A case study in optimisation of injection moulding using recycled HDPE

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Sammandrag:

Syftet med det här slutarbetet är att få mera information och kunskap om att välja parameter inställningar för formsprutning. Teoridelen omfattar formsprutnings processen och egenskaperna av det använda materialet. Metoder for optimering samt metoder för mätning av kvalitet undersöks. För att resultatet av den verkliga optimeringen skall kunna jämföras med en simulation omfattas också funktionen samt resultat tolkningen för simulation av formsprutning. En provformsprutning gjordes för att få startvärden. Ett optimerings experiment utfördes på fem nivåer med fem kontroll faktorer. Massa, area och hållfasthet valdes som kvalitetsfaktorer. Taguchi S/N förhållanden räknades ut, nominellt den bästa valdes för area och störst den bästa för massa och hållfasthet. En en- vägs ANOVA gjordes för varje parameter för massa, area och hålfasthetsmätningarna. Simulationerna gjordes med både Autodesk Moldflow och Solidworks Plastics. Båda simulationerna hade överraskande lika resultat för övergångstryck (ungefär 50 MPa) och fyllningstid (3 sekunder). De flesta av simulationsresultaten var givna på så olika sätt att det inte går att jämföra dem. Flödesfronts temperaturen hade den största skillnaden. Att använda hållfasthet som en kvalitetsfaktor för återvunnet HDPE plast för ANOVA analys fungerade inte eftersom materialet var så svagt att ingen av faktorerna kunde värderas som betydelsefull. För en smälttemperatur på 220 °C hade både kyl tid och eftertryckstid nära resultat för både optimeringen och simulationerna.

Nyckelord:	Formsprutning, återanvänt HDPE, optimering, simulering, Taguchi, ANOVA,
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Abstract:

The purpose of this thesis is to learn more about how to choose injection moulding parameters. Theory will cover the process of injection moulding and describe the properties of the material used. Methods for optimisation and methods of measuring the quality of the product is studied. The result of the practical optimisation is compared to results of software simulations. The function and result interpretation of the simulations of injection moulding are covered as well. A test injection moulding was done to gain some starting parameters. An optimisation experiment was done using five control factors on five levels. Mass, area and tensile strength were chosen as quality factors. Taguchi S/N ratios were calculated, nominal the best was chosen for the surface area measurements and larger the better was chosen for mass and tensile measurements. A one-way ANOVA was done for each of the parameters for mass, area and tensile quality measurements. Simulations were done using both Autodesk Moldflow and Solidworks Plastics. Both simulations had surprisingly close results in Switchover pressure (approximately 50 MPa) and fill time (3 seconds). A lot of the simulation results were expressed in quite different ways and are therefore hard to compare with each other. The flow front temperature had the largest difference. The only thing that did not work was the usage of tensile strength as a quality factor for the recycled HDPE in the ANOVA analysis as the material was so weak that no one of the factors could be determined as significant. At a 220°C melt temperature, both cooling time and holding time had similar results for both the optimisation and simulation.

Keywords:	Injection moulding, recycled, HDPE, optimisation, simulation, Taguchi, ANOVA
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Tiivistelmä:

Tämän lopputyön tarkoituksena on kartuttaa tietoa ja osaamista ruiskuvalu parametrien valinnassa. Teoria osuus käsittää ruiskuvalu prosessin ja käytetyn materiaalin ominaisuudet. Optimointi menetelmiä ja laadun mittaus menetelmiä tutkitaan. Jotta todellisen optimoinnin ja simulaation tuloksia voitaisiin vertailla käsittää työ myös ruiskuvalusimulaation toiminnot ja tulosten tulkinnan.

