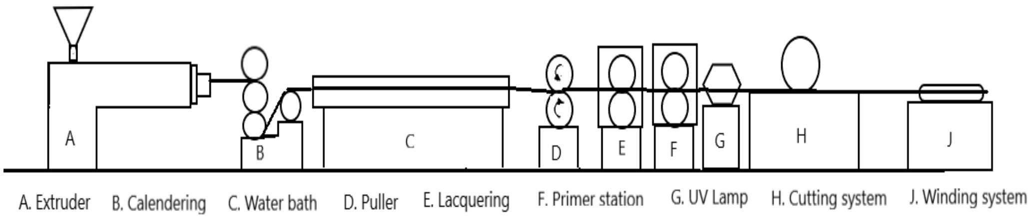


Figure 3-1: Scheme of extrusion line

Basic extrusion line has an extruder in which the granular or powder polymers are melted and transmitted through a screw to the die where is shaped as desired. After the die, the polymer goes to water bath for sizing and cooling where the exact shape becomes permanent by cooling. A Puller which consists of rubber rollers pulls the polymer through into cutter or winder. In order to give it the final shape, the extruded polymer is cut through the cutter. After cutting, cut extruded polymers are coiled up in a winder for handling. Below, the extrusion line has been investigated showing the units used in the experiments, extruder, calendering, water bath, puller stations, UV lamp, slitter and winder.

3.1.1 Extruder unit

This is the first unit in which the melting or plastification take place through heating generated from the heater in barrel and pressure generated by the screw, after feeding the polymer into screw. Feeding system is divided into two groups, dry ingredient and liquid feeders. Depending on use, the feeding system can be integrated with dosing system. In this study, dosing system is used for dosage of color pigments. After feeding, the polymer goes to the screw which is classified into two groups; single screw and twin screw extruders.

Single screw extruders have a barrel and a screw. There are three zones along the screw which have different functions, feed or solid conveying zone, compression or melting zone and metering or melt conveying zone, as shown in Figure 3-2.

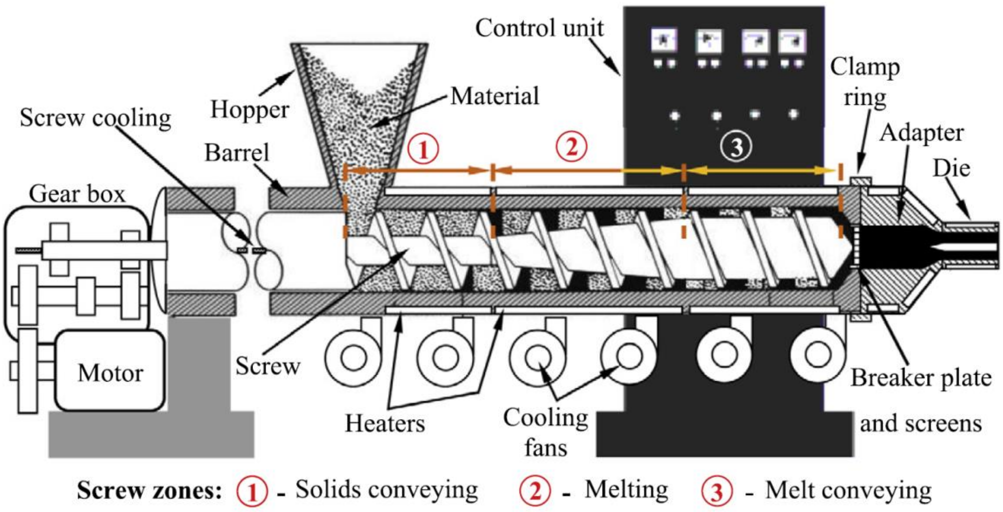


Figure 3-2: Extrusion zones [Abeykoon, 2011]

Along the screw, compression increases as its diameter increases. Feeding zone provides the continuous flow of the raw material coming from feeder to the further zones by starting the melting. Screw geometry, such as the pitch, flight angle and flight depth, determines the transfer capacity. In the compression zone, the melting is fully completed due to special screw elements, such as kneading blocks and interrupted cut flight. In the metering zone, the molten polymer is compressed by the screw region with shallow flights and short pitches to make it ready for die (Fang and Hanna, 2010).

Double-screw extruders have a barrel and double screws, counter rotating and co-rotating. They have good quality mixing and higher capacity compared to single screw. They have similar zones with functions as in single screw extruder. The length of these zones is depending on the material being processed. For amorphous polymers, these zones have almost equal long. Heating is provided by heaters inside the barrel, compression takes place by shearing between barrel and screw as in single screw extruders. The melt characteristics depending on materials due to different viscoelastic properties are strongly affected by screw design features such as, the ratio of effective length of screw to the diameter of screw, L/D, the compression ratio, channel depth, flight, pitch and helix angle as seen in Figure 3-3.

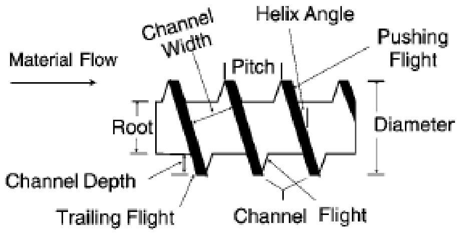


Figure 3-3: Screw elements [Giles et al., 2005]

After the screw, the extruder head is found at the end of extruder in which consist of die and breaker plate as shown in Figure 3-2. Breaker plate, found between screw and die, is used to keep dirt and foreign substances out from the die with the help of screens for thermal homogeneity. Die, mounted at the end of the extruder through the adapter, is used to give final size and shape of polymer products. Molecular orientation of polymer starts here by being pulled in flow direction.

3.1.2 Calendering

Calender is a roll system which have more than one roller and used generally in producing thin, sheet or film, products. Just after the extrusion, extruded softened polymer comes to the calender rollers which are internally heated. Its thickness is gradually decreased in nip regions where is contact area between two rollers by compressing the polymer between them. The thickness is equal to the clearance between rollers. Since the polymer being processed follows the faster roller and sticks more to the hotter roller, smaller roller is used end of this process to peel the polymer off and the middle roller is cold to avoid sticking the polymer (N.N., 2013). The first upper roller which has structure is used to give specific texture to the polymer upper surface in case of desired while compressing the polymer melt.

There is three types of calender arrangements, I, L and Z types as shown in Figure 3-4. In I type, there is an outward force pushing the rollers away at each nip. L type has one roller perpendicular to the adjacent roller, so that, forces cause less influence on other rollers. In Z type, each pair of roller are placed at vertical angle to the adjacent in order to avoid forces coming from others.

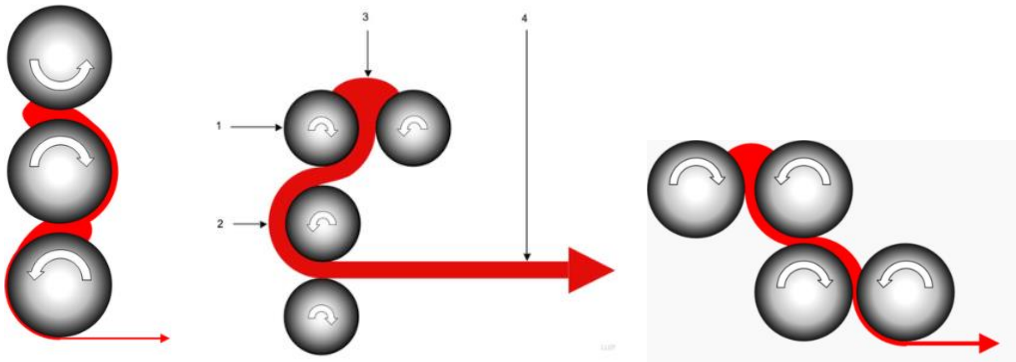


Figure 3-4: Calender types;I (left), L (middle), Z (right) [N.N., 2013]

Main advantage of using calender is to produce completely flat and high sensitive thickness polymer products. Also, for heat sensitive polymers, it minimizes the thermal degradation.

3.1.3 Cooling water bath

After calendering, the extruded polymer, which was given the final thickness and texture below T_g during calendering, comes to water bath in order to be cooled down below T_g. It is aimed that the polymer is transformed from the molten state to the solid state which has sufficient mechanical properties in order not to be deformed in post-processes.

At first, the cooling was done by blowing air, then, developed by water immersion in a static bath, followed by circulating water cooling in a bath since it provides higher cooling rate due to high heat transfer coefficient. In this project, circulating water which provides forced convection with pump and vacuum is used for cooling profile which should be uniform. If the part is cooled nonuniformly, the shrinkage occurs by solidification of one side before other side. Also, in cooling stage, when one side is exposed to force, the molecules are oriented in this side resulting in shrinkage differently both sides, consequence, warping.

The cooling time is affected by polymer depending properties, thermal conductivity which is a measure of transmitted heat through unit thickness of the material, and heat capacity which is amount of heat needed for changing temperature by one degree.

The length of cooling bath is affected by profile thickness and line speed. In case of thicker products or higher line speeds, the length of water bath is expected to be longer to provide enough coolant residence time for avoiding any distortion could be caused by post-processes, such as pulling, slitting or winding (N.N., 2017).

3.1.4 Puller

Puller systems are used to control the tension on the extruded material by pulling it with rotational speed from the die through the solidification steps. Dimensional control and the stability of the profile is depending on the puller speed which is generated through two rotating rubber rollers.

The puller speed determines the final product dimensions, thickness and wideness, as the extrusion throughput rate does. That is why the puller speed must be matched (+-%0,5) to the throughput rate in order to achieve correct dimensions. In case of some periodic changes in the puller speed can cause dimensional instability. In any case of slippage in the puller causes increase in thickness in some sections (Giles et al., 2005). The optimum puller speed should be little higher than the process speed to keep the tension avoiding from curling, warpage and distortion. This extra speed, known as drawdown, should be minimum as much as possible, because high values cause increase in residual stresses and shrinkage in the final product (N.N., 2017).

Pressure applied between rollers should be enough for positive contact and no slippage, however should be low enough to avoid distortion and surface marks. Excess pressures can deform the profile of the part. The puller may be a long distance from the die. In this project, it is found after the water bath. However, it must be aligned with the extruder properly in order not to have warpage due to molecular orientation.

3.1.5 Lacquer, UV and primer stations

According to the demands from customers, the polymer is colored in extruder blending with powder colour pigments. Then, the extrudate goes to calendering, water bath and pullers, respectively. After the puller, the extrudate goes to lacquer station. Here, the extrudate upper surface is coated with lacquer by being pressed between two rubber rollers in order to give gloss property depending on customer demand. The rubber rollers are applying the lacquer on surface by pulling and pressing the extrudate. The point is here that the rollers are working in same way with the puller. So, the roller speed and pressure for lacquering should be matched with the puller values for sufficient lacquering.

The lacquer is a chemical coating used also for UV resistance. They have photoinitiators and have to be processed with the help of UV lamp for curing. That is why lacquering station is not enough alone for lacquering, the extrudate goes to UV lamp for curing after lacquering station. UV lamp applies UV radiation to the extrudate operated with normal process speed by being controlled the light intensity which should be optimized. The point is here that UV lamp heats the extrudate up applying radiation. When the light intensity increases, the heating increases as well. This heating could cause shrinkage, warpage and increase in thermal induced residual stresses in the product.

After curing, the extrudate goes to primer station depending on use in service. The extrudate lower surface is here coated with primer by pressing between two rollers as in lacquering station for use in service. The roller speed and pressure should be sufficient for priming instead of higher values causing distortion in the product. Primer and lacquer stations have not been used in this project, however, UV lamp was once used in the experiments to see its influences.

3.1.6 Slitting station

Slitting is used to split the extrudate up to five equal bands as a cutting system, since it is used in plastic thin sheets and does not cause any local melting when compared to other cutting systems, such as laser, hot knife cutting. Slitting station, which consists of flattener roller flattening the extrudate over the metal plate, cutting cylinder which have knives and positioner discs on it, and puller, can be seen Figure 3-5.

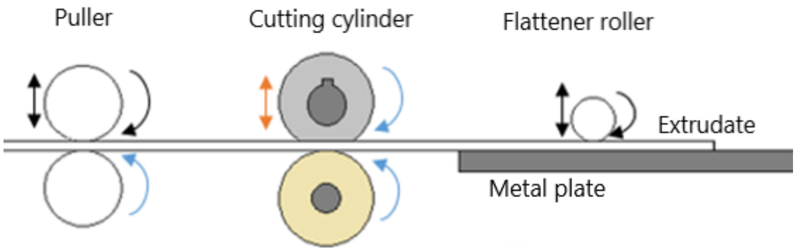
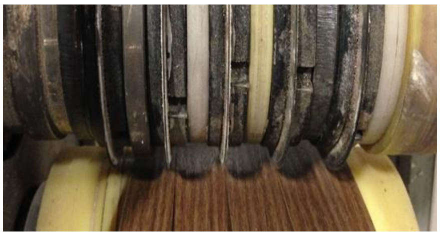


Figure 3-5: Slitting station and elements

After the extrudate is flattened by the roller, it is slit into four bands in equal width by being pressed it between knives and counter rotating cylinder and cutting continuously by rotating the knives. In the meantime, it is pulled by the puller continuously. Here, the cutting cylinder slits the polymer by generating compressive stresses between cutting cylinder and counter rotating cylinder which defines the cutting path. This process is called score slitting, where the angle of tip is important for cut quality and the lifetime of knife as seen in Fig.3-6 below.



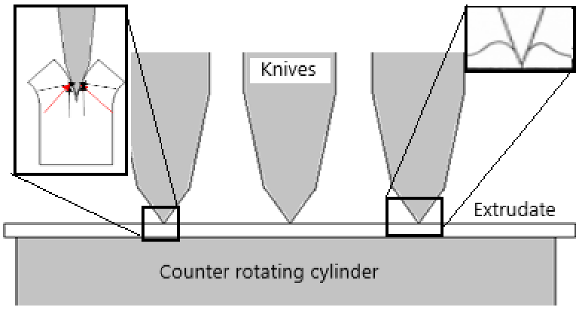


Figure 3-6: Cutting cylinder elements and cutting forces at the knife tip

As told above, the angle of the knife tip important for cutting, when the angle decreases, cutting forces which the knife have to bear increases, consequently, life time of the knife decreases.On the other hand, when the angle increases, the knife tip starts to crush the product in slit edge causing bulge in edges as can be seen in Figure 3-6 at the right corner. This compression causes deformation in slit edges. When the knife is sharp, the slit edge will be smooth, but there will be dust. After using it, the knife becomes dull and rounded, in this case, there will be chips instead of dust in slit edge. Another concern is about counter rotating cylinder which is made of polyamide. As soon as, any defect or scratch happens in surface, this causes a gap, where the polymer could be squeezed and teared instead of being slit (N. N., 2013).

In addition to tip angle, the diameters of knives are also important for good slitting. When there is difference between two adjacent knives, the stripes can not be slit at the same time, but teared. This tearing may cause deformation or micro crack in slit edge in which residual stresses are formed. That is why same diameter is important to slit the band at the same time equally.

3.1.7 Winding station

After slitting, separated extrudates are winded for packaging as a finished product in winding station. This process is carried out with up to five winders for winding slitted extrudates separately. Winding station consists of a vertical puller, a cutter, a core and a winder table which the winding process are carried out through the rotating wheel connected to electrical motor, and have buttons controlling the process on it, as seen in Figure 3-7.

Exrudates coming from slitting are pulled and adjusted by the puller changing flowing axis to winding axis. Adjusted extrudates are cut through the cutter when the order finished and end product has been obtained. Extrudates are winded around the core which defines the inner diameter of rolls. So this winding process is basically combined of pulling and winding processes.

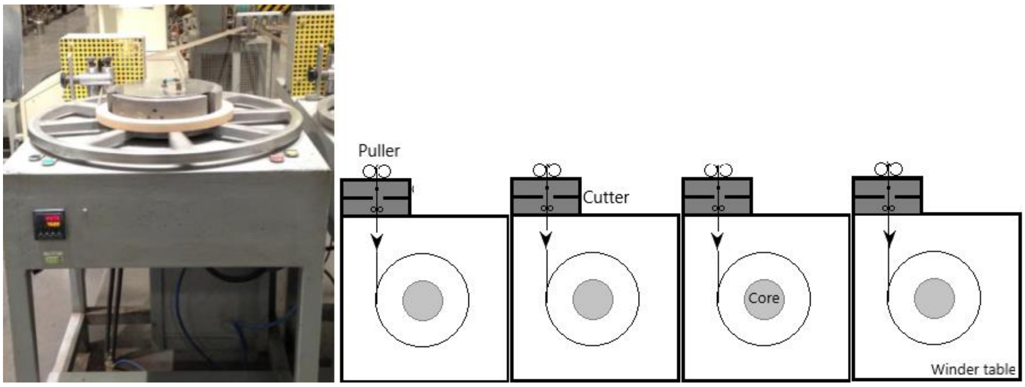


Figure 3-7: Example winder and configuration of winders in a line

Roll quality is used to satisfy the customer demands, defining the shape, size or consistency in thin products. Since the roll density, called as roll hardness, is a contributing cause of roll quality, it is used to define the differences between good and poor quality rolls. Roll density shows how much soft or hard the roll is. Soft rolls, which were winded too loose, cause problem during handling and storing due to failure of roundness. Each rotation of the roll for unwinding cause loose and tight tension which result in stresses. Hard rolls, which were winded too tight, bring also some problems. They cause blocking by sticking to each other of very thin layers due to high tension. Hard rolls show also bagginess and wrinkling problem. The web may have thicker and thinner areas as it is not highly precise. When these thicker points overlap during winding continuously, it is deformed creating ridge, which is known as bagginess. Hard rolls have more residual stresses due to high tension (Smith, 2007). The tension is changing during winding depending on roll diameter. As seen in Figure 3-8, when the roll diameter increases, the tension at outside decreases.

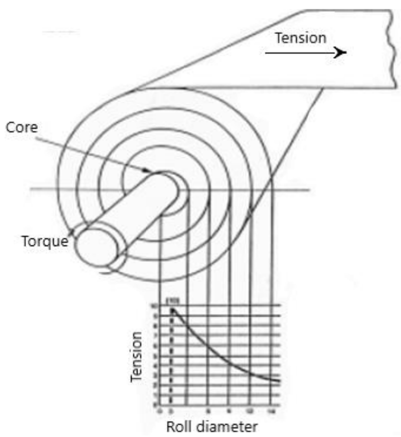


Figure 3-8: Change of tension depending on diameter during winding [N. N., 2013]

There are three principles for controlling the roll hardness; tension, nip and torque principles, shortly called TNT by Smith. In tension principle, when the product is pulled with more tension, more harder winded rolls are produced as shown in Figure 3-9. For this reason, roll hardness can be improved in elastic films by controlling the tension which could be calculated empirical or from modulus of elasticity (Smith,2007).