Lähtöarvot saatiin kokeiluruiskuvalusta. Optimointikoe tehtiin viidellä muuttujalla ja viidellä valvontatekijällä. Paino, pinta-ala ja vetolujuus valittiin laatu tekijöiksi. Tagutchi S/N suhteet laskettiin, nimellinen paras valittiin pinta-alalle ja suurin paras painolle ja vetolujuudelle. Yksisuuntainen ANOVA tehtiin jokaiselle parametrille painolle, pinta-alalle ja vetolujuudelle. Simulaatiot tehtiin sekä Autodesk Mouldflow että Solidworks Plastics ohjelmia käyttäen. Molemmissa simulaatioissa oli yllättävän samanlaiset tulokset sekä siirtymä paineessa (noin 50 MPa) että täyttöajassa. Suurin osa simulaatiotuloksista oli ilmaistu niin eri tavoin, että niitä on vaikea vertailla. Virtaus rintaman lämpötilassa oli suurin ero. Vetolujuuden käyttäminen laatutekijänä kierrätetyn HDPE muovin ANOVA analyysissä ei toiminut koska materiaali oli niin heikko, että ainuttakaan muuttujaa ei voitu todeta merkittäväksi. Lämpötilassa 220 ° C sekä jäähdytys ajalla, että jälkipaineajalla oli samanlaisia tuloksia sekä optimoinnissa että simulaatioissa.

Avainsanat:	Ruiskuvalu, uusiokäytetty HDPE, optimointi, simulaatio, Taguchi, ANOVA
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UTÖKAT SAMMANDRAG

Syftet med det här slutarbetet är att få mera information och kunskap om att välja parameter inställningar för formsprutning.

Att välja rätt parametrar kräver ofta praktisk erfarenhet. En bra fråga är om de parametrar som valts ar de bästa möjliga eller om det fortfarande vore möjligt att göra dem ännu lite bättre.

Teoridelen omfattar formsprutnings process och egenskaperna av det använda materialet. Metoder for optimering samt metoder för mätning av kvalitet undersöks.

Målet för optimeringen I det här arbetet är att göra kvaliteten så bra som möjligt inte att göra produktions tid så snabb som möjligt. Därför kommer metoder for att mäta kvalitet på formsprutade produkter att studeras.

Resultatet från optimeringsexperimentet jämfördes med resultat från mjukvarusimuleringar därför granskas funktionen och resultat tolkningen av formsprutnings simulationer.

Forsknings målen för arbetet är:

1 Att fastställa ifall använda optimerings metoder är fungerande för återvunnet plast

2 Att jämföra optimerings resultat för ett återvunnet material och ett referens material.

3 Att utvärdera ifall tiden som krävs för optimerings uträckningar är värd att spendera på att göra dem.

För att resultatet av den verkliga optimeringen skall kunna jämföras med en simulation omfattas också funktionen samt resultat tolkningen för simulation av formsprutning.

En provformsprutning gjordes för att få startvärden. Ett optimerings experiment utfördes på fem nivåer med fem kontroll faktorer. Massa, area och hållfasthet valdes som kvalitetsfaktorer. Massa och area mättes.

Hållfasthets prov gjordes på en Testometric dragprovningsmaskin enligt ASTM D 638-67T standard. Taguchi S/N förhållanden räknades ut, nominellt den bästa valdes för area och störst den bästa för massa och hållfasthet.

En en- vägs ANOVA gjordes för varje parameter för massa, area och hålfasthetsmätningarna för både det återvunna HDPE plasten och referens plasten.

För referens materialet var både eftertryckstiden och eftertrycket betydelsefulla för mas mätningen. För area mätningen var kyltiden och eftertrycket betydelsefulla. Dragtestsmättningen hade smälttemperatur, eftertryckstiden och eftertrycket som betydelsefulla faktorer.

För det återvunna materialet var eftertryckstid betydelsefull för mas mätningen. I area mätningen var smälttemperatur och eftertryckstiden betydelsefulla faktorer. Dragtestsmättningen hade inga betydelsefulla faktorer.

Eftertrycks tid förekom som betydelsefull fyra gånger medan smälttemperatur och eftertryck förekom tre gånger.

Simulationerna gjordes med både Autodesk Moldflow och Solidworks Plastics. Båda simulationerna hade överraskande lika resultat för övergångstryck (ungefär 50 MPa) och fyllningstid (3 sekunder).

De flesta av simulationsresultaten var givna på så olika sätt att det inte går att jämföra dem. Flödesfronts temperatur hade den största skillnaden.

Enligt en jämförelse av resultat från Taguchi och ANOVA metoderna verkar den bästa smälttemperaturen för det återvunna materialet vara 214 °C eftersom det förekommer två gånger i topp listan för S/N förhållanden.

För referens materialet verkar 230 °C vara den bästa temperaturen eftersom parameter kombination nummer 11 hade den här temperaturen och den var först i S/N ranking listan för både massa och hålfasthets mätningarna.

Nivå fem var den enda återkommande nivån för eftertrycks tid. Nivå fem var också återkommande för eftertryck för båda materialen.

Kyltiden var antagligen inte betydelsefull i någon av kvalitetsmätningarna för att alla kyltider som användes var tillräckligt långa för att kyla ner delen, därför kan den kortaste kyltiden användas.

Fastän insprutnings hastigheten inte var betydelse full så var det mest återkommande värdet i S/N förhållande jämförelsen på nivå 3 som är det mittersta värdet.

Båda simulationerna hade överraskande lika övergångs tryck på ungefär 50 MPa och en fyllningstid på 3 sekunder. De visade också en krympnings böjning av provstycket vilket ibland händer med formen som användes så den här delen av simulations resultaten stämmer med verkligheten rätt bra.

En stor del av simulations resultaten var uttryckta på helt olika sätt vilket gör att resultaten är svåra att jämföra. Flödes hastighet är en av parametrarna som inte går att jämföra eftersom Autodesk Moldflow har mätt flödesfronts hastighet medan Solid Works Plastics har mätt inloppsflödeshastighet, det här gör att till och med enheterna är totalt olika.

Flödesfronts temperaturen hade den största skillnaden. Den maximala slutkraften som simulationerna räknat ut hade en skillnad på en faktor av tio. Det var intressant att Solid Works Plastics indikerade att kärn och ytlagren skulle ha olika inriktning.

Animationen i Solid Works Plastics hade fint och jämnt flytande flödesfront vilket förstärks av att Autodesk Moldflow inte visar några sammanfognings linjer.

Det är värt att uppmärksamma att startparametrarna var rätt bra och att skillnaderna mellan de olika nivåerna av parametervärden var små vilket gjorde att skillnaderna i S/N förhållanden också var låga.

När man jämför resultat från experimentet och simulationerna är den första likheten att 20 sekunders kyltid från experimentet, och att Autodesk simulationen som också anger att delen är tillräckligt avkyld för att vara klar för utstötning på 20 sekunder. Optimerings experiment ger alltså samma kyl tid som en av simulationerna.

Simulationerna optimerar inte smälttemperatur eftersom den bestäms av material informationen i programmen. Materialet som valdes för båda simulationerna hade en smälttemperatur på 220° C.

XY diagrammer för tryck på injections punkten visar ett jämnt eftertryck av 40 MPa vilket inte är nära någondera av resultaten från optimeringen men å andra sidan så har mjukvaran inte egentligen analyserat eftertryck utan valt att uttrycka det som ett tryck i slutet av formfyllningen värde istället.

Däremot hade simulationen valt att hålla trycket aktivt i 13 sekunder enligt XY diagrammet för tryck på injections punkten .Det här är rätt nära till 14 sekunder eftertryckstid som var resultatet av optimeringen.

Mjukvarorna analyseras inte heller insprutnings hastighet för att de är mer fokuserade på tryck och flödeshastighet eftersom dessa är mindre beroende av specifika egenskaper på individuell formsprutnings maskiner.

Att använda hållfasthet som en kvalitetsfaktor för återvunnet HDPE plast för ANOVA analys fungerade inte eftersom materialet var så svagt att ingen av faktorerna kunde värderas som betydelsefull.

För en smälttemperatur på 220 °C hade både kyl tid och eftertryckstid lika eller nära resultat för både optimeringen och simulationerna.

Tid som spenderats på att göra uträkningarna är värd att använda för att göra dem eftersom det på lång sikt är möjligt att utveckla ett sätt att göra dem en rutinmässig del av produktions processen. Att fylla i färdigt gjorda tabeller kräver mycket mindre arbete än att göra helt nya uträckningar varje gång.

CONTENTS

Figures

Enclosure Figures

Tables

FOREWORD

The dedication of this thesis work goes to you,
if you stick with reading it until the very
end.