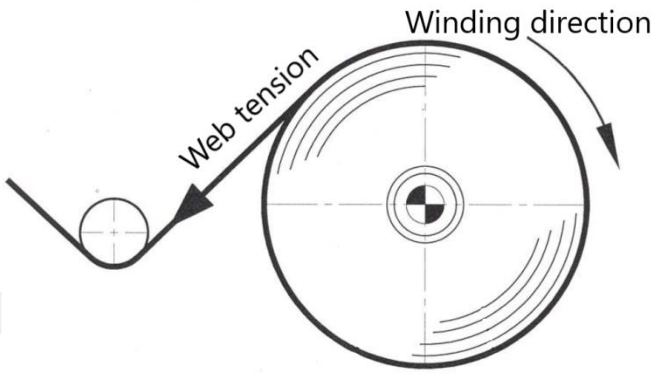


Figure 3-9: Scheme of tension principle for roll hardness [Smith,2007]

For inelastic films, nip principle is used to control the roll hardness by applying nip load to remove the air between layers, as seen in Figure 3-10.

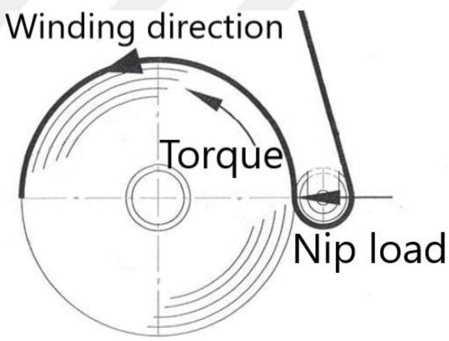


Figure 3-10: Scheme of nip principle for roll hardness [Smith,2007]

In torque principle, the tension is generated in the center of roll and transferred through the layers and tightens the inner layers. The basic idea underlying here is same with the tension principle (Smith, 2007).

4 Introduction to Design of Experiments

Experiment is a scientific test where the input parameters are changed depending on a given rule to study the reasons for this change in the result. They are used in almost all areas to investigate the performance of systems and processes. These processes can be combination of methods, machines and people that convert any input to an observable result which was defined as banana in this project. While some of these input parameters are controllable, some can be uncontrollable. The aim of the experiment is to know most effective parameters on the result and how to use them to minimize the uncontrollable parameters (Cavazutti, 2013).

Some developed techniques enable the experiments to be performed in an efficient way. These techniques used for improving experiments are called design of experiments (DOE) or experimental design. This technique includes some statistical methods to avoid experimental noises, which deviate the results, by analyzing the results. These basic methods are replication, randomization and blocking. Replication is used to obtain more precise datas by repeating the tests. Randomization enables the tests to be performed randomly, so that the result can be achieved independently from the conditions used before. Blocking is used to avoid bias effect by organizing the experiments in groups which are similar to one another. So that, the precision could be achieved (Cavazutti, 2013).

Now, the terminology used in DOE will be shortly explained. As mentioned before, the problem to be studied must be defined, then, chosen the parameters as input variables. Each parameter must have defined range of variability which is known design space. This range is limited in DOE, so that qualitative and quantitative variables can be coped with. Levels, that show the number of different values a parameter, and DOE method are chosen depending on appropriate number of experiments. In DOE, desired result and the experiments to be conducted are known as response variable and sample space respectively.

Most common DOE techniques used in practice are randomized complete block design, full factorial, fractional factorial, latin hypercube sampling and central composite design. In this project, full factorial experimental design has been used.

Full factorial is the most used experimental design. The experiment number is calculated by multiplying levels of parameters. In case of one three-levels and two two-levels parameters, the number of experiments to be performed is 12 (3x2x2), as seen in Table 4-1.

	Parameters		
Test No	**Blade**	**Spacer disc**	**Flattener**
1	New	Plastic	with
2	New	Plastic	without
3	New	Metal	with
4	New	Metal	without
5	Used	Plastic	with
6	Used	Plastic	without
7	Used	Metal	with
8	Used	Metal	without
9	Grinded	Plastic	with
10	Grinded	Plastic	without
11	Grinded	Metal	with
12	Grinded	Metal	without

Table 4-1: Example full factorial test design

After choosing the parameters which could have influence on banana, tests have been performed according to full factorial design. After collecting the results, these results have been statistically analyzed by using two features of Minitab software which is most common for statistical DOE. One of these used features is the main effects plot which shows the main influences of parameters on banana and how these affect the banana. Other feature is the interaction plot where the relations between parameters, and influences of them on banana can be seen. These features can be seen in the chapter of Experimental works.

5 Experimental Works

5.1 Cutting experiment

Since the slitting is the first planned process to be studied in this project, the experimental works has started with cutting test as seen below in detail.

5.1.1 Cutting test procedure

Extrudate is separated into 4 parts, each called as edge band, at the end of the line. After slitting, 4 slitted edge bands are winded separately. In this test, banana effect will be searched by studying slitting process. Blades, which have cutting edges, spacer discs, which are put between blades according to desired width of edge bands, and flattener, which provides the product to go to the cutting cylinder flat, were choosed as a parameter. Results will be detailed interpreted.

The aim of this test is to investigate the effects of some components of cutting station, such as blade, spacer disc and flattener, on banana problem. Three blades, new, used and grinded, were used in this test as levels of parameter. Spacer discs were used as metal and plastic. These tests were also conducted either with flattener or without flattener. According to results, next actions should be able to be taken to reduce the effect.

As mentioned above, the parameters to be studied were defined to see their influence on banana effect. According to these parameters, the test plan was prepared as in Table 5-1.

Test No	Blade	Spacer disc	Flattener
1	New	Plastic	with
2	New	Plastic	without
3	New	Metal	with
4	New	Metal	without
5	Used	Plastic	with
6	Used	Plastic	without
7	Used	Metal	with
8	Used	Metal	without
9	Grinded	Plastic	with
10	Grinded	Plastic	without
11	Grinded	Metal	with
12	Grinded	Metal	without

Table 5-1: Cutting experiment test plan

Recycled ABS flakes were used in these tests. New counter rotating castamide cylinder were used for each blades during the test. The calibration of line were made according to the dimension of samples, which are thickness and width, before the tests. When reached the desired dimensions, the test was done according to the process parameters as in Table 5-2. Blades were chosen with 0.20mm deviation in diameter which is in tolerance area.

Process Parameters			
Dimension	23mmx0,8mm	**Material**	Recycled flakes ABS
Embossing	No	**Water bath**	Yes
Lacquer	No	**Primer**	No
UV Lamp	No	**Cutting**	Yes
Winding	No		

Table 5-2: Cutting test process parameters

After adjustment of the line according to dimension of edge bands, 4 slit edge bands were taken at the same time depending on their position, describing that 4 is machine side 1 is operator side. Then, their banana values were measured and the samples were labeled as X(test no).Y(sample no).Z(position no) which can be seen in Figure 5.1.

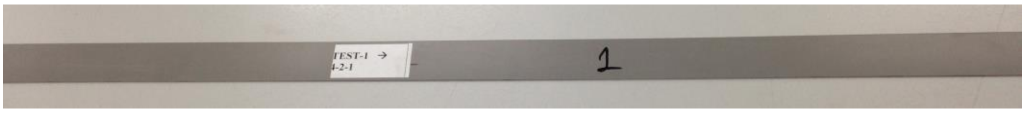


Figure 5-1: Labeled 2 meters sample for cutting test

During measurement, the samples were cut to exact 2m long. Afterwards, four more sample were taken regarding repetition number for each test, after cutting before winding. In total, 240 samples were tested for four different positions, five repetitions and twelve test batches (4x5x12=240). For each blade, the counter rotating cylinder has been changed to new one. Samples were measured two times as just after the production and after 48 h.

Fig.5-2 below shows how the banana measurement table works. Green (0-8mm) and yellow area (8-12mm) are in tolerance area. But the red area (>12mm) is for rejection. In Figure 5.2, two samples which one of them is upwards, the other is downwards depending on the flow direction of extrusion can be seen. The ones going up were marked '+ value', the others going down were marked '- value'.

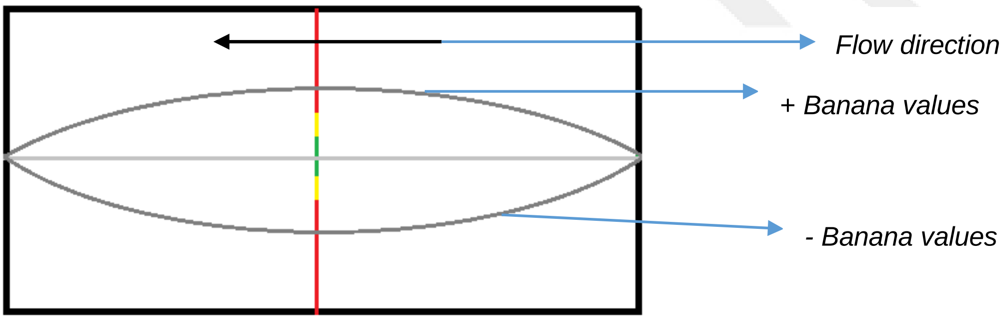


Figure 5-2: Banana measurement table

As in Figure 5.3, only 5.,6.,7. and 8. tests were observed and marked according to '+,-' values mentioned above. This situation should be taken into account for interpretation. Other tests were not marked in this way, they could be + or – values.

5.1.2 Cutting test results

The numerical values of results can be found in the Appendix.

It can be seen that the statistical analysis of results by using data means in Figures below. Main effects plot shows that the direct influence of main parameters, which are blade, spacer disc, flattener, position and time, on banana problem. Interaction plot shows that the effect of observed parameters on banana shape problem.

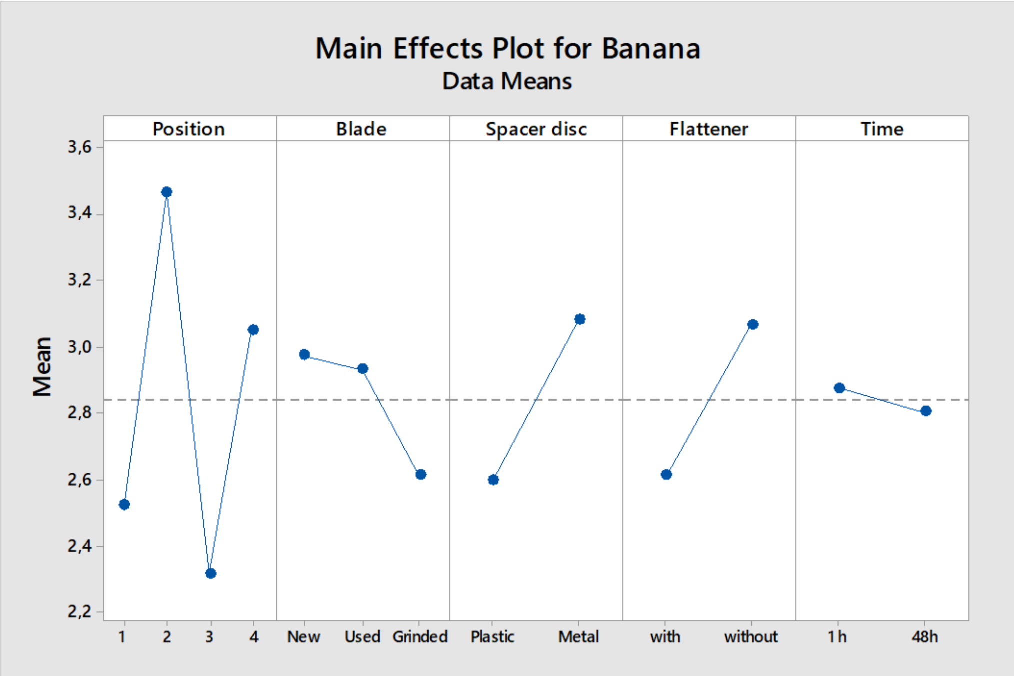


Figure 5-3: Cutting test main effects plot

As seen in Figure 5.3, second position, which is next to operator side, have more banana shape than others, fourth position, which is at the machine side, is the second one. For blade types, grinded blade have better results, then used and new ones. Grinded blade could be sharper than others. It was able to cut without tearing, therefore, it had less effect. The diameter difference between blades of grinded blades have minimum difference when compared to new blades or used blades. Type of spacer discs and flattener have slighter influence on banana effect. It can be seen that plastic spacer discs and flattener have slightly positive effect on banana. It is also surprising that measurements after 48 hours have better results. That means some parts tend to be straight or stable in time.

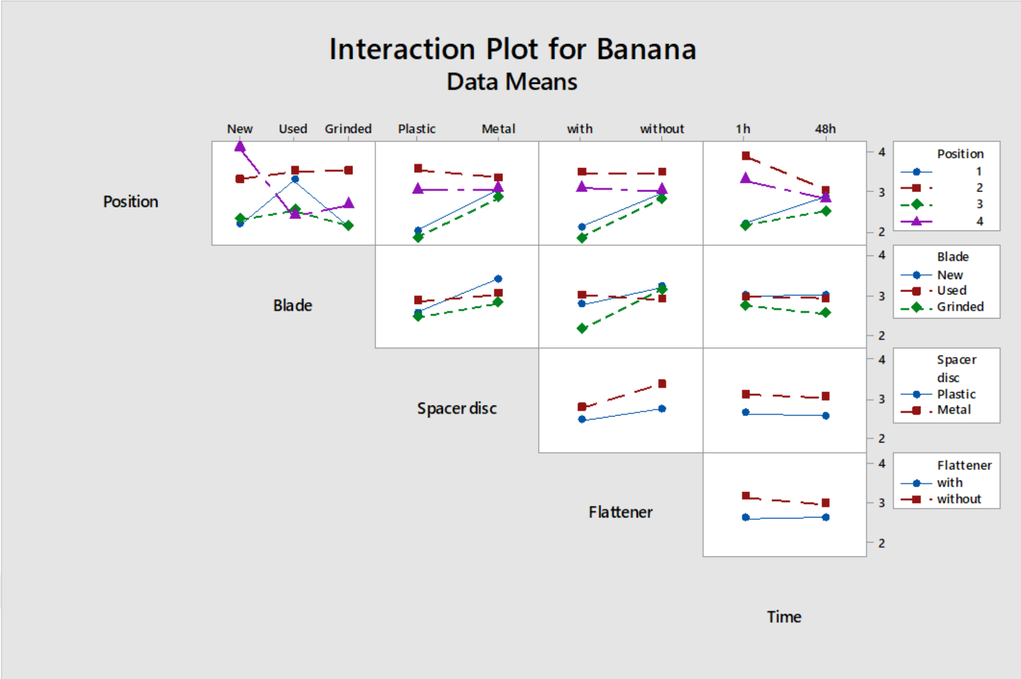


Figure 5-4: Cutting test interaction plot

To sum up, according to this test, the banana measurements are in tolerance area because the mean is around 3mm, and maximum banana is around 9 mm. They are small numbers than encountered in production. So it could be said that the influence of cutting system on banana is not big as much as expected. Grinded blades have less banana effect. But it should be considered that difference between results of parameters is too small, for example 0,5mm in metal and plastic spacer discs. That could be originating from variations in measurement. The deviation during measurements could be in millimeter level.

	1.Repetition		**2.Repetition**		**3.Repetition**		**4.Repetition**		**5.Repetition**	
Test no	**1h**	**48h**	**1h**	**48h**	**1h**	**48h**	**1h**	**48h**	**1h**	**48h**
5	+3	+2	+3	+2	+4	+3	+5	+4	0	+1
6	+4	+1	+4	+1	+3	+5	+1	+5	+5	+5
7	0	+4	+4	+5	+6	+5	+6	+5	+5	+6
8	+4	+4	+2	+1	+3	+4	+2	+4	0	-1

Table 5-3: Results between 5-8 tests according to 1.position

	1.Repetition		2.Repetition		3.Repetition		4.Repetition		5.Repetition	
Test no	**1h**	**48h**	**1h**	**48h**	**1h**	**48h**	**1h**	**48h**	**1h**	**48h**
5	-4	-4	-4	-4	-4	-6	-4	-5	-2	-4
6	-5	-2	-5	-2	-2	-3	-3	-4	-2	-4
7	-5	-6	-4	-3	-4	-2	-5	-4	-5	-5
8	-1	0	-1	-3	-4	-4	-5	-4	+4	+1

Table 5-4: Results between 5-8 tests according to 2.position

	1.Repetition		2.Repetition		3.Repetition		4.Repetition		5.Repetition	
Test no	**1h**	**48h**	**1h**	**48h**	**1h**	**48h**	**1h**	**48h**	**1h**	**48h**
5	0	+3	+1	+3	0	0	+3	+2	+2	+1
6	+4	+4	+4	+3	+2	+3	+3	+2	-1	+1
7	+2	+4	+3	+1	+1	+2	+3	+2	+1	+5
8	+5	+3	+2	+4	+3	+3	+5	+4	-3	-2

Table 5-5: Results between 5-8 tests according to 3.position

	1.Repetition		2.Repetition		3.Repetition		4.Repetition		5.Repetition	
Test no	**1h**	**48h**	**1h**	**48h**	**1h**	**48h**	**1h**	**48h**	**1h**	**48h**
5	-4	-2	-3	-4	-4	-1	-3	-2	-2	-1
6	0	-4	-2	-3	-3	-3	-5	-5	-2	0
7	-3	-1	-2	0	-2	-1	-2	-1	-1	-4
8	-6	-5	-1	-2	-3	-3	-2	0	+1	+2

Table 5-6: Results between 5-8 tests according to 4.position

Also during measurement, it was realized that banana shape may be depending on position. While the banana shapes of 1st and 3rd positions were mostly downwards, for 2nd and 4th position the bananas are mostly upwards as seen in Table 5.3, Table 5.4, Table 5.5 and Table 5.6. For further tests, this measurement method depending on flow direction was applied.

5.2 Winding experiments

After the cutting test, winding tests were performed. Because the number of parameters is too much, winding tests were divided into six different tests.

5.2.1 Procedure of winding test.1

Extruded product is separated into 4 parts, each one called as edge band, at the end of the line. After slitting, 4 slitted edge bands are winded separately. In this test, banana effect will be searched by studying winding process. Torque of winder, which can be adjusted by spring and screw mechanism, winding temperature, which is temperature during winding, and working duration of vertical feeder which can be adjusted to pull the stripe and push it to winder were chosen as a parameter.