LIST OF ABBREVATIONS AND SYMBOLS

A_s	Sectional area of the screw
S_D	Dosage distance
S_{Dst}	Position of the screw
S_{UP}	Switching point
V_F	Shot volume
n_s	Rotational speed of the screw
s_{DK}	Decompressing distance
t_E	Injection time
t_K	Cooling time
t_{ND}	Holding pressure time
t_k	Cooling time
v_E	Injection velocity in
v_{Umax}	Maximal peripheral velocity in
y_i	Each observed value
°C	Degrees of Celsius
2,5D	Two and a half dimensional
2D	Two dimensional
3D	Three dimensional
4S	Four standard deviations
a	Number of runs in the experiment
ANOVA	One way analysis of variance

b	Number of levels of each factor
C	Control factors
c	Number of columns in the array
CAD	Computer aided design
cm^2/s	Cubic centimetres per second
c_m	Machine process capability
cm/s	Centimetres per second
cm^2	Square centimetre
cm^3	Cubic centimetre
c_p	Process capability
D	Diameter of the screw
DF	Degree of freedom
FDM	Fused deposition modelling
FEM	Finite element method
g	Grams
g/cm^3	Grams per cubic centimetre
HDPE	High-Density Polyethylene
L	Indicator of latin square design
LSL	Lower specification limit
m	Mass
M	Signal factors
m	Meter

m/s	Meters per second
Mm	Millimetre
mm/s	Millimetres per second
MPa	Megapascal
N	Noise factors
n	Number of values for each trial condition
PPM	Parts per million
RHDPE	Recycled high-density Polyethylene
s	Standard deviation
S/N	Signal to noise
s^{-1}	Hertz
SNR	Average response values
STL	Standard Triangle Language
USL	Upper specification limit
Σ	Sum
$Pmax$	Maximum injection pressure
$Vmax$	Maximum shot size
μ	Predictable part of the response
ρ	Density
σ	Unpredictable part of the response

1 INTRODUCTION

1.1 Aim

The purpose of this thesis is to learn more and gain information and knowledge about how to choose injection moulding parameters. Choosing parameters is something that requires practical experience. A good question is how one knows if the chosen parameters are the best ones possible or if it would still be possible to change them a little bit more to get even better ones.

Theory will cover the process of injection moulding and describe the properties of the material used. Methods for optimisation will be researched for the theory part of the thesis. The methods of optimising the parameters are limited to those that reasonably can be done by an engineering student.

The optimisation of the process will, in this case, be done with the goal of getting the plastic product as good as possible and not getting a production time as short as possible. Methods of measuring the quality of the product will, therefore, be studied. As the result of the practical optimisation will be compared to results of software simulations the development, function and result interpretation of the simulations of injection moulding will be covered as well.

1.2 Objectives

1. To determine if these methods of optimisation are viable to use with recycled plastic.
2. To compare optimisation results of recycled material with a reference material and results from computer simulations.
3. To evaluate whether the time required for optimisation calculations is worth spent on doing them.

1.3 Theory

1.3.1 Injection moulding

An injection moulding machine consists of the main components in Figure 1: the plasticizing unit, the clamping unit and a mould. The plasticizing unit melts the polymer. The plastic enters the plasticizing unit trough a hopper to the screw chamber or barrel where the friction from the screw and heat from heating elements melt the plastic. The screw accumulates the plastic to the inside of the nozzle trough which it is injected into the mould. The clamping unit opens and closes the mould and keeps it tightly closed. The clamping can be of a mechanical or hydraulic type. (1)

The mould determines the shape of the injection moulded product and cools the molten plastic into a solid and ejects the finished part out from the mould and the injection moulding machine. The mould can have a cold runner or a hot runner system. (1)

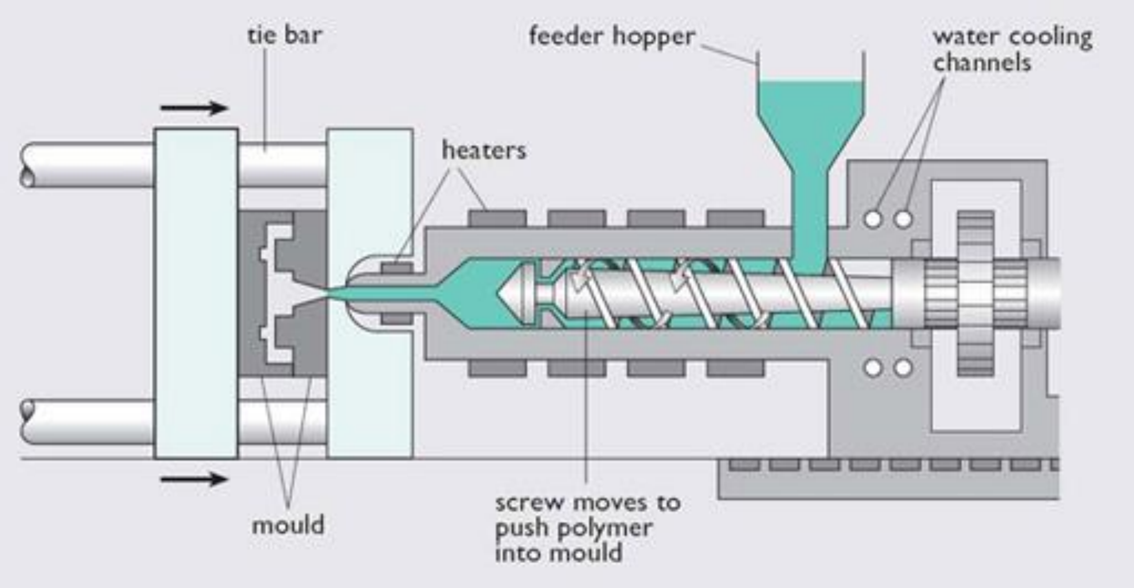


Figure 1: Injection moulding machine schematic (2)

Injection moulding machines are internationally classified according to MANUFACTURER T/P where T is the metric tonne clamping force, F and definition of P are:

$$P = \frac{\mathrm{Vmax} * \mathrm{Pmax}}{1000} \qquad \textit{Equation 1}$$

$Vmax$ is the maximum shot size in cm^3

$Pmax$ is the maximum injection pressure in bar

(1)

The injection moulding cycle starts with the mould closing and molten plastic being injected into the mould cavity. When the plastic hits the walls of the mould cavity, it starts to cool down. When the cavity is filled, a holding pressure is kept on to fill the cavity a little bit more as the cooling plastic shrinks. When the gate is frozen the holding pressure is no longer needed, and the cooling starts. Because the screw no longer needs to maintain the holding pressure, it moves back and rotates to move the next shot of plastic in front of it to be ready for the next injection. When the part is cooled enough the mould opens, and the part is ejected. A new cycle can then start with the mould closing. (1)

1.3.2 HDPE and recycling

1.3.2.1 High-Density Polyethylene

Polyethene is one of the plastics used in largest volume by the plastics industry. Polyethene is used in producing items by injection moulding, extrusion and thermoforming. It has toughness and stiffness required for producing hollow parts and chemical-, electrical- and water- resistance as advantages. HDPE has an excellent processing flexibility, chemical resistance and balanced mechanical properties and it has a semi-crystalline structure. (3)

1.3.2.2 Recycling process

Mechanical recycling converts used items into new ones by melting and remoulding them. Before recycling, plastics must be separated and sorted according to plastic type. As plastic products often come in contact with other compounds during use, it is important to clean it to remove contaminants. Surface contaminants can be removed by washing with water. Washing with water is not enough if the contamination is hydrophobic or has been absorbed by the polymer, in these cases a solution containing caustic soda and surfactants can be used. Depending on the material and its ability to absorb and bind water it might require drying before processing. A recycling system contains identification and separation of plastics, grinding, washing, drying, extrusion and granulation. (4)

1.3.2.3 Degradation

Degradation reactions can be thermal, mechanical, chemical, photo, biodegradation or a combination of them. The most common reaction in most polymers during reprocessing is mechanical degradation and thermos oxidation. It is thought that polymers become brittle below a critical molecular weight. Therefore, it is assumed that the number average molecular weight should not fall to under half of its original value for polyolefins. (4)

1.3.3 Optimization

1.3.3.1 Empirical Method

The following empirical method is used to determine parameters on Engel injection moulding machines.

Temperature

Temperatures of the barrel and nozzle should be chosen according to material and recommendations from the material supplier. To identify the barrel and nozzle see Figure 1 on page 18. According to a commonly used rule, the temperature of the section of the barrel next to the nozzle should be 10 °C higher than the nozzle temperature. (5)

Mould temperature

The temperature of the mould is chosen according to recommendations for the type of plastic used. The mould temperature is controlled using an external tempering unit. The temperature of the mould affects the cooling time and the holding time. The cooling time increases with two percent if the temperature of the mould increases with one degree. (5)

Mould closing force

The baseline for the mould closing force is the maximum capacity of the machine. The closing force F_s can be calculated as:

$$\mathrm{F_s} = \mathrm{A}_{\mathrm{proj}} \times \mathrm{Pw_{max}} \times 0{,}0001 \qquad \textit{Equation 2}$$

Where.