The aim of this test is to study winding process by analysing effects of parameters, to find reasons, parameters which have influence on banana effect. In this test, torque, temperature and the vertical feeder were investigated. Other parameters will be studied after this test. According to results, next actions should be able to be taken to reduce the effect.

As mentioned above, the parameters to be studied were defined to see their influence on banana effect. According to these parameters, the test plan was prepared as in Table 5-7.

TEST PLAN-1					
Test No	**Torque (kgFcm)**	**Temp. (°C)**	**Duration (sec)**	**Measurement**	**Time(h)**
1	**1kgF** x 32cm	27	4	Inner + Outer	1h+48h
2	**1kgF** x 32cm	27	600	Inner + Outer	1h+48h
3	**1kgF** x 32cm	33	4	Inner + Outer	1h+48h
4	**1kgF** x 32cm	33	600	Inner + Outer	1h+48h
5	**3kgF** x 32cm	27	4	Inner + Outer	1h+48h
6	**3kgF** x 32cm	27	600	Inner + Outer	1h+48h
7	**3kgF** x 32cm	33	4	Inner + Outer	1h+48h
8	**3kgF** x 32cm	33	600	Inner + Outer	1h+48h
9	**5kgF** x 32cm	27	4	Inner + Outer	1h+48h
10	**5kgF** x 32cm	27	600	Inner + Outer	1h+48h
11	**5kgF** x 32cm	33	4	Inner + Outer	1h+48h
12	**5kgF** x 32cm	33	600	Inner + Outer	1h+48h

Table 5-7: Test plan no.1

Torque was calculated by using analog hand scale for measuring force and distance from the center of winder as seen in Figure 5-5. Since the all measurements were conducted from the fixed point, force will be used for expressing the torque.

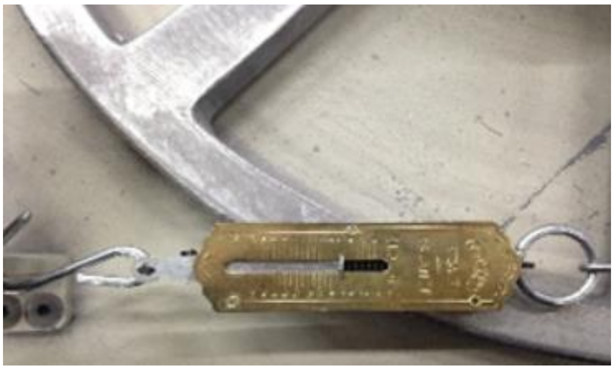


Figure 5-5: Force measurement from the fixed point for torque

Winding temperature was achieved by using UV lamp. With UV lamp, 33°C was measured by infrared thermometer, without UV lamp, 27°C was reached during winding. The duration of vertical feeder was adjusted by changing time relay. 4 secs which are already used in production and 600 secs which mean continuous working for one roll were applied.

When reached the desired dimensions, the test was done according to the process parameters as in Table 5-8. Blades were chosen with 0.20mm deviation in diameters which is in tolerance area.

Process Parameters			
Dimension	23mmx0,8mm	**Material**	Recycled flakes ABS
Embossing	No	**Water bath**	Yes
Lacquer	No	**Primer**	No
UV Lamp	No/Yes	**Cutting**	Yes
Winding	Yes		

Table 5-8: Process parameters during the test

After adjustment of the line according to the dimensions of the edge bands, 4 winded rolls have been taken depending on their position, describing that 4 is machine side 1 is operator side as seen in Figure 5.6. After taken each roll, banana from outer 2m and inner 2m were measured and they were labeled as X(test no).Y(sample no).Z(position no) considering the flow direction, considering '+,-' values. Totally, we had 12 (test batch)x 5(repetitions) x4(winder number)=240 rolls. Two measurements were conducted as just after the production and after 48 hours.

Figure 5-6: Sample rolls for after winding tests

5.2.2 Winding test.1 results

It can be seen that the statistical analysis of results depending on banana effect problem in Figures below. It can be seen that the normal distribution of banana for all samples according to lower and upper limit, -12 and 12, in Figure 5-7. 9,69% of all samples have exceeded this limit.

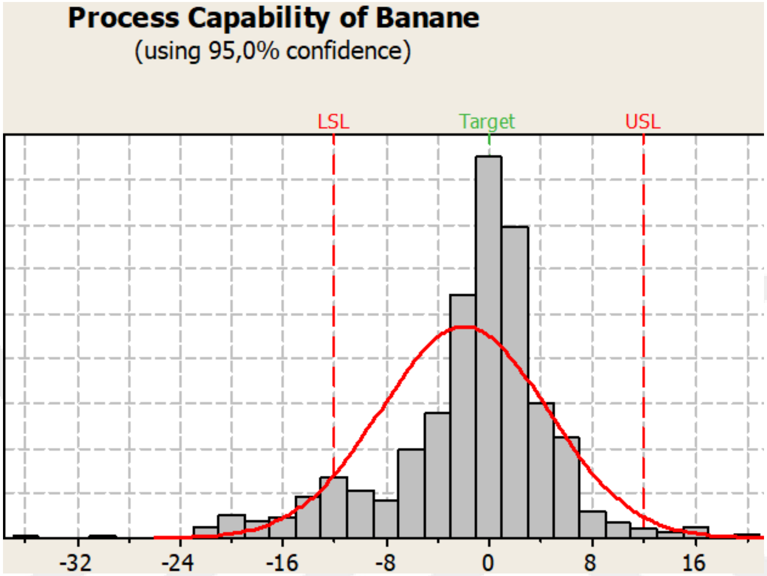


Figure 5-7: Normal distribution of banana according to test.1

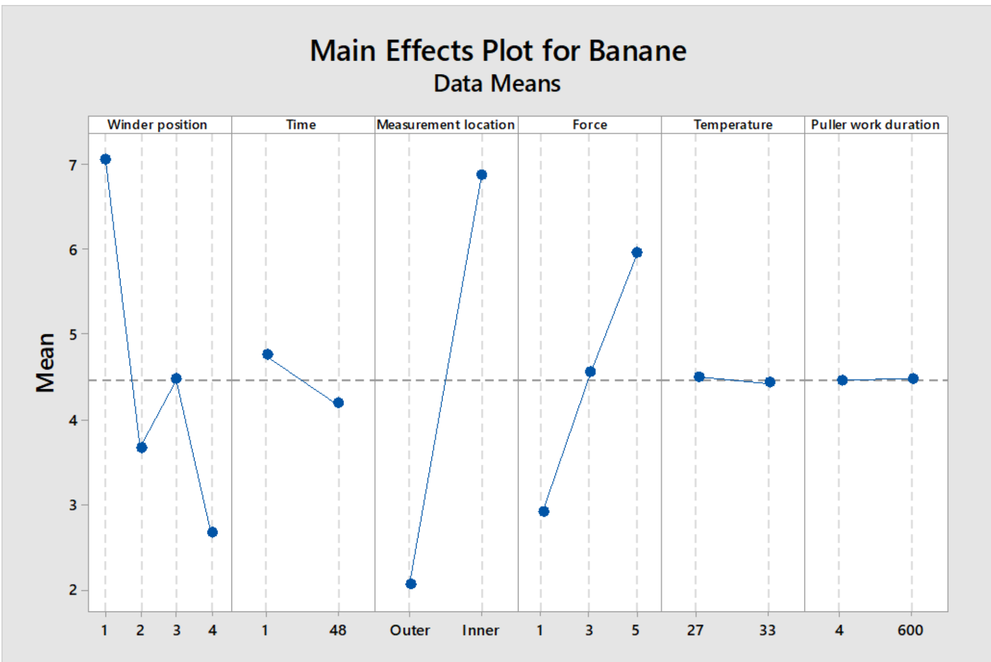


Figure 5-8: Winding test.1 main effects plot

As seen from the results, first position, which is operator side, has more banana shape than others, fourth position, which is at the machine side, is the least one. It is seen that the banana decreased with time slightly, and there is a big difference between inner and outer measurements. Inner parts of roll have more banana, possibly because of increasing roll hardness and compressive stresses. For torque, there is clearly seen a trend which is increasing with high force. Winder working with higher torque causes more banana problem. Winding temperature and the working duration of vertical feeder have slight effect as seen in Figure 5.8.

It was observed that the banana decrease with time was also seen in the cutting test before. This decrease acting like recovery was not that much also in the cutting test. But the point could be important is that this recovery is seen more in the test of 1 kgF, seen less in the test of 5 kgF. This could be the reason of the temporary and plastic deformation, relating to viscoelastic property. Another effect influencing this recovery could be winding quality. If the bad quality winded rolls stayed, there could happen unstable stresses which could block the recovery inside of the roll. The change depending on the winder position seems zigzag as seen in cutting test. This could be because of former processes. This should be considered later.

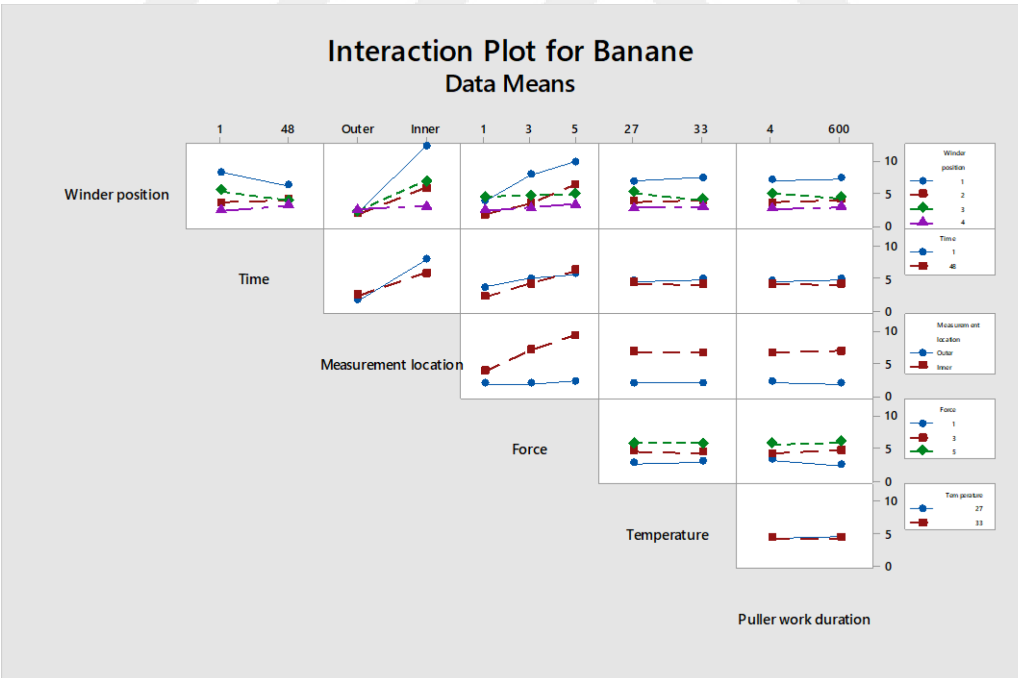


Figure 5-9: Winding test.1 interaction plot

Also, although the rolls have been stayed winded, the banana did not increase as expected, on the contrary it decreased especially in the tests of 1 and 3 kgF. In the tests of 5kgF, this is unsteady, that could be because of bad winding quality which has been observed for these rolls.

To sum up, according to this test, 90,31% of the banana measurements are in tolerance area This is relatively bigger value than the results of cutting test. So it can be said that the influence of winding system on banana is much bigger than the influence of cutting system.

This comments above were done according to obtained results from the banana measurement. This should not been forgot that this measurement is highly dependent on the person who is conducting the measurement and reading the value. Because of that, some faults based on operator could be possible. In addition to measurement errors, because of production errors based on difficulty of winders which is about the non-constant force could be reason of some faults.

After considering these difficulties mentioned above, this test was repeated with 1 kgF, 3kgF and 5kgF.

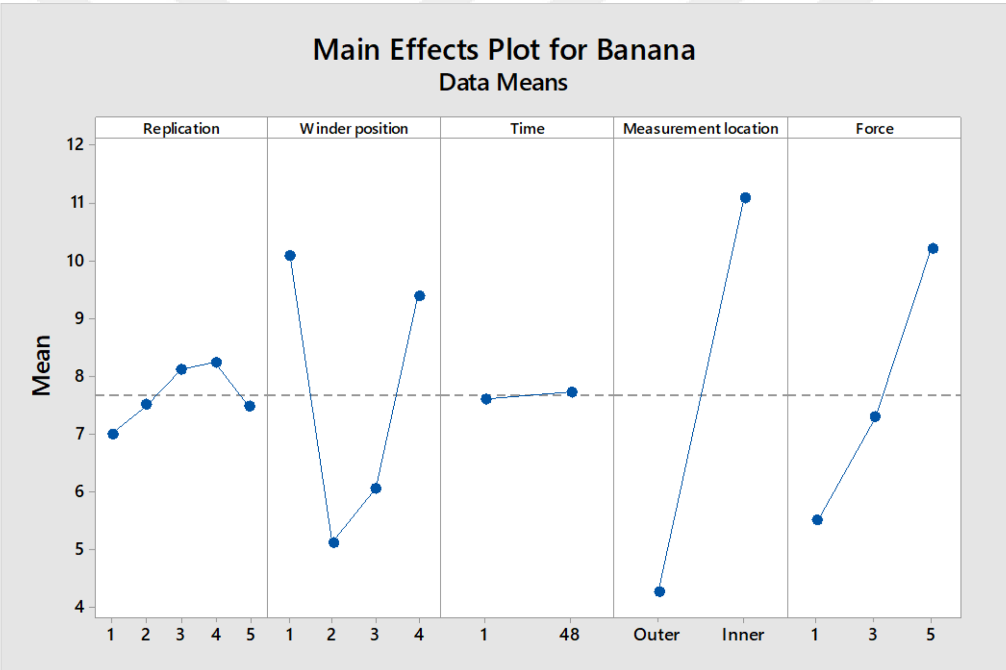


Figure 5-10: Repeat of winding test.1 main effects plot

Same trend was obtained as in Figure 5-10 which shows increasing banana value with increasing pulling forces. So it can be said that the winding process have bigger influence on banana because of winding force which could increase the roll hardness.

5.2.3 Procedure of winding test.2

As discussed above, because the number of samples is too much, winding test were divided into different tests. In this test, core types and diameters were studied. Three types of cores were used: default core

(Ø32cm), hard core(Ø50cm), and soft core with insulation pad(Ø50cm) as seen in Figure 5-11.

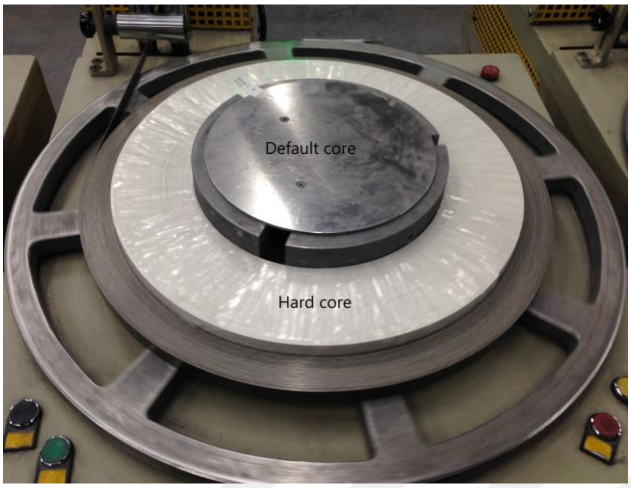


Figure 5-11: Default and hard core

As mentioned above, the parameters to be studied were defined to see their influence on banana effect. According to these parameters, the test plan was prepared as in Table 5.9 below.

TEST PLAN-2			
Test No	**Core**	**Measurement**	**Time(h)**
1	**No core (32cm)**	Inner + Outer	1h+48h
2	**Hard core (50cm)**	Inner + Outer	1h+48h
3	**Soft core (50cm)**	Inner + Outer	1h+48h

Table 5-9: Test plan 2 for core type

Two different cores were prepared for this test. Hard cores were made of ABS edge band roll in 32mm inner, 50mm outer diameter. Soft cores were made of insulation pad in 32mm inner, 50mm outer diameter.

When reached the exact dimensions, the test was done according to the process parameters in Table 5-10. Winding force was chosen 1kgF, since it was found that it has less effect on banana in the former test. Grinded blades, which was found that it has less effect on banana, were chosen with 0.20mm deviation in diameters which is in tolerance area.

Process Parameters			
Dimension	23mmx0,8mm	**Material**	Recycled flakes ABS
Embossing	No	**Water bath**	Yes
Lacquer	No	**Primer**	No
UV Lamp	No	**Cutting**	Yes(Grinded)
Winding	Yes(1kgF)		

Table 5-10: Process parameters for test 2

After adjusting the line according to the dimensions of edge band, 4 winded rolls were taken as in the previous tests. Same procedure with former tests was applied. Totally, 60 rolls were obtained (3x5x4=60).

5.2.4 Winding test.2 results

It can be seen that the statistical analysis of results depending on banana problem in Figures below. Main effects plot shows that the direct influence of core types, position, time and measurement location, on banana problem. Interaction plot shows that interactions between these parameters on banana problem.

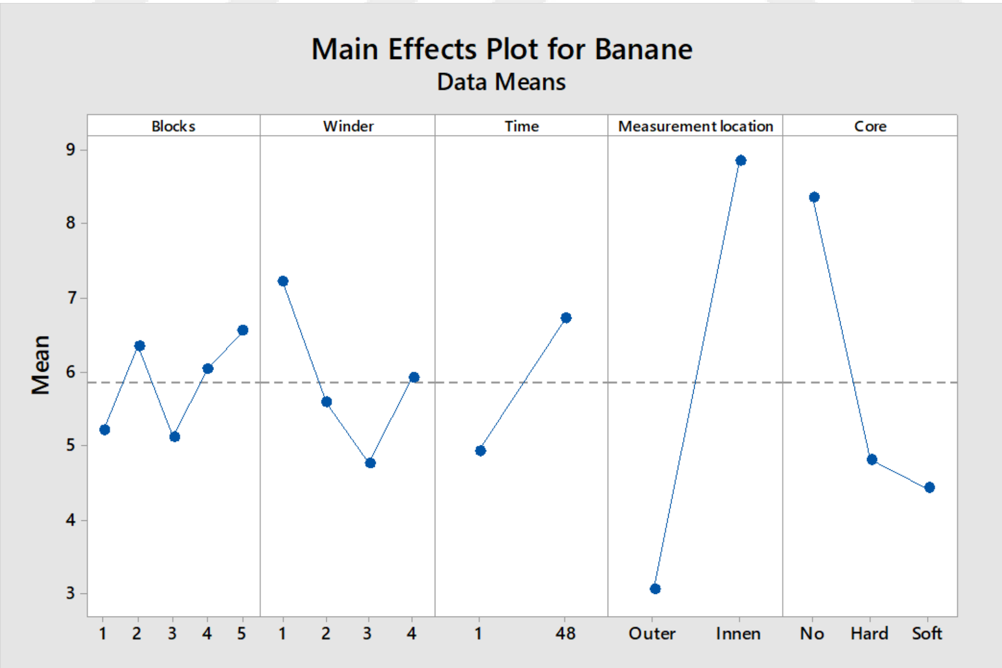


Figure 5-12: Winding test no.2 main effects plot

According to these results, the banana effect increases with time waiting for 48 h. Inner side of roll has much more banana than outer side. Pulling forces depending on core type at the beginning of winding can be seen in Figure 5-13. F_1 which is applied to the inner side of default core while winding, F_2 which is applied to the inner side of hard core and soft core because they have equal diameter, can be calculated from torque equation below.