F_s is mould closing force in 10^{-5} N

A_{proj} is the projected area of the mould in mm^2

Pw_{max} is the internal pressure of the mould in bar.

To be sure about using enough force for closing the mould 30% of the value from the formula is added to get the final value for the mould closing force. (5)

Cooling time

The following formulas can be used for estimating the cooling time.

$t_k = s\ (1 + 2s)$ For mould temperatures lower than 60 °C. *Equation 3*

$t_k = 1{,}3s\ (1 + 2s)$ For mould temperatures higher than 60 °C. *Equation 4*

Where:

t_k is cooling time

s is the thickness of the part in mm

(5)

Injection

The injection velocity is the velocity that the screw uses to press the molten plastic into the mould. An estimating injection velocity v_E calculation can be done using the formula:

$$\mathrm{v_E} = \frac{\mathrm{V_F}}{(\mathrm{t_E} \times \mathrm{A_S})}$$ *Equation 5v*

Where

v_E is injection velocity in cm/s

V_F is Shot volume in cm^3 $V_F = \frac{m}{\rho}$ where m is mass in grams and ρ is density in g/cm^3

t_E is injection time in seconds

A_s is sectional area of the screw in cm^2

(5)

Often a profile for injection velocity is used. Changes in injection velocity affect the injection pressure limit and the switching point, which is a point in the screws position where the injection pressure changes to holding pressure. The injection pressure limit protects the mould from suddenly getting a too high internal pressure.

The switching point needs to be empirically found. When searching for the switching point, the holding pressure needs to be 0. The switching point has been found when the cavity of the mould is full. For getting the starting point of the attempts, the following formula can be used.

$$\mathrm{S_{UP}} = \mathrm{S_{Dst}} + \mathrm{s_{DK}} - 0{,}9\ \mathrm{S_D} \qquad \textit{Equation 6}$$

Where

S_{UP} is the switching point in mm

S_{Dst} is the position of the screw in mm

s_{DK} is decompressing distance in mm

S_D is dosage distance in mm

(5)

Holding pressure

The holding pressure time t_{ND} can be estimated using the formula:

$$\mathrm{t_{ND}} = 0{,}2\times \mathrm{t_K} \qquad \textit{Equation 7}$$

Where

t_{ND} is the holding pressure time in s

t_K is the cooling time in s

The optimal holding pressure time can be found by setting the holding pressure to 30 bars and producing and, then measuring the mass of a part. After producing each part, the mass of it is measured and when the mass of the part no longer changes the optimal time has been found. When the optimal holding pressure time is found the holding pressure is found by gradually increasing the pressure until no visual defects in the product can be found. (5)

Dosage

The dosage velocity is the velocity with which the screw moves the distance of dosage, and it is dependent on the rotational velocity of the screw. It is recommended to start with the rotation velocity that is achieved when the peripheral velocity is 0, 2 m/s. In most cases, it is still useful to start with a 50% rotational velocity. The maximal peripheral velocity for a specific material can be calculated using the formula:

$$\mathrm{v_{Umax}} = \pi \times \mathrm{D} \times \mathrm{n_s} \qquad \textit{Equation 8}$$

Where:

v_{Umax} is maximal peripheral velocity in m/s

D is the diameter of the screw in m

n_s is the rotational speed of the screw in s^{-1}

Changes in the rotational speed of the screw will cause shifts in the friction and changes in the friction will change the temperature of the molten plastic and the compression of the plastic melt in front of the screw. Switching point and dosage time will also be affected if the rotational speed of the screw is changed. The back pressure is material dependent and is the pressure on the hydraulic cylinder during the dosage phase. (5)

1.3.3.2 Taguchi Method

The Taguchi method, or robust engineering method, is a method that strives to improve the performance of the product in customer use environment through variability reducing in a cost- effective way. In the method, there are two definitions of quality; customer-driven quality and engineered quality. Customer driven quality includes colour, size, appearance and function. The aim of the method is to improve engineered quality. The goal is to remove defects, failure, pollution, vibration and noise. (6)