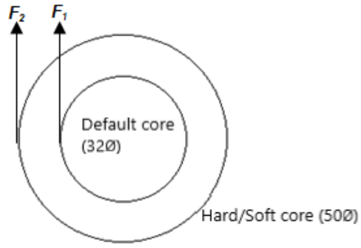


Figure 5-13: First applied pulling forces during winding depending on core type

$\tau = F \times L$, when put 32kgFcm to the torque value;

$1kgF \times 32cm = F1 \times (32cm \div 2),\, F1 = 2kgF$

$1kgF \times 32cm = F2 \times (50cm \div 2),\, F2 = 1{,}28kgF$

It can be seen that starting force of default core test is 2kgF, while the starting forces of hard/soft core are 1,28kgF. When winding diameter increases, the pulling forces decrease proportionally depending on the constant torque. So, starting forces which are corresponding for inner side of roll are biggest value for a roll, ending forces which are corresponding for outer side of roll are the lowest value for a roll. During winding, inner side of a roll is always exposed to higher forces than outer side of a roll. This explains why inner side has more banana than outer side of a roll. Also, It could explain one of the differences between no core, hard core and soft core test results.

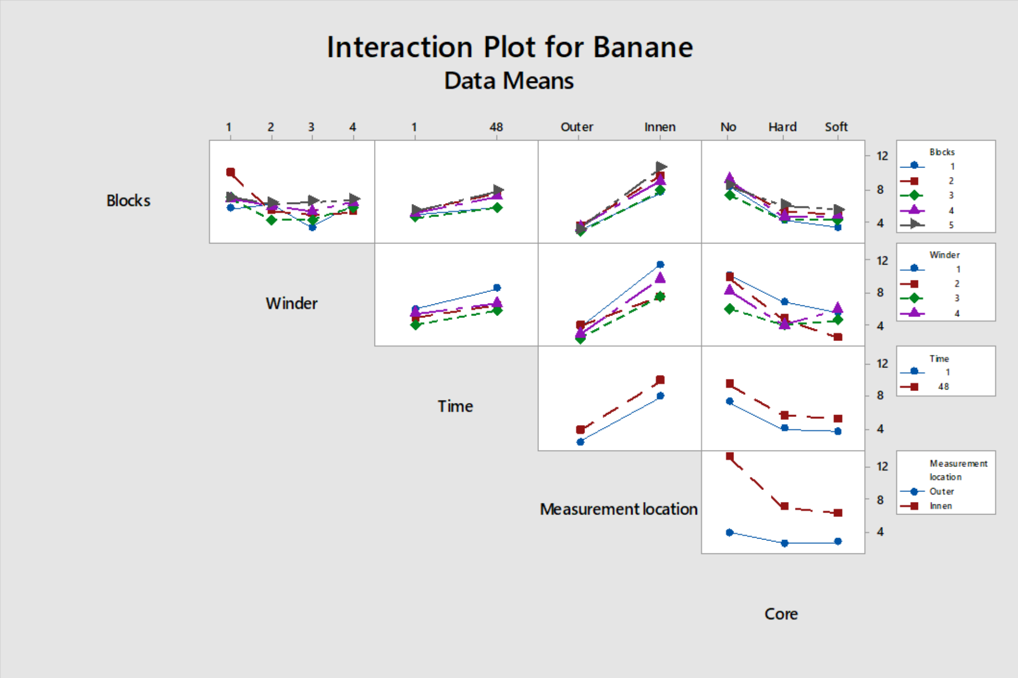


Figure 5-14: Winding test no.2 interaction plot

In Figure 5-14, repetitions, named Blocks here, have same trend, so that, there was not important deviations between them during the test. The other reason can be roll hardness. As each layer applies compressive stress into former inner layer because of centre winding working principle, these compressive stresses increase as winding continues and layers increase, roll hardness increases as well. Scheme of stress distribution can be seen in Figure 5-15.

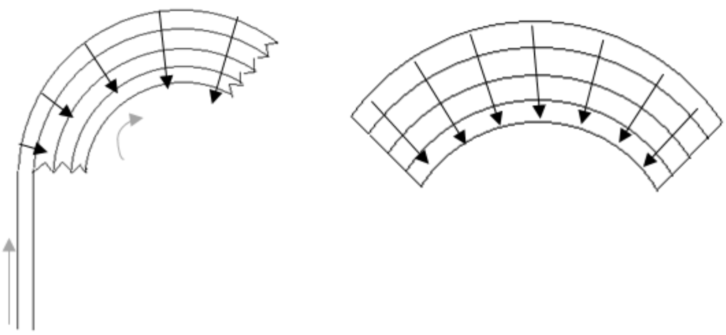


Figure 5-15: Compressive stresses during rotation (left), increasing compressive stresses into inner layers (right)

After winding a roll, inner side would have been pressed more than other layers especially for default and hard core, but for soft core, insulating pad might have absorbed some pressure. It can be seen that soft core inner side have less banana from the interaction plot above between core type and measurement location. However, use of soft core needs much effort during test, it is not practical, therefore, hard core was used. Consequently, it can be deduced that the core diameter has an important influence on banana, increasing the core diameter causes less banana and reduces the difference between inner side and outer side of a roll due to less number of layer.

5.2.5 Procedure of winding test.3

It was seen in previous works that the banana is seen more in thinner edge bands depending on the thickness of the edge band. Since edge bands with 0.8mm thickness is the thinnest product, all tests were done with 23mm x 0.8mm edge bands due to being most requested order by customer. In this test, it was aimed to see the effect of the width of the edge band. Test plan was created depending on width of edge band differently from 23 mm. 16 mm, which is lower than 23 mm and 43 mm which is higher than 23 mm were chosen as a parameter, as in Table 5.11 below.

TEST PLAN – 3			
Test no	**Width**	**Measurement Num**	**Time (h)**
1	16 mm	Outer + Inner	1h+48h
2	43 mm	Outer + Inner	1h+48h

Table 5-11: Winding test plan 3 for wideness

After adjusting the line depending on the desired dimensions in the test plan, the test was made according to the process parameters below.

Process Parameters			
Dimension	16/43mm x 0,8mm	**Material**	Recycled flakes ABS
Embossing	No	**Water bath**	Yes
Lacquer	No	**Primer**	No
UV Lamp	No	**Cutting**	Yes(Grinded)
Winding	Yes(1kgF)		

Table 5-12: Process parameters for Winding test plan 3

Since the dimension changed in this test, two winders were used instead of four winders. Then, same procedure with former tests for collecting sample was used.

5.2.6 Winding test.3 results

It can be seen that the statistical analysis of results depending on the wideness of edge band. Main effects plot can be seen in Figure 5-16.

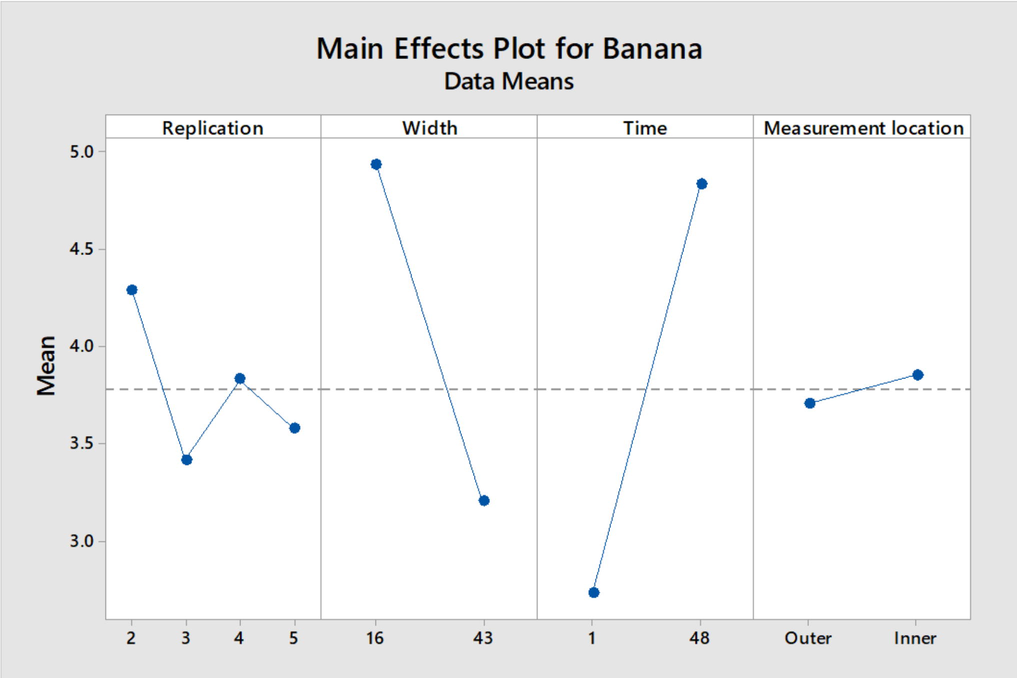


Figure 5-16: Winding test 3 main effects plot

From the results and main effects plot, it is observed that wider edge bands have less banana than narrower edge bands. Increase in wideness decreases the tendency of the distortion. Narrower edge bands are easily affected by the distortion. Expansion and thickening of the edge band cause an increase of strength in thickness and wideness direction. These strengths resist to longitudinal distortion.

5.2.7 Procedure of winding test.4

During winding, sometimes feeding of the edge band into the winder changes in up and down. This unstable movement in vertical axis causes winding which has wavy surface on winder wheel. The aim of this test is to study winding process by comparing winding surface, described by winding quality to see their effect on banana shape. In this test, two types of winding quality were studied, as seen in Figure 5-17.

Figure 5-17: Winding quality; smooth(left), nonsmooth(right)

As mentioned above, the parameters to be studied were defined to see their influence on banana effect. According to these parameters, the test plan was prepared as in Table 5-13.

TEST PLAN-4			
Test No	**Winding quality**	**Measurements**	**Time(h)**
1	Smooth	every 15 meters	1h+48h
2	Nonsmooth	every 15 meters	1h+48h

Table 5-13: Winding test plan 4

Before and after the cutter, there are some rollers which are used to adjust the edge band for constant feeding as seen in Figure 5-18. Irregular and regular winding quality were achieved by changing these rollers for simulating winding qualities for this test.

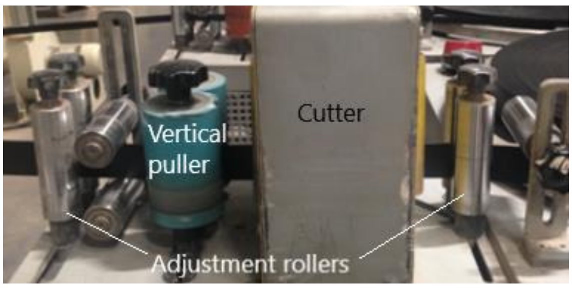


Figure 5-18: Adjustment rollers used for pretending both winding qualities

After the adjustment of the line and reached the desired dimensions depending on the test plan, the test was made according to the process parameters as in Table 5-14. 1kgF winding force and grinded blades have been chosen due to their less effect on banana.

Process Parameters			
Dimension	23mm x 0,8mm	**Material**	Recycled flakes ABS
Embossing	No	**Water bath**	Yes
Lacquer	No	**Primer**	No
UV Lamp	No	**Cutting**	Yes(Grinded)
Winding	Yes(1kgF)		

Table 5-14: Process parameters for winding test plan 4

After the test, 4 winded rolls have been taken depending on their position, describing that 4 is machine side 1 is operator side. After taken each roll, banana values for every 15 meters were measured to see its behavior within a roll, same procedure with previous tests was applied. Totally, 40(2x5x4) rolls were produced.

5.2.8 Winding test.4 results

Main effects and interaction plots for this test can be found below.

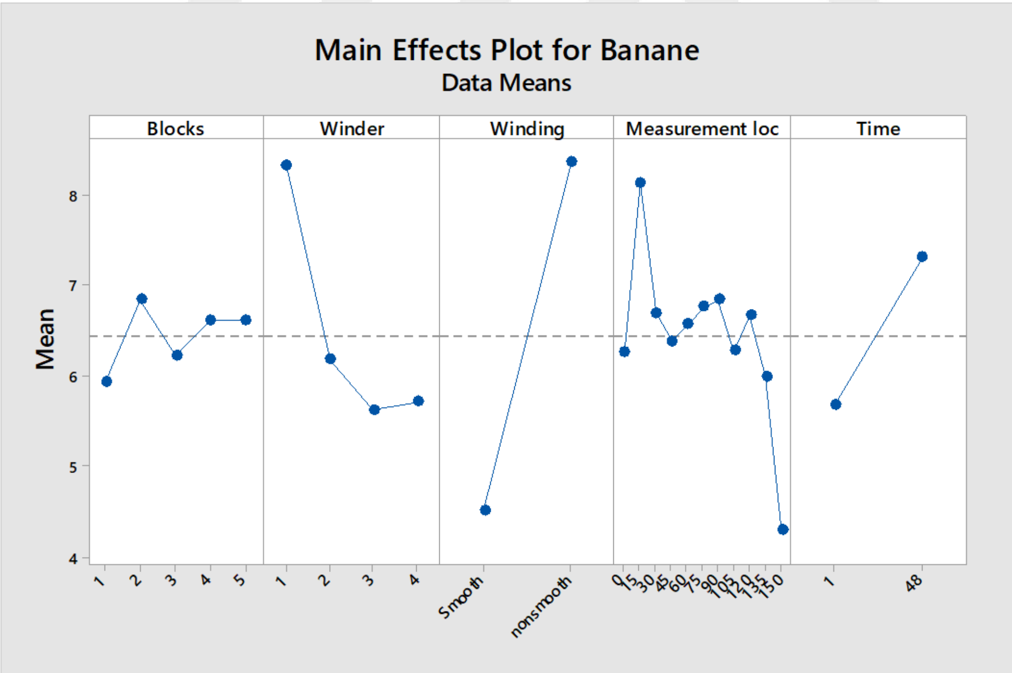


Figure 5-19: Main effects plot for winding test 4

Replications are between 6mm and 7mm, it can be said that there is no big deviation between replications. The point is that there is a big difference between smooth and nonsmooth, wavy winding surfaces. This is seen in Figure 5-20.

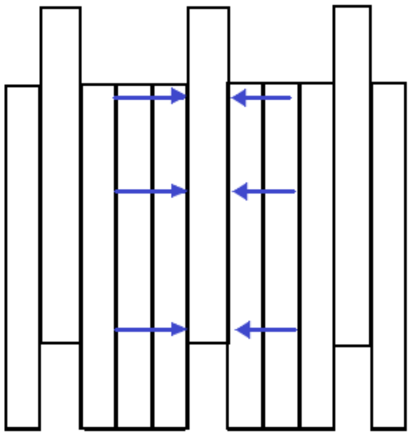


Figure 5-20: Compression stress state in wavy winded layers

Layers press to each other irregular in nonsmooth winding. This causes big difference in compression forces along the width. According to the results, pressed side of width has compression, the other side has tension. It is seen that these layers cause banana shape, because the compression has shortening and the tension has extending tendency.

Another finding is the banana distribution which shows the behaviour of banana within a roll for every 15 meters. The biggest values are in inner side close to end, because there is much more double-sided compression than others. It is also seen that these values increase with waiting time.

Figure 5-21: Interaction plot for winding test 4

In Figure 5-21, the interactions between the parameters can be seen. After this test, it can be said that the compression between layers has big influence on banana. That is why after this test, it was thought that these induced compressive stresses should be relieved.

5.2.9 Procedure of winding test.5

Depending on request from the customers, rolls can be produced up to 225 meters for edge bands with 0.8 mm thickness. All tests were conducted with 150 meters which are average length of existing orders. In this test, the roll length was tested by choosing 75 and 150 meters as a parameter in order to see the influence of roll length on banana. 75 meter will have less diameter, consequently, less layers and roll hardness. It is expected that it has less banana than 150 meter samples.

The other parameter is winded, hard rolls which are usually done, and loose rolls. It may relieve the induced stresses, as an output of former test. Loose rolls will have less roll hardness than tight winded rolls.

As mentioned above, the parameters to be studied were defined to see their influence on banana effect. According to these parameters, the test plan was prepared as in Table 5-15.

TEST PLAN-5				
Test No	**Roll length(m)**	**Rewinding**	**Measurements**	**Time(h)**
1	75	No rewinding	every 15 meters	48
2	75	Rewinding	every 15 meters	48
3	150	No rewinding	every 15 meters	48
4	150	Rewinding	every 15 meters	48

Table 5-15: Winding test plan 5

The length of rolls is adjusted by digital counter which was installed to the winder table by entering the requested number. Rewinding means that opening the rolls for loosening after the production, then, winding them again. In case of rewinding, it was aimed to see the influence of loosening for stress relieving. In case of no rewinding, the rolls were taped tightly for packaging just after the production without waiting time. However, for rewinding samples, rolls were loosened manually then waited for a time for stress relieving. After 48 hours, they were taped for packaging.

When the exact dimensions is obtained, the test was done according to the process parameters as in Table 5-16. Winders were adjusted to 1kgF, grinded blades was used, and adjustment cylinders were used for smooth winding quality.

Process Parameters			
Dimension	23mm x 0,8mm	**Material**	Recycled flakes ABS
Embossing	No	**Water bath**	Yes
Lacquer	No	**Primer**	No
UV Lamp	No	**Cutting**	Yes(Grinded)
Winding	Yes(1kgF), Smooth		

Table 5-16: Process parameters for winding test 5

After taken each roll, same procedure for labeling and banana measurement for every 15 meters were applied. 80 rolls were produced in total (4x5x4). Only one measurement was made after 48 hours.

5.2.10 Winding test.5 results

The numerical values of results can be found in the Appendix. Main effects and interaction plots can be found in Figures below.

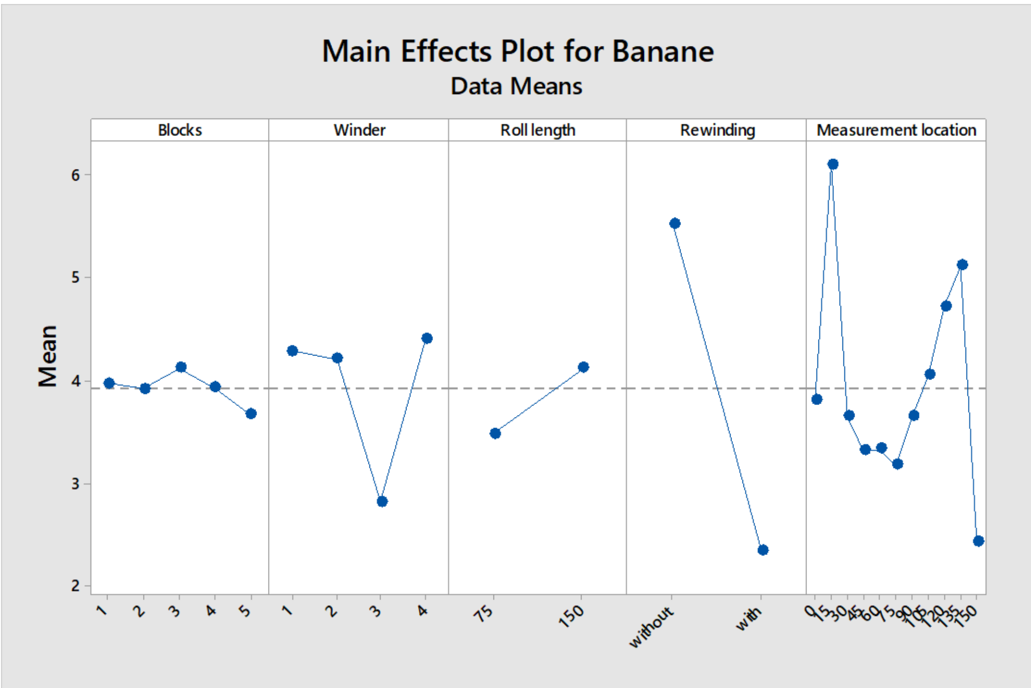


Figure 5-22: Main effects plot for winding test 5

Replications are around 4 mm, no big deviation were observed between replications. Roll length has an influence on banana. When the roll length increases, roll diameter increases resulting in increasing number of layers, compression increases which causes banana. These compressive stresses increase the roll density as well.

The main finding is that loosening of rolls releases the stresses. If looked the values, it is seen that any banana values for rewinded samples do not excess 12 mm which is tolerance area. But for tight rolls, directly taped after production, induced residual stresses become permanent increasing in time.

As in former test, inside parts of roll, first 15 meters, has more banana. There is also surprising increase between 105 – 135 meters.

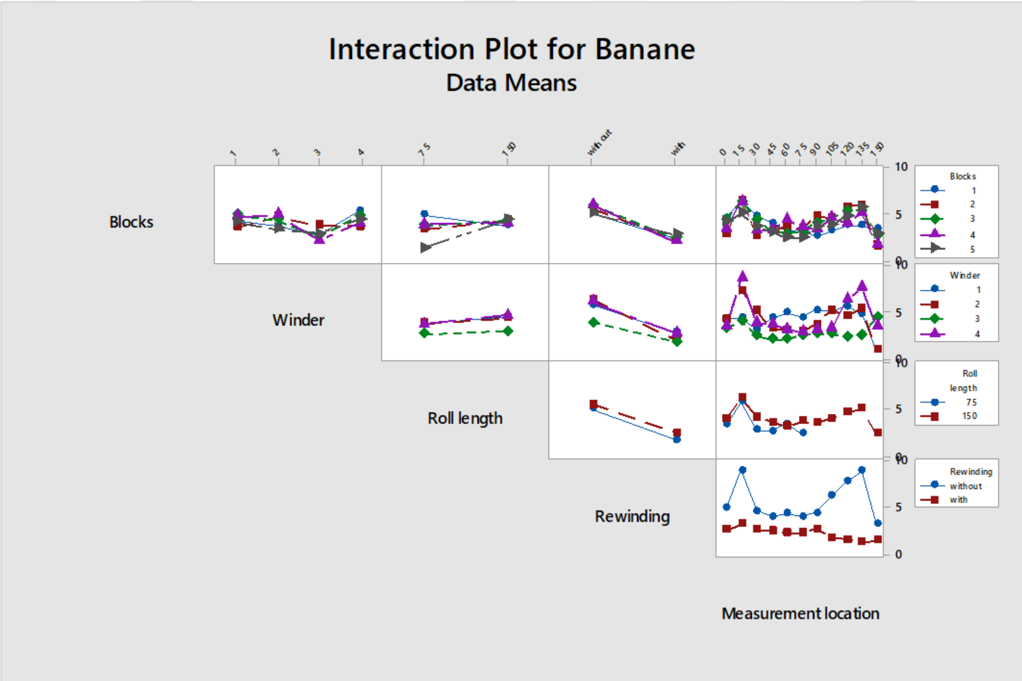


Figure 5-23: Interaction plot for winding test 5

When looked the interaction of rewinding and measurement location, increase depending on measurement for every 15 meters is only seen in no rewinding samples. That means, banana values of rewinded samples are not highly dependent upon inner parts of roll when compared to no rewinding samples.

5.2.11 Procedure of winding test.6

As a result of the tests which is done so far, it is seen that loosening of the rolls have more important due to stress relieving than other parameters which have also effect on banana. Therefore, it was more focused on different winding types in this test.

The aim of this test is to compare different winding types. In former tests, it was seen that loosening of roll could be partially solution for banana problem. That is why, the test plan was created as seen in Table 5-17.

TEST PLAN-6			
Test No	**Winding type**	**Measurements**	**Time(h)**
1	With rewinding	0,15,30,120,135, 150m	48
2	Without rewinding	0,15,30,120,135, 150m	48
3	Manual rewinding	0,15,30,120,135, 150m	48
4	Automatic rewinding	0,15,30,120,135, 150m	48

Table 5-17: Winding test plan 6

For rewinding samples, they were loosened and waited for 24 hours after the production, then, were taped. For without rewinding samples, they were directly taped without waiting time after the production. For manual rewinding samples, the rolls were manually relaxed and just then rewinded tightly without waiting time after the production. In automatic rewinding, the samples were manually loosened and just then rewinded automatically, then, were taped. An automatic winder was used for this. Automatic rewinding and rewinding samples were produced with a core (Ø40cm), because they will be reduced to 32 cm during rewinding.

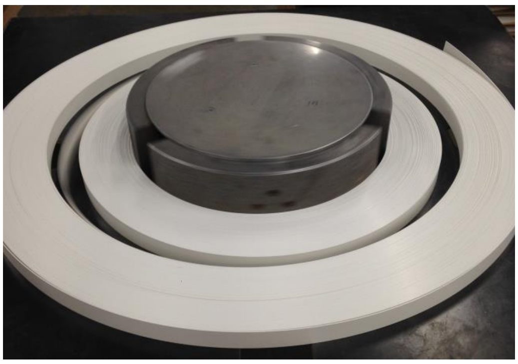


Figure 5-24: During automatic rewinding

However, other samples, no rewinding and manuel rewinding were produced without a core, so that, they have 320 mm inner diameter. At the end, all samples have same inner diameter, 320 mm.

The test was done according to the process parameters as in Table 5-18. Winders were adjusted to 1kgF, grinded blades were used, and adjustment cylinders were used for smooth winding quality.

Process Parameters			
Dimension	23mm x 0,8mm x 150m	**Material**	Recycled flakes ABS
Embossing	No	**Water bath**	Yes
Lacquer	No	**Primer**	No
UV Lamp	No	**Cutting**	Yes(Grinded)
Winding	Yes(1kgF), Smooth		

Table 5-18: Process parameters for winding test 6

Measurements were done in the first and last 30 meters which are the critical values found in the former test results. After taken each roll, they have been labeled as in former tests. Totally, 80 rolls(4x5x4) were produced. They were measured once after 48 hours.

5.2.12 Winding test.6 results

Main effects and interaction plots can be found in Figure 5-25. The numerical values can be found in the Appendix.

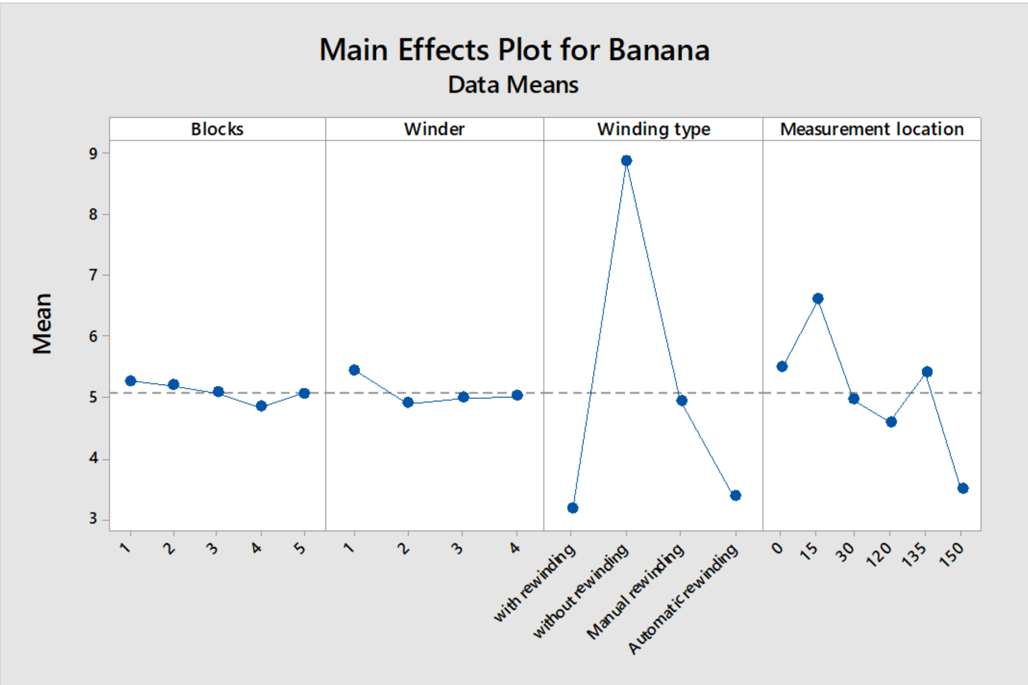


Figure 5-25: Main effects plot for winding test 6

As can be seen in Figure 5-25, rewinding and automatic rewinding are successful for relieving induced stresses. They have around 3mm banana as average and no value out of tolerance range. However, manuel rewinding was not successful for stress relieving when compared to rewinding and automatic rewinding samples. Nevertheless, it is still better than no rewinding samples. As in other tests, this result shows similar banana distribution within a roll. Peak value is in the first 15meters.

Another important finding of automatic rewinding is that the waiting time can be reduced to minutes from hours. For this, only extra process, which is automatic winder for rewinding, has been added to the line after the production in this test.

This test was also applied to the normal production conditions in which granule ABS is used instead of recycled flakes to produce edge bands with 1mm x 23mm x 225 m in dimension. Results are similar with this test. It can be said that this modified winding process will be successful in the normal production conditions as well.

5.3 Tensile testing according to ASTM D882

All tests were done with recycled material, because it would be high cost otherwise. It is not known whether there is any difference between using recycled or granule polymer. Therefore, mechanical properties of both recycled and granule polymer were studied by tensile testing according to ASTM D882 standards.

ASTM D882 test method is used to see tensile properties of thin plastic films. According to this standard, the thin polymer sheet is stretched until breaking point in order to measure tensile modulus, elongation, the yield strength and the ultimate strength. This procedure is similar with ASTM D638, but only difference is that ASTM D882 is for polymers lower than 1mm thickness. It is kept in mind that this test result is changing at different ambient temperatures for thermoplastics.

The samples were prepared with 5 repetitions, and the test was conducted in EGGER Brilon Holzwerkstoffe GmbH Main test laboratory according to the test plan as in Table 5-19.

Test No	Material	Temperature
1	Recycled flakes ABS	20˚C
2	granule ABS	20˚C
3	granule ABS	40˚C

Table 5-19: Tensile test plan

As mentioned, recycled ABS and virgin granule ABS were chosen. Another parameter is temperature during the test chosen for searching its influence on mechanical properties. Test 1 and 2 can be compared to observe the effect of material type, Test 2 and 3 can be compared to observe the effect of temperature. 40˚C was chosen as a parameter because the measured temperature representing surface temperature can be up to 40˚C during winding.

Samples were prepared with 0,8mm x 23mm x 230mm dimensions. Then they were tested by using tensile testing equipment with 50 mm/min speed. Test 3 samples were heated to 40˚C before testing. Then plots below were obtained from software installed to testing equipment.

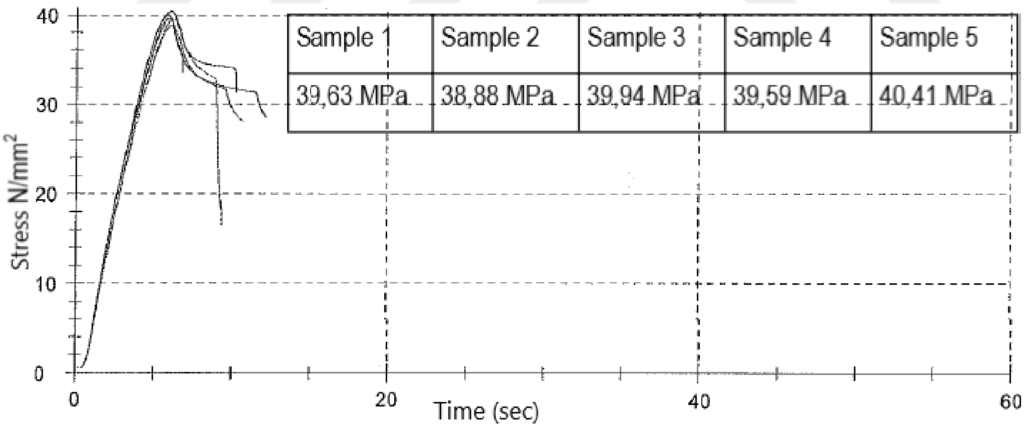


Figure 5-26: Tensile test result from Test 1

In the first test, the average tensile strength for the recycled flakes ABS is 39,69 N/mm^2, as can be seen in Figure 5-26.

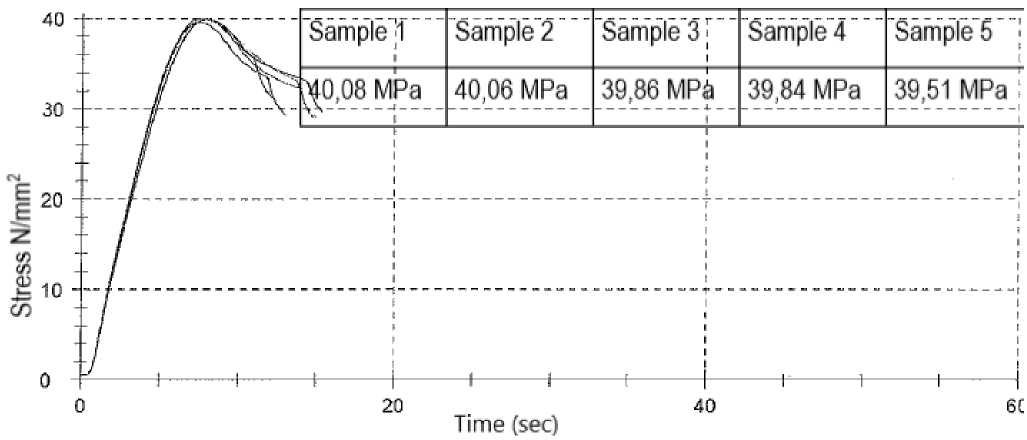


Figure 5-27: Tensile test result from Test 2

In the second test, the average tensile strength for the virgin granule ABS at 20˚C is 39,87 N/mm^2.

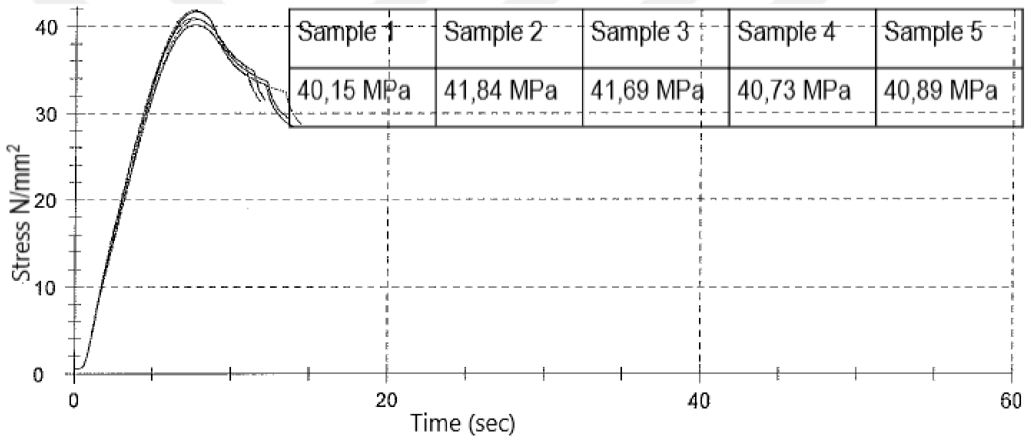


Figure 5-28: Tensile test result from Test 3

As seen in Figure 5-28 from the third test, average tensile strength for the virgin granule ABS at 40˚C is 41,06 N/mm^2.

Consequently, it is seen that the formulation has no big difference whether it is recycled granule or virgin granule ABS. The reason of slight differences in stress might be the foreign particles that were mixed in recycled ABS. Recycled material may have color pigments, primer or lacquer particles. 20˚C temperature difference, between 20˚C and 40˚C, do not cause any change in molecular level due to lower than T_g, consequently on mechanical properties. However, it should be kept in mind that 40˚C is the surface temperature and inner temperature during winding could be much more than this temperature. This is depending on the extruder heat conditions, line speed, product dimensions, water bath condition and the power of UV lamp.

6 Results & Discussion

Through this project, polymer properties and extrusion technology were studied. Afterwards, tests were created for investigation of longitudinal distortion problem which could be cause of unequal strains and stresses at both sides of edge band according to design of experiments (DOE). Cutting and Winding processes were investigated by making these tests and analyzing the results statistically as explained in Experimental works chapter.

In the cutting test, chosen parameters depending on process were researched by keeping other parameters constant which could change the result. Samples were taken after cutting before winding process in order to eliminate the winding influence. According to the results, it is seen that all measured banana values are in tolerance area. Average values and difference between parameters are too much lower than expected. This test was repeated, and it is seen that these results did not change.

After the cutting test, winding tests were conducted with the followed way in the cutting test. In the first test, the influence of pulling force provided by winders, changing temperature during winding by UV lamp and feeding duration of edge band were studied. It is seen that the pulling force has an important influence on longitudinal distortion. Another finding is that automatic feeding duration and 7˚C difference in temperature have not influence on banana. It should be known that the difference in temperature is provided by UV lamp in which the extrudate is exposed to high temperatures for curing the lacquer. With this, it was aimed to release the thermal stresses which might be induced by being heated. However, because the result did not change, it is said that thermal stresses are not active.

In the second test, the effect of winding diameter was investigated by using different cores. The result shows that the banana problem decreases as the diameter becomes higher. Rolls with higher diameter have smaller number of winded layers, that is, less compressive stresses which decrease as the number of layers decreases. These rolls have also lower roll hardness. Roll hardnes gets bigger, as the number of layers increases. Roll hardness is a term related to winding tension. This tension can be also adjusted by torque which has also influence on banana problem.

The finding of the third test is that banana problem is related to dimensions. Thinner and narrower edge bands have more tendency to the banana problem. Risk of banana increases with decreasing thickness and wideness. So, the strength in thickness and width directions prevents to be deformed by stresses causing banana problem.

In the fourth test, winding quality was compared with smooth and wavy winding surfaces. It is observed from the result that smooth winding quality has less banana due to equal compressive stress distribution between layers, however, wavy surface has unequal stress distribution which could cause longitudinal distortion. Moreover, the banana every 15 meters was measured to see banana behavior within a roll. It is seen that the first 15 meters have highest banana values in a roll due to increasing compressive stresses from outer to inner and increasing number of layers.

Roll length and rewinding effect were studied in the fifth test. According to the result, it is seen that higher roll length causes more banana due to increasing number of layers causing more roll hardness. Rewinding effect was considered that it could reduce stresses by loosening the rolls. Tight rolls due to winding tension after production were loosened manually by opening the layers from both outer and inner side. The air enters into between all layers during loosening. Then, they were waited for two days. It was observed that they have no banana value out of tolerance, and these values are lower than expected. As a result of this rewinding process, it is seen that loose layers can be a solution for releasing the induced stresses during winding.

As an important output of the previous test, it was seen that rewinding process as a winding type has an influence on banana and can be a partial solution for it. In sixth test, the winding types were tested by introducing new winding processes. It was aimed to have an idea for the required time for relieving stresses, and to find best solution depending on decreasing time loss. Rewinding, that is used in the previous test, normal winding, automatic rewinding, in which an automatic winder is used for rewinding after production, and manual rewinding, in which rolls are loosened and rewinded manually, were chosen for this test as parameters to be tested. According to the results, automatic rewinding has similar results with rewinding which was the best solution so far. Automatic rewinding takes 3 minutes for rewinding in automatic winder, but it means one more process to be added to the production line. Rewinded and waited rolls could take days and cost labour for rewinding. Consequently, it is seen that the required time to release the induced stresses in order not to become permanent stresses is not long, on the contrary, few minutes are enough.

Totally, seven different tests were conducted in this study. While some tests were repeated to check the reproducibility of results, some tests were repeated due to some technical difficulties and problems. These problems will be explained below.

One of them is about winders pulling the polymer with torque which must be constant to apply constant pulling force. It was seen that these forces are changing unstable, due to friction problem in the mechanism of rotational movement. This problem was reduced with the help of maintenance of winders.

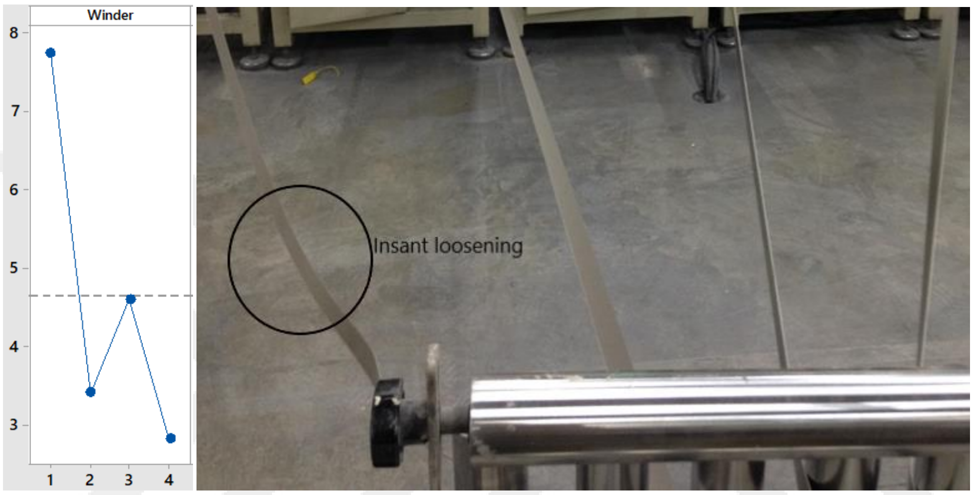


Figure 6-1: Results before maintenance

As seen in Fig.6-1 above, it is seen that forces are changing 1-4 kgF, causing slacking and stretching of edge bands during production. This caused a rapid increase in longitudinal distortion of first position which is winded in the first winder as in plot in Figure 6-1. After maintenance, this change in force was reduced to gram-force levels instead of kilogram-force. The results, thus, became more reasonable as shown in Winding test 3 in the Experimental works chapter. These unconstant forces could cause a change in molecular orientation by inducing unequal stress distribution.

These changing forces inducing unstable stresses stretch the polymer discontinuously due to viscoelastic properties of polymer. With the acceptance of higher inner temperature, creep mechanism could take place with unequal strains. Longitudinal distortion can occur in case that the both sides of edge band have unequal strains. The side which has lower strain pull the other edge which has higher strain toward itself. The side with lower strain have compression, applying tension to the side with higher strain, deforming the band as resembling banana shape.

Since ABS is a thermoplastic, it can be recycled many times by being melted and shaped. Even if this is beneficial for the company due to saving material and cost, it should be known that every recycle process changes the polymer properties at every turn. Although, it does not make remarkable difference in tensile properties as seen in Tensile testing chapter, it decreases the molecular mass due to existence of any substance from lacquer, primer, color pigments or foreign substance. After multiple reprocessing of polymers, these micro substances could degrade the molecular chain and make them shorter, because their existence between molecules hinders the intermolecular bonds, and lower the viscosity (Scaffaro et al., 2012). This scission of the polymer chain causes higher melt flow index after multiple recycling process (Fei et al., 2013). Due to shorter chains, chain segments can be easily moved. We could say that recycled polymers could have lower glass transition temperature. In some tests, macro substances were found in the extrudate which is deformed by them. Figure 6-2 shows tearing by metal particle which could be from broken blade tip.

Figure 6-2: Teared edge band due to macro foreign substance

This metal substance in recycled polymer changes dimensions, such as thickness, as it deforms the polymer. It could also affect the molecular orientation by degrading the polymer chain. It could induce orientation stresses between adjacent chains.

Another difficulty which could give an idea is changing thickness along the width in an edge band. Normally, thickness measurement is made before starting production, during the adjustment of the line. 0.03 mm is maximum allowable thickness deviation along the width for an edge band in the production standards. All thickness measurements were made by using a digital caliper manually.

While it was not expected that any thickness change along the width due to use of calendering in which the polymer are pressed to have precise thickness after the extrusion, but, it was found that some samples have thickness deviation as seen in Figure 6-3.

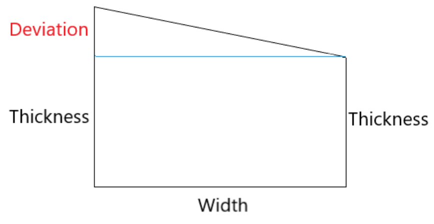


Figure 6-3: Exaggerated thickness deviation of an edge band along the width

The thickness was measured with a digital caliper manually from both sides from left to right according to the flow direction directing out of page. Results can be seen in both Tables below.

Samples	Sample1		Sample2		Sample3		Sample4		Sample5	
Thickness(mm)	77-80		81-76		78-72		82-77		84-77	
Measurement	Out	In	Out	In	Out	In	Out	In	Out	In
Test-3	1	6	2	20	10	20	1	11	1	20

Table 6-1: Banana values of samples from the first winder

In Table 6-1, it can be seen that the thickness deviation with banana values of samples from the first winder. In Table 6-2, it is seen that the results of samples from the fourth winder. Both were conducted under the same test conditions except from different winders.

Samples	Sample1		Sample2		Sample3		Sample4		Sample5	
Thickness(mm)	77-81		71-80		73-78		75-79		77-82	
Measurement	Out	In	Out	In	Out	In	Out	In	Out	In
Banana	0	11	0	25	1	23	1	12	3	22

Table 6-2: Banana values of samples from the fourth winder

As a result of this, it is seen that thickness deviation could cause in longitudinal distortion at inner side of a roll. So, it can be said that the thickness difference along width is an important reason of banana when its effect is combined with winding tension after winding, while the banana values at outer side have no remarkable difference. The compression on edge band which has thickness deviation cause an unequal compressive stress which could deform the edge band by orienting at molecular level.

Main cause of this thickness deviation is considered as seen in Figure 6-4. It was observed that embossing rollers used in calendering was swaying about on the extrudate by moving up and down in horizontal axis instead of pressing it precisely. This provides unequal compression periodically, which one side is pressed more, while the other less. While one side is thinner, the other become thicker. After a while, the opposite would happen. Calendering has a critical importance, because it is where the polymer is at glass transition temperature at which it is easily affected by any compression, which would result in molecular orientation stresses.

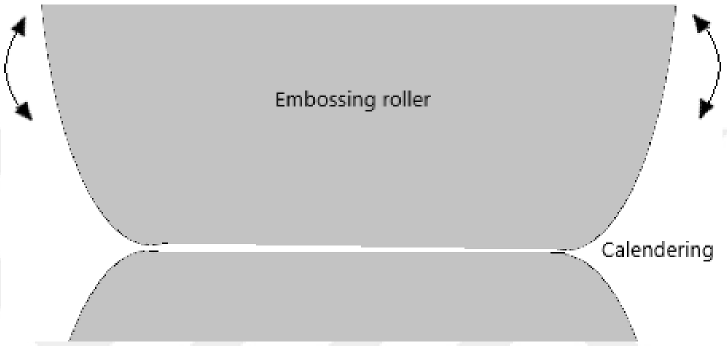


Figure 6-4: Embossing roller moving up and down in horizontal axis

Another difficulty should also be considered that rollers used in puller station for pulling the polymer by being pressed in between two rubber rollers. Double sided compression with friction creates pulling tension contributing to the molecular orientation. These rollers had some defects on surface which deforms the diameter as in Figure 6-5.

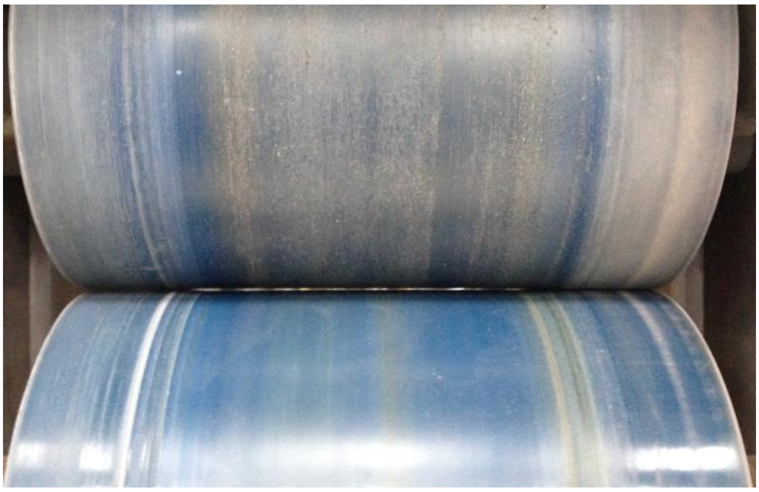


Figure 6-5: Deformed rubber rollers used in puller

These rollers can not apply equal compression for extrudate. During production, both sides are pressed and pulled, while the middle side is only pulled. That can cause orientation stresses by stretching the middle side of extrudate.

These problems was solved before the test using new undeformed rubber rollers and fixing the embossing roller in order not to effect the test results.

However, there was another problem which was not solved but noticed. It is about the alignment of all rollers used in the line. These rollers were not aligned along the line as can be seen in Figure 6-6.

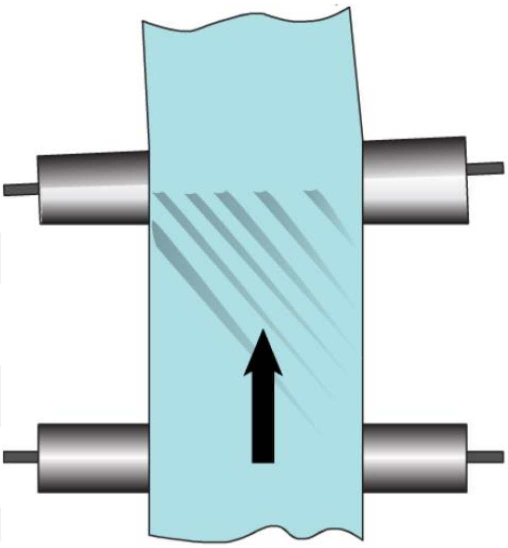


Figure 6-6: Misaligned roller [Eggen, 2012]

Machine misalignments for each process such as primer or lacquering station can also lead to roller misalignment, because they have own rollers except the carrier rollers. These carrier rollers are used to transfer the extrudate by applying the required tension for molecular orientation. This tension avoids the shape memory effect which the molecules turn back to molten state instead of being elongated as well. However, misaligned rollers apply unequal tension distribution along the width by applying forces in different directions.

As in compression of rollers and embossing roller in calendering, these misaligned forces can lead to orientation stresses. As in Fig.6-6, molecule chains at the left side are under compressive stresses, while molecule chains at the right side are under tensile stresses. This could cause longitudinal distortion inside which can show up after slitting.

Consequently, it is concluded that the force is the main cause in this longitudinal distortion problem. When the extrudate is considered having without thickness, it could be imagined that it was formed of entirely fibers instead of polymer chains. The bonds which are linking the polymer chains to each other are weaker than other bonds which are linking the molecules to each other within the polymer chain. This is why the strength in the flow direction is higher than the strength in the width direction. In case of any unequal force along the width in viscous region can change the stress distribution which some could cause a distortion.

In case of any thickness deviation through the width, it could be considered that there are more fibers in thicker side, while less fibers in thinner side. Even if they are pulled with equal forces, their resistance to elongation will be difference. Because the force applied to unit area will be difference. Thinner side would have more strain values, while thicker side would have less strain. This is why it is seen that thinner edge is the outer side of banana which is longer than inner side of banana. In another finding for this, when slitted a sample with banana value around 20mm due to thickness deviation, it was seen that the banana value decreased due to obtained lower thickness deviation after slitting.

As a result of these tests, it is seen that the winding tension causes stresses locked in molecules which can be released by relieving the tension as early as possible. In time, the polymer is cooled down and these stresses become permanent frozen-in stresses since the entropy of molecules goes to the equilibrium state. This can be understood with the help of viscoelasticity, because, the stresses deform the polymer elastically at first. Other main cause is the force applied to the sample during winding generated by the winder torque. It is seen that the pulling force and the torque contribute to the roll hardness which is another important reason for banana problem.

7 Summary & Outlook

Longitudinal distortion is a problem which is seen mostly in extrusion profiles. Since it causes deformed edge bands which look like a banana, therefore, this is known as banana problem. It creates undesired situation for customers and, consequently, the company. The purpose of this study is to find the causes of this problem by investigating the process parameters in order to minimize or avoid this problem.

After searching about amorphous polymers and characteristics of ABS, the extrusion process and its units were studied by focusing the longitudinal distortion problem. In experimental works, winding and cutting processes were observed to choose the parameters which could have an effect on banana problem. The parameters for cutting process are blades, spacer discs and flattener. The other parameters for winding process are the torque, the winding temperature, feeding duration, waiting time, core types, wideness of extrudate, winding quality, roll length, the effect of rewinding and winding types. With these parameters, seven different tests were made in total. Then, the results of these tests were analyzed with the help of DOE.

According to the results, it was found that cutting process is not as important as winding process, because it has no banana value out of tolerance. However, winding process has many parameters causing banana problem. Firstly, the torque generated from the winder changes the roll hardness which induces residual stresses within the polymer. When the torque increases, the pulling force rises and increases the roll hardness. Another parameter is winding diameter which showed that increasing winding diameter by using a core decreases the banana problem because the number of layers compressing each other increases with decreasing winding diameter depending on constant length of roll. This parameter is also related to the roll hardness.

Another finding is that inner part of a roll which is produced and winded first has more banana value, because the diameter increases the tension through the inner parts of a roll. Another test exhibited that unequal compression of these layers in case of winding quality of nonsmooth and wavy causes banana problem as well. By making measurements for every 15 meters, the behaviour of banana problem within a roll is seen. In another finding, it is seen that banana problem increases in time, because the residual stresses become permanent frozen stresses with time. The length of roll has also an influence on banana problem. The banana problem increases with increasing roll length. The rewinding process was considered to release the locked residual stresses. In this process, the roll was loosened by relaxing all layers manually just after the winding process, then, these rolls were waited for 24 hours. Since it had no banana value out of tolerance, it was successful in releasing residual stresses. Considering the required waiting time and bigger influence on banana, it was aimed to change the winding process. The waiting time was reduced to minutes from hours with new process. In this process, called automatic rewinding, the rolls are produced with bigger core, then, they are winded in automatic rewinder starting with the inner part by reducing its diameter.

As a result of, the best case, which has parameters giving the best results, was defined by doing and analyzing the tests. After determining the biggest effect, some improvements were applied to decrease the banana problem. The best case is as the following:

- Grinded blades with flattener
- Torque of 32 kg cmF as giving pulling force of 1 kgF
- 500 mm winding diameter by using core
- Thicker and wider edge bands as much as possible
- Smooth winding quality giving flat surface
- Roll length of 75 meters
- Rewinding process where the rolls are loosened, then, rewinded

Besides the best case findings, it has been seen from the difficulties and technical problems that changing forces, thickness deviation in width, misaligned rollers, deformed rollers and calendering have an important influence on banana problem. With these tests, the entire line of extrusion were investigated except the water bath and the extruder. These can be studied for further works to find other reasons for this longitudinal distortion problem originating from these processes. The best case explained above can be used in these further tests to minimize the effect of these processes.

8 Nomenclature

mm	Millimeter
cm	Centimeter
m	Meter
L	Length
D	Diameter
V	Volume
ρ	Density
Pa	Pascal
MPa	Megapascal
N	Newton
T	Temperature
T_g	Glass transition temperature
˚C	Celsius
K	Kelvin
h	Hour
t	Time
min	Minute
sec	Second
F	Force
kg	Kilogram
kgF	Kilogram force
τ	Torque
ε	Strain
σ	Stress

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Appendix

Contents

A1 Cutting test results

Test No	1.Position										2.Position									
	1.Sample		2.Sample		3.Sample		4.Sample		5.Sample		1.Sample		2.Sample		3.Sample		4.Sample		5.Sample	
	1h	48h	1h	48h	1h	48h	1h	48h	1h	48h	1h	48h	1h	48h	1h	48h	1h	48h	1h	48h
1	2	0	2	1	2	1	0	0	2	1	4	5	2	3	2	2	3	4	6	2
2	0	3	0	0	1	2	3	3	2	4	5	4	4	5	5	4	5	2	3	3
3	0	3	1	4	0	2	2	6	0	3	3	4	2	3	3	1	3	4	4	4
4	5	2	2	4	5	4	4	2	4	4	2	1	3	5	4	4	5	1	3	2
5	3	2	3	2	4	3	5	4	0	1	-4	-4	-4	-4	-4	-6	-4	-5	-2	-4
6	4	1	4	1	3	5	1	5	5	5	-5	-2	-5	-2	-2	-3	-3	-4	-2	-4
7	0	4	4	5	6	5	6	5	5	6	-5	-6	-4	-3	-4	-2	-5	-4	-5	-5
8	4	4	2	1	3	4	2	4	0	-1	-1	0	-1	-3	-4	-4	-5	-4	4	1
9	0	2	0	1	0	2	0	3	0	2	5	2	5	5	5	3	4	0	2	3
10	1	7	0	2	0	4	3	1	0	2	4	5	4	0	3	3	6	7	4	1
11	0	0	2	1	2	0	1	2	0	2	4	1	4	0	5	1	4	1	5	4
12	6	7	2	4	3	4	6	6	4	3	4	4	6	2	5	4	4	1	7	5

Test No	3.Position	4.Position

	1.Sample		2.Sample		3.Sample		4.Sample		5.Sample		1.Sample		2.Sample		3.Sample		4.Sample		5.Sample	
	1h	48h	1h	48h	1h	48h	1h	48h	1h	48h	1h	48h	1h	48h	1h	48h	1h	48h	1h	48h
1	0	0	2	2	1	2	1	0	1	1	4	6	4	4	5	3	2	4	6	5
2	2	1	1	0	0	0	3	2	1	5	4	1	5	3	5	3	2	4	4	3
3	2	3	1	4	1	3	1	4	1	4	5	2	5	6	6	6	6	3	6	3
4	4	3	4	5	5	5	5	4	5	3	5	5	2	4	5	5	2	4	5	3
5	0	3	1	3	0	0	3	2	2	1	-4	-2	-3	-4	-4	-1	-3	-2	-2	-1
6	4	4	4	3	2	3	3	2	-1	1	0	-4	-2	-3	-3	-3	-5	-5	-2	0
7	2	4	3	1	1	2	3	2	1	5	-3	-1	-2	0	-2	-1	-2	-1	-1	-4
8	5	3	2	4	3	3	5	4	-3	-2	-6	-5	-1	-2	-3	-3	-2	0	1	2
9	1	1	1	3	1	4	2	1	3	3	2	0	3	6	3	4	3	1	3	1
10	1	2	1	2	2	4	2	3	3	0	3	2	3	2	4	3	4	0	4	2
11	0	2	1	3	0	1	1	2	3	2	3	2	4	2	3	2	3	1	2	2
12	0	0	2	2	1	2	1	0	1	1	2	1	3	2	2	1	2	5	2	9

A2 Winding test results

A2.1 Test.1

Test	1.Winder																			
	1.Sample				2.Sample				3.Sample				4.Sample				5.Sample			
	1 h		48 h		1 h		48 h		1 h		48 h		1 h		48 h		1 h		48 h	
	Out	Inn	Out	Inn	Out	Inn	Out	Inn	Out	Inn	Out	Inn	Out	Inn	Out	Inn	Out	Inn	Out	Inn
1	1	-3	0	-1	0	-3	6	-2	0	-10	2	-3	5	-2	2	0	1	-6	5	0
2	1	-7	4	-2	1	-5	1	-1	2	-4	5	0	2	-6	5	-2	0	-7	4	-4
3	-3	-13	-2	-5	0	-12	0	-2	-3	-14	-2	3	-2	-11	0	-2	-2	-11	-2	1
4	0	-10	0	-4	1	-14	-2	-5	0	-12	0	-4	1	-9	1	-1	1	-16	-1	-2
5	-2	-13	1	-13	-1	-18	-1	-14	0	-15	-4	-17	-2	-20	-2	-15	-1	-19	-3	-10
6	-2	-18	6	-14	-1	-21	-7	-12	-2	-19	1	-6	-1	-15	2	-5	-2	-22	-2	-13
7	1	-17	-3	-11	0	-20	-2	-12	-3	-21	1	-12	1	-8	0	-4	0	-22	-1	-5
8	2	-14	-3	-7	1	-15	0	-10	0	-13	-5	-7	-2	-12	-2	-3	-1	-17	-10	-13
9	0	-13	-4	-12	0	-20	4	-17	-2	-21	2	-12	0	-19	-5	-18	0	-23	3	-17
10	0	-19	0	-6	3	-21	3	-10	0	-20	0	-16	1	-22	0	-12	1	-17	1	-12
11	1	-15	-4	-15	7	-17	4	-14	-2	-20	2	-15	3	-13	7	-14	2	-13	-2	-15
12	5	-18	0	-15	1	-23	1	-19	3	-17	-6	-36	1	-22	-1	-30	2	-20	-2	-19

Test No	2.Winder																			
	1.Sample				2.Sample				3.Sample				4.Sample				5.Sample			
	1 h		48 h		1 h		48 h		1 h		48 h		1 h		48 h		1 h		48 h	
	Out	Inn	Out	Inn	Out	Inn	Out	Inn	Out	Inn	Out	Inn	Out	Inn	Out	Inn	Out	Inn	Out	Inn
1	3	-1	2	2	0	0	5	5	4	-4	5	-2	1	0	-3	4	3	1	3	0
2	0	-1	-2	-1	1	-1	0	-2	2	0	2	0	0	-1	3	2	2	0	1	0
3	-2	5	1	2	-1	-1	-1	-2	0	-4	0	-1	1	-4	-2	1	2	0	-1	0
4	2	0	-2	0	0	-2	-1	-5	1	0	-1	1	3	-3	1	0	0	-2	0	0
5	-2	0	0	-2	2	0	1	-2	-1	1	2	1	2	0	7	5	1	1	1	1
6	0	3	1	6	0	-1	-1	-1	0	3	3	11	0	5	-4	3	1	-20	-1	-11
7	2	1	-2	0	-2	6	-1	4	2	3	1	2	1	4	1	6	1	6	4	1
8	1	8	0	8	1	-10	0	-10	0	-11	4	-7	0	-8	-2	3	1	-16	2	12
9	0	11	2	10	1	-12	5	9	0	-12	-3	7	0	-12	0	-14	0	6	3	14
10	2	6	0	1	2	21	2	15	1	6	-4	5	0	10	2	19	3	10	-13	12
11	2	9	1	15	1	15	5	8	3	1	1	15	3	6	1	10	5	15	-2	-20
12	2	13	-1	16	0	7	0	-15	3	11	2	-3	-6	4	2	5	0	8	1	-2

Test No	3.Winder

	1.Sample				2.Sample				3.Sample				4.Sample				5.Sample			
	1 h		48 h		1 h		48 h		1 h		48 h		1 h		48 h		1 h		48 h	
	Out	Inn	Out	Inn	Out	Inn	Out	Inn	Out	Inn	Out	Inn	Out	Inn	Out	Inn	Out	Inn	Out	Inn
1	-4	-12	-1	-10	-5	-12	-5	-8	-5	-9	-4	-7	1	-5	0	-2	2	-8	1	-7
2	1	-5	-2	-3	1	-6	0	-2	1	-4	1	-3	-1	-1	2	-4	-1	-7	-1	0
3	-4	-11	-4	-2	-5	-10	-4	-7	-2	-6	-7	-5	-4	-7	-3	-3	-2	-11	0	-2
4	2	-11	0	-2	-2	-13	-2	-4	-2	-13	-1	-4	-4	-7	-3	-3	-3	-8	0	-1
5	-4	-9	-2	-5	-2	-11	6	-9	-3	-10	-2	-7	-3	-8	-6	-8	-1	-11	3	-2
6	0	-13	0	-5	-2	-14	0	-8	-1	-16	2	-6	-2	-14	1	-5	0	-15	-3	-5
7	0	-8	-5	-5	-4	-6	4	-1	1	-5	0	-6	1	-6	4	-1	-2	-4	-1	-5
8	7	-9	0	0	0	-6	0	1	0	-13	-1	-2	0	-4	1	-2	-3	-10	-7	-3
9	0	5	5	-3	-3	-6	-3	-9	0	-13	5	-9	0	-15	-2	-9	0	-20	3	-7
10	0	-3	-8	6	0	-6	-5	-8	0	-15	-3	-13	-1	13	0	-3	1	-10	0	-12
11	2	-7	-10	-9	0	-2	0	-12	-1	3	-1	-7	0	-6	0	-6	2	-6	1	-2
12	1	-6	0	4	-3	-6	-4	-6	0	-5	0	-2	-6	3	-3	-5	3	-3	0	-12

Test No	4.Winder				
	1.Sample	2.Sample	3.Sample	4.Sample	5.Sample

	1 h		48 h		1 h		48 h		1 h		48 h		1 h		48 h		1 h		48 h	
	Out	Inn	Out	Inn	Out	Inn	Out	Inn	Out	Inn	Out	Inn	Out	Inn	Out	Inn	Out	Inn	Out	Inn
1	-2	-6	2	0	4	-7	0	-3	-2	-2	0	-2	-2	-5	-2	-2	-3	-7	-2	-4
2	-2	-10	-4	-3	-2	-1	1	-1	-3	-3	0	1	-1	-5	-4	-4	-2	-5	2	-1
3	2	-3	4	2	1	-2	6	1	3	-3	2	1	-1	-2	4	4	0	0	2	0
4	-1	-2	0	2	0	0	0	1	1	-1	1	0	3	0	3	2	0	-2	1	1
5	0	0	2	-2	1	-3	1	-1	0	-1	5	4	0	1	3	5	0	1	0	4
6	0	1	0	1	1	1	2	0	1	-3	5	5	0	-1	6	4	1	-7	5	5
7	4	3	2	4	4	-4	10	5	3	-6	3	3	0	-4	0	4	1	-6	4	5
8	0	-5	-1	1	3	0	6	4	-1	-1	-2	3	0	0	7	4	0	4	3	5
9	0	-1	2	0	0	1	2	2	0	0	3	0	1	2	6	5	1	4	0	2
10	1	3	5	8	5	-4	8	2	3	-2	7	3	4	1	9	6	1	1	8	6
11	0	1	5	2	5	-2	2	-10	5	-4	0	-2	2	-1	4	1	5	-2	2	-6
12	2	-6	2	-4	2	2	2	-6	6	-2	2	6	-2	-4	2	-2	6	-5	4	-8

A2.2 Test.2

Test	1.Winder

	1.Sample				2.Sample				3.Sample				4.Sample				5.Sample			
	1 h		48 h		1 h		48 h		1 h		48 h		1 h		48 h		1 h		48 h	
	Out	Inn	Out	Inn	Out	Inn	Out	Inn	Out	Inn	Out	Inn	Out	Inn	Out	Inn	Out	Inn	Out	Inn
1	0	-14	11	-19	-4	-25	0	-20	-3	-34	-7	-16	-2	-35	-5	-20	-8	-22	-7	-22
2	0	-9	1	-5	-4	-6	2	-20	-6	-4	-2	-20	-2	-9	-1	-11	-4	-8	-1	-20
3	-2	-1	4	0	-2	-15	9	-12	-6	-4	-1	-6	-6	-4	5	-9	-1	-11	2	-8

Test No	2.Winder																			
	1.Sample				2.Sample				3.Sample				4.Sample				5.Sample			
	1 h		48 h		1 h		48 h		1 h		48 h		1 h		48 h		1 h		48 h	
	Out	Inn	Out	Inn	Out	Inn	Out	Inn	Out	Inn	Out	Inn	Out	Inn	Out	Inn	Out	Inn	Out	Inn
1	-4	-13	-7	-21	-5	-10	-6	-15	-6	-10	-8	-9	-9	-13	4	-20	0	-13	-7	-20
2	-4	-7	4	-7	-4	-6	2	-10	-7	-2	-2	-1	-2	-3	-4	-6	-2	-5	-3	-12
3	-3	-3	-2	0	-3	0	-1	-2	0	7	1	-2	0	-1	-9	0	2	0	-8	3

Test No	3.Winder									
	1.Sample		2.Sample		3.Sample		4.Sample		5.Sample	
	1 h	48 h	1 h	48 h	1 h	48 h	1 h	48 h	1 h	48 h

	Out	Inn	Out	Inn	Out	Inn	Out	Inn	Out	Inn	Out	Inn	Out	Inn	Out	Inn	Out	Inn	Out	Inn
1	-3	-3	-2	0	0	-7	5	-12	0	-10	3	-10	-1	-12	3	-13	-4	-12	5	-13
2	-2	-6	3	-5	-2	-2	4	-11	-2	0	0	-6	0	-5	-4	-6	0	-6	-3	-12
3	0	-8	1	-7	-1	-3	-6	-5	-1	-8	-2	-7	-5	-4	0	-10	0	-9	-1	-12

Test No	4.Winder																			
	1.Sample				2.Sample				3.Sample				4.Sample				5.Sample			
	1 h		48 h		1 h		48 h		1 h		48 h		1 h		48 h		1 h		48 h	
	Out	Inn	Out	Inn	Out	Inn	Out	Inn	Out	Inn	Out	Inn	Out	Inn	Out	Inn	Out	Inn	Out	Inn
1	2	14	-4	15	1	15	-7	9	0	17	5	9	2	10	-7	15	1	15	-4	9
2	1	4	-5	-3	0	4	4	2	0	5	5	5	3	11	1	5	1	12	5	2
3	0	11	5	6	0	12	9	20	1	12	-1	13	2	8	-1	10	3	12	1	20

A2.3 Test.3

Width	3.Winder

in mm	1.Sample				2.Sample				3.Sample				4.Sample				5.Sample			
	1h		48h		1h		48h		1h		48h		1h		48h		1h		48h	
	Out	Inn	Out	Inn	Out	Inn	Out	Inn	Out	Inn	Out	Inn	Out	Inn	Out	Inn	Out	Inn	Out	Inn
43	-2	-3	-6	-5	1	-1	1	-3	-2	0	-7	0	0	-1	-3	0	-2	-1	-1	-4
16	2	-8	-5	-10	1	11	-9	-7	7	-2	7	-1	-9	-6	-8	-6	-11	-3	-12	-7

Width in mm	4.Winder																			
	1.Sample				2.Sample				3.Sample				4.Sample				5.Sample			
	1h		48h		1h		48h		1h		48h		1h		48h		1h		48h	
	Out	Inn	Out	Inn	Out	Inn	Out	Inn	Out	Inn	Out	Inn	Out	Inn	Out	Inn	Out	Inn	Out	Inn
43	-14	-2	-20	-8	0	-1	-21	-5	-3	-1	-20	-3	-5	-5	-10	-6	4	2	-13	-2
16	-4	1	-9	-2	-4	-5	-8	-8	-1	-4	-9	-7	-4	-4	11	-5	2	4	-7	-6

A2.4 Test.4

1.Winder 1.Sample																					
1h											48h										
0	15	30	45	60	75	90	105	120	135	150	0	15	30	45	60	75	90	105	120	135	150

1	0	2	5	7	6	8	12	4	3	2	0	-6	2	7	7	9	13	13	10	4	5
-8	7	10	8	14	12	11	9	11	14	1	-16	-5	-3	9	8	10	17	15	13	12	-9
1.Winder 2.Sample																					
1h											**48h**										
0	**15**	**30**	**45**	**60**	**75**	**90**	**105**	**120**	**135**	**150**	**0**	**15**	**30**	**45**	**60**	**75**	**90**	**105**	**120**	**135**	**150**
-10	-4	2	4	5	2	5	1	1	3	4	11	-6	-5	12	4	20	20	15	15	10	8
-8	7	8	9	10	15	11	10	15	9	0	-8	10	10	18	17	16	13	14	14	9	5
1.Winder 3.Sample																					
1h											**48h**										
0	**15**	**30**	**45**	**60**	**75**	**90**	**105**	**120**	**135**	**150**	**0**	**15**	**30**	**45**	**60**	**75**	**90**	**105**	**120**	**135**	**150**
-4	4	3	4	7	4	3	5	6	5	1											
3	12	8	8	10	13	14	11	13	12	0	-5	13	22	25	21	13	21	15	11	12	5
1.Winder 4.Sample																					
1h											**48h**										
0	**15**	**30**	**45**	**60**	**75**	**90**	**105**	**120**	**135**	**150**	**0**	**15**	**30**	**45**	**60**	**75**	**90**	**105**	**120**	**135**	**150**
-5	-12	0	2	10	5	7	9	8	4	3	0	-14	-4	-2	7	6	14	17	13	-5	-4
-2	3	12	17	16	14	20	10	9	7	2	-3	8	10	14	17	15	14	15	15	13	12
1.Winder 5.Sample																					
1h											**48h**										
0	**15**	**30**	**45**	**60**	**75**	**90**	**105**	**120**	**135**	**150**	**0**	**15**	**30**	**45**	**60**	**75**	**90**	**105**	**120**	**135**	**150**
-15	-4	5	6	8	11	8	8	7	9	3	-7	-4	5	-3	-2	12	15	16	14	15	6
-2	7	15	13	9	8	4	-2	12	5	1	-4	11	14	13	12	13	4	8	12	12	6
2.Winder 1.Sample																					
1h											**48h**										
0	**15**	**30**	**45**	**60**	**75**	**90**	**105**	**120**	**135**	**150**	**0**	**15**	**30**	**45**	**60**	**75**	**90**	**105**	**120**	**135**	**150**

5	5	8	5	4	3	2	0	-1	0	1	5	4	9	5	4	2	0	0	2	0	4
2	15	10	11	9	8	8	0	-3	-2	-3	-5	-8	-5	-6	-2	0	8	10	5	4	-4
2.Winder 2.Sample																					
1h											**48h**										
0	**15**	**30**	**45**	**60**	**75**	**90**	**105**	**120**	**135**	**150**	**0**	**15**	**30**	**45**	**60**	**75**	**90**	**105**	**120**	**135**	**150**
2	2	4	3	2	0	0	-9	-8	-11	-12											
-8	12	12	7	4	6	3	4	1	2	1	0	12	11	12	11	7	8	-6	4	8	6
2.Winder 3.Sample																					
1h											**48h**										
0	**15**	**30**	**45**	**60**	**75**	**90**	**105**	**120**	**135**	**150**	**0**	**15**	**30**	**45**	**60**	**75**	**90**	**105**	**120**	**135**	**150**
3	6	3	1	0	-1	-2	0	1	0	0											
2	18	14	17	8	9	7	11	5	5	0	5	14	4	5	8	2	9	9	8	8	0
2.Winder 4.Sample																					
1h											**48h**										
0	**15**	**30**	**45**	**60**	**75**	**90**	**105**	**120**	**135**	**150**	**0**	**15**	**30**	**45**	**60**	**75**	**90**	**105**	**120**	**135**	**150**
6	15	7	3	1	2	0	0	-10	-9	0	0	13	8	-6	-5	-5	-8	-4	-11	-4	-4
6	12	14	12	16	14	10	8	4	2	2	2	12	8	8	2	8	3	10	9	8	10
2.Winder 5.Sample																					
1h											**48h**										
0	**15**	**30**	**45**	**60**	**75**	**90**	**105**	**120**	**135**	**150**	**0**	**15**	**30**	**45**	**60**	**75**	**90**	**105**	**120**	**135**	**150**
12	12	8	4	3	3	2	-3	-3	-13	0	11	9	6	6	-7	-4	-5	-4	-3	7	0
5	20	16	12	15	6	4	5	8	-3	-4	10	12	7	9	8	12	10	3	8	10	3
3.Winder 1.Sample																					
1h											**48h**										
0	**15**	**30**	**45**	**60**	**75**	**90**	**105**	**120**	**135**	**150**	**0**	**15**	**30**	**45**	**60**	**75**	**90**	**105**	**120**	**135**	**150**

-6	-5	-3	2	2	0	1	0	3	0	-4	-10	-13	-6	-4	-3	-3	-2	0	-1	-3	-3
-5	1	5	7	10	10	13	4	6	6	7	20	12	0	0	-9	-3	4	6	10	11	10
3.Winder 2.Sample																					
1h											**48h**										
0	**15**	**30**	**45**	**60**	**75**	**90**	**105**	**120**	**135**	**150**	**0**	**15**	**30**	**45**	**60**	**75**	**90**	**105**	**120**	**135**	**150**
0	0	1	0	1	2	1	0	2	0	0	10	-10	-10	-7	-3	-2	4	-2	-2	-2	-5
2	12	6	4	3	9	7	7	-10	-7	-12	-9	7	-6	-5	-6	6	-9	-4	-9	-16	-5
3.Winder 3.Sample																					
1h											**48h**										
0	**15**	**30**	**45**	**60**	**75**	**90**	**105**	**120**	**135**	**150**	**0**	**15**	**30**	**45**	**60**	**75**	**90**	**105**	**120**	**135**	**150**
-8	-3	1	0	1	0	2	1	3	3	-1	9	7	2	1	0	0	3	0	5	5	7
3	6	7	4	12	6	8	10	6	-4	-8	8	6	5	10	12	8	6	4	8	-13	-10
3.Winder 4.Sample																					
1h											**48h**										
0	**15**	**30**	**45**	**60**	**75**	**90**	**105**	**120**	**135**	**150**	**0**	**15**	**30**	**45**	**60**	**75**	**90**	**105**	**120**	**135**	**150**
-6	-4	1	2	1	3	2	0	2	3	-1	7	-10	-12	-6	-6	-3	-4	-4	-5	-10	-8
-2	9	6	10	7	4	8	7	3	1	0	-8	6	8	8	6	-5	-8	-4	-14	-8	-9
3.Winder 5.Sample																					
1h											**48h**										
0	**15**	**30**	**45**	**60**	**75**	**90**	**105**	**120**	**135**	**150**	**0**	**15**	**30**	**45**	**60**	**75**	**90**	**105**	**120**	**135**	**150**
-22	-12	0	2	0	1	2	1	0	0	-4	-14	-9	-4	-5	0	1	4	2	1	0	0
-4	-12	-7	-13	4	11	-7	-13	-7	-12	-2	8	-9	6	5	8	14	15	12	9	10	12
4.Winder 1.Sample																					
1h											**48h**										
0	**15**	**30**	**45**	**60**	**75**	**90**	**105**	**120**	**135**	**150**	**0**	**15**	**30**	**45**	**60**	**75**	**90**	**105**	**120**	**135**	**150**

-5	0	0	0	1	5	5	3	2	1	1	-4	-8	-8	0	1	2	0	4	2	3	0
3	8	11	7	7	7	8	7	12	4	-3	-8	-4	3	3	9	12	14	10	10	14	-8
4.Winder 2.Sample																					
1h											**48h**										
0	**15**	**30**	**45**	**60**	**75**	**90**	**105**	**120**	**135**	**150**	**0**	**15**	**30**	**45**	**60**	**75**	**90**	**105**	**120**	**135**	**150**
-20	0	0	0	1	0	0	0	0	-1	-4	-11	-12	-5	-6	-7	-4	-4	-3	-3	-2	-1
7	7	12	14	8	14	7	12	7	6	-6	-4	-4	12	14	11	15	12	9	11	13	-8
4.Winder 3.Sample																					
1h											**48h**										
0	**15**	**30**	**45**	**60**	**75**	**90**	**105**	**120**	**135**	**150**	**0**	**15**	**30**	**45**	**60**	**75**	**90**	**105**	**120**	**135**	**150**
-5	-4	-3	0	-3	0	0	0	0	0	-7	-5	-14	-10	-7	-6	-7	-7	-6	-5	-5	-8
6	12	11	8	14	11	16	12	16	8	-6	-5	-8	8	-5	13	5	11	8	7	12	-8
4.Winder 4.Sample																					
1h											**48h**										
0	**15**	**30**	**45**	**60**	**75**	**90**	**105**	**120**	**135**	**150**	**0**	**15**	**30**	**45**	**60**	**75**	**90**	**105**	**120**	**135**	**150**
-7	0	2	3	2	1	1	0	0	1	0	-7	-12	-5	-4	-4	-3	-5	-3	-10	-5	-8
4.Winder 5.Sample																					
1h											**48h**										
0	**15**	**30**	**45**	**60**	**75**	**90**	**105**	**120**	**135**	**150**	**0**	**15**	**30**	**45**	**60**	**75**	**90**	**105**	**120**	**135**	**150**
-4	0	3	0	1	0	0	0	1	0	0	-4	-3	0	-2	-6	-4	-4	-3	-3	0	-5
3	14	13	5	1	7	0	13	3	2	12	0	8	6	9	6	10	7	6	6	5	-7

A2.5 Test.5

1.Winder 1.Sample											1.Winder 2.Sample											1.Winder 3.Sample										
0	**15**	**30**	**45**	**60**	**75**	**90**	**105**	**120**	**135**	**150**	**0**	**15**	**30**	**45**	**60**	**75**	**90**	**105**	**120**	**135**	**150**	**0**	**15**	**30**	**45**	**60**	**75**	**90**	**105**	**120**	**135**	**150**
-12	5	4	5	8	4						0	8	4	4	7	5						-5	-7	4	8	5	5					
											-3	0	0	2	1	1						-4	0	2	3	-1	1					
-6	0	2	4	5	4	6	3	6	2	0	0	-3	-6	1	4	6	5	11	11	8	0	-13	0	4	4	5	8	8	8	10	14	3
1	4	4	8	5	6	3	4	3	1	1	0	4	0	5	5	5	5	4	2	2	0	1	5	6	5	4	5	2	1	3	2	-1

1.Winder 4.Sample											1.Winder 5.Sample										
0	**15**	**30**	**45**	**60**	**75**	**90**	**105**	**120**	**135**	**150**	**0**	**15**	**30**	**45**	**60**	**75**	**90**	**105**	**120**	**135**	**150**
-8	-10	2	8	15	4																
1	4	3	2	0	0						0	2	1	0	0	0					
-10	-2	-4	4	10	9	8	5	8	8	1	-3	2	3	3	3	4	6	5	9	8	-3
0	3	4	4	5	6	5	4	0	0	1	-5	5	4	7	5	7	4	5	2	2	0

2.Winder 1.Sample											2.Winder 2.Sample											2.Winder 3.Sample										
0	**15**	**30**	**45**	**60**	**75**	**90**	**105**	**120**	**135**	**150**	**0**	**15**	**30**	**45**	**60**	**75**	**90**	**105**	**120**	**135**	**150**	**0**	**15**	**30**	**45**	**60**	**75**	**90**	**105**	**120**	**135**	**150**
7	10	5	1	0	2						3	9	5	-1	-11	0						6	12	7	-1	-8	-6					
											4	3	2	0	1	2						6	3	4	3	0	0					
5	14	10	3	4	0	0	-4	-2	-9	0	5	13	7	5	-1	-10	-10	-14	-13	-14	0	7	13	7	5	4	-1	-7	-9	-6	-8	-1
3	0	5	5	4	3	3	0	1	0	2	6	4	4	3	6	3	1	0	0	0	-1	0	3	5	3	3	3	2	1	1	0	0

2.Winder 4.Sample											2.Winder 5.Sample										
0	**15**	**30**	**45**	**60**	**75**	**90**	**105**	**120**	**135**	**150**	**0**	**15**	**30**	**45**	**60**	**75**	**90**	**105**	**120**	**135**	**150**

4	13	3	-8	-12	-6																
0	2	3	1	0	0						1	3	2	2	0	1					
10	17	10	6	-2	-8	-6	-13	-13	-12	2	4	5	7	7	0	-3	-4	-6	-7	-8	-2
0	2	1	0	1	3	2	2	3	0	0	4	6	6	-4	0	0	3	3	0	3	1

3.Winder 1.Sample											**3.Winder 2.Sample**											**3.Winder 3.Sample**										
0	**15**	**30**	**45**	**60**	**75**	**90**	**105**	**120**	**135**	**150**	**0**	**15**	**30**	**45**	**60**	**75**	**90**	**105**	**120**	**135**	**150**	**0**	**15**	**30**	**45**	**60**	**75**	**90**	**105**	**120**	**135**	**150**
0	8	5	4	3	-5						2	8	3	-6	-1	4						2	6	7	3	0	-3					
											4	5	2	1	0	3						-2	-1	2	0	2	-3					
-5	7	5	4	1	4	0	3	0	-2	-3	3	3	0	-4	-6	-5	-8	-7	-9	-13	-10	0	4	1	1	2	-3	-3	-6	-6	-6	-6
-6	0	0	0	-1	0	-1	0	2	0	-6	-5	2	1	3	1	2	5	0	0	0	-1	-3	0	3	0	0	0	3	0	-2	5	-4

3.Winder 4.Sample											**3.Winder 5.Sample**										
0	**15**	**30**	**45**	**60**	**75**	**90**	**105**	**120**	**135**	**150**	**0**	**15**	**30**	**45**	**60**	**75**	**90**	**105**	**120**	**135**	**150**
0	2	0	2	-4	-7																
-2	1	2	-1	1	-1						-3	2	1	0	2	0					
0	5	5	5	2	2	3	-4	1	-1	-5	-14	9	3	3	5	1	1	1	2	1	2
-6	2	1	0	2	0	0	5	0	0	-2	-2	4	4	0	5	2	2	0	1	1	-5

4.Winder 1.Sample											**4.Winder 2.Sample**											**4.Winder 3.Sample**										
0	**15**	**30**	**45**	**60**	**75**	**90**	**105**	**120**	**135**	**150**	**0**	**15**	**30**	**45**	**60**	**75**	**90**	**105**	**120**	**135**	**150**	**0**	**15**	**30**	**45**	**60**	**75**	**90**	**105**	**120**	**135**	**150**

3	13	5	2	0	4						3	10	2	-4	-8	4						7	13	6	6	2	0					
											4	5	0	2	3	0						3	3	0	2	-1	2					
5	7	8	10	4	6	10	-16	-14	-17	-6	4	15	5	5	3	1	0	0	-10	-8	0	10	14	7	2	4	-5	-5	-7	-11	-10	-5
2	4	3	4	0	6	4	3	2	2	1	0	5	2	5	2	3	4	0	-1	3	0	1	5	5	5	5	4	2	3	4	3	-1

4.Winder 4.Sample											4.Winder 5.Sample										
0	**15**	**30**	**45**	**60**	**75**	**90**	**105**	**120**	**135**	**150**	**0**	**15**	**30**	**45**	**60**	**75**	**90**	**105**	**120**	**135**	**150**
3	12	1	-5	-10	3																
4	4	3	0	4	-2						2	3	1	1	2	0					
5	17	6	2	1	-1	0	0	-5	-17	2	3	7	5	2	0	3	-4	-8	-12	-13	-6
2	4	3	4	0	6	4	3	2	2	1	2	9	5	7	5	6	5	0	2	5	4

A2.6 Test.6

1.Winder																													
1.Sample						2.Sample						3.Sample						4.Sample						5.Sample					
0	**15**	**30**	**120**	**135**	**150**	**0**	**15**	**30**	**120**	**135**	**150**	**0**	**15**	**30**	**120**	**135**	**150**	**0**	**15**	**30**	**120**	**135**	**150**	**0**	**15**	**30**	**120**	**135**	**150**
2	2	3	0	-3	-4	2	6	5	-3	-4	-3	0	3	2	-3	-7	-5	1	5	0	-2	-4	-2	1	2	2	-4	-4	0
-12	-10	-10	-6	-15	-5	5	-5	-6	-12	-14	-5	-11	-10	0	-15	-16	-9	-9	-12	-13	-10	-16	-8	-6	-12	-15	-12	-15	-7
-4	-5	0	-10	-7	-3	-13	-10	2	-6	-7	-6	5	0	2	-7	-11	0	-6	-5	2	5	6	4	-5	-10	4	-7	-3	-2
4	2	1	-9	-7	-4	-4	-7	-5	-2	-4	-4	4	-6	0	-4	-2	-2	3	-2	-1	-6	-3	-2	1	-3	-4	-6	-3	-5

2.Winder

1.Sample						2.Sample						3.Sample						4.Sample						5.Sample					
0	**15**	**30**	**120**	**135**	**150**	**0**	**15**	**30**	**120**	**135**	**150**	**0**	**15**	**30**	**120**	**135**	**150**	**0**	**15**	**30**	**120**	**135**	**150**	**0**	**15**	**30**	**120**	**135**	**150**
1	2	0	-7	-5	-5	9	10	6	-7	0	0	5	4	0	-2	-6	-2	6	7	7	-2	-5	-6	6	7	4	-2	-4	-3
10	10	9	12	9	0	6	14	8	6	5	-6	4	12	6	10	15	-4	-5	12	11	8	11	4	7	4	5	10	12	-7
0	3	1	-4	-2	-4	2	3	6	-2	-5	-5	2	-4	-6	-2	-4	-5	3	-4	2	-5	-5	-4						
10	4	3	-4	-2	0	5	7	4	-2	-4	-2	3	4	5	-2	-3	-2	8	-3	4	1	0	4	6	5	2	-2	-2	0

3.Winder																													
1.Sample						2.Sample						3.Sample						4.Sample						5.Sample					
0	**15**	**30**	**120**	**135**	**150**	**0**	**15**	**30**	**120**	**135**	**150**	**0**	**15**	**30**	**120**	**135**	**150**	**0**	**15**	**30**	**120**	**135**	**150**	**0**	**15**	**30**	**120**	**135**	**150**
-7	0	1	-5	-6	0	-5	-7	3	-2	2	0	-5	5	-4	1	5	0	2	1	1	-3	1	2	-2	3	0	1	-2	3
-11	-13	-13	-4	-5	-6	-6	-9	-8	-5	-8	1	-10	-11	-9	8	-11	-4	-13	-10	-12	-4	-8	0	-7	-12	-13	-5	-8	8
-12	-12	-6	1	4	-5	-10	-10	-9	2	0	5	-8	-13	-6	-2	1	4	-8	-8	-5	3	4	6	-8	-10	-7	3	4	4
0	-6	-7	2	-2	2	-6	4	-5	0	3	-3	-5	-6	-5	0	3	2	-2	1	-7	2	5	2	-6	2	4	1	2	0

4.Winder																													
1.Sample						2.Sample						3.Sample						4.Sample						5.Sample					
0	**15**	**30**	**120**	**135**	**150**	**0**	**15**	**30**	**120**	**135**	**150**	**0**	**15**	**30**	**120**	**135**	**150**	**0**	**15**	**30**	**120**	**135**	**150**	**0**	**15**	**30**	**120**	**135**	**150**
5	8	4	-6	-4	-4	5	6	0	0	-2	0	-5	2	0	1	3	1	4	3	4	0	-4	-4	3	1	0	2	2	2
7	15	11	-12	-14	5	11	12	13	11	14	-2	-6	14	9	12	13	5	6	10	-10	6	7	0	-6	9	7	10	12	7
-6	5	9	4	0	5	-6	4	-4	1	0	7	7	8	4	-2	-2	-13	-3	6	4	4	0	-2	3	9	4	7	4	10
0	7	3	0	-5	-1	7	8	2	-1	0	-5	3	4	3	-3	-1	-2	6	6	7	1	4	0	3	2	3	5	1	0