The quality problems are caused by usage conditions such as environment, deterioration and wear as degradation, and individual differences manufacturing imperfections for example. In the design of a new product, the optimisation stages are concept design, parameter design and tolerance design. (6)

The more of a design that has been done, the more noise factors there is. The number of control factors is larger when a design process starts. Robust engineering methods should be done at the start of the design process because it is easier, and will have a larger impact on making the process as good as possible. (6)

Following principles are used to develop robust engineering:

1 **Energy transformation principle** is used to find an ideal function that controls energy transformation from the input signal to the output response of the system. The energy transformation is maximised by minimising the effect of noise factors that cannot be controlled. S/N signal to noise ratios are the term in which energy transformation is measured. The higher the S/N ratio, the better the energy transformation and the better the system. (6)

2 **Exploration between control and noise factor**. The influence of control factors on each other is not of interest. The interaction between the noise factors and the control factors is what is to be studied since the goal is to make robust design against the noise factors. (6)

Design problems can be divided into static and dynamic problems. Static problems consisted of smaller the better (0 is the desired value), nominal the best, larger the better (as large response as possible) and ordered categorical response (a scale of good/ bad categories). (6)

Nominal the best responses have a not extreme target, and they are continuous, and the S/N ratio is:

$$\eta = 10\, log\, 10\ \frac{\mu^2}{\sigma^2} \qquad \textit{Equation 9}$$

Where μ is the predictable part of the response and σ the unpredictable part of the response. (6)

The larger, the better quality characteristics are used for strength, process yield and component life. The SNR ratio for the larger, the better is given by the formula:

$$\mathrm{SNR} = -10\, log \left[\frac{1}{\mathrm{n}} * \sum \frac{1}{\mathrm{y}_\mathrm{i}^2}\right] \qquad \textit{Equation 10}$$

Where:

n is the number of values for each trial condition

y_i is each observed value (7)

3 **Orthogonal arrays** are used to minimise the number of experiment runs or test combinations.

The orthogonal arrays are indicated as $L_a (b^c)$, where:

a is a number of runs in experiment

b is a number of levels of each factor

c are the number of columns in the array

L is an indicator of Latin square design

Two or three levels of a factor are the most common. (6)

4 **Two-step optimisation** is used for selecting the optimal designs factor level combination from the experiment that has been done. Variability is first minimised by maximising S/N ratios. Then the process settings are adjusted to the level desired. Settings are easier to adjust after the minimising of variability. The responses from nominal the best and dynamic design problems are used in the two-step optimisation. The mean will be adjusted to meet the requirement in nominal the best cases. (6)

5 **Quality loss function and online quality** engineering are related to tolerance design. After de best settings have been determined by using parameter design, the quality loss function is used to do tolerancing. If the target and performance are different, there is a loss that is proportional to the square of the difference between the target value and actual performance value. This approach is recommended for designing safety factors. (6)

EXPERIMENT

A robust design is achieved by finding the optimal factor combination. Optimal factor combination is found by variating the factors affecting the product/process by changing their values or levels of them. (6)

All factor combinations are studied in full factorial experiments. To reduce time, cost and material only a fraction of the total number of experiments is done in a fractional factorial experiment. (6)

PARAMETERS

M signal factors are set by the engineer based on engineering knowledge to either get target performance or express planned output. More than one signal factor can be used in combination, for example, one for rough adjustments and another for fine ones. (6)

C control factors are the specific product parameters. More than one value can be taken by each control factor, and these different values are mentioned as levels. The goal is to determine levels so that they as well as possible make the product robust against or insensitive to noise factors. (6)

N noise factors are factors that cannot be controlled as they change between units of the product, between environments and with time. Noise can be ignored, controlled or eliminated, its effect can be compensated for, and its effect can be minimised.(6)

There are nine practical steps in the Taguchi method, these steps are:

1 Understanding and formulating the problem.

2 Identifying with characteristics of output performance are most relevant to the problem.

3 Control factor, noise factor and signal factor identification.

4 Factor level and degree of freedom interaction selection, if possible.

5 Orthogonal array design.

6 Experiment preparation.

7 Doing an experiment and collecting the data.

8 Experiment result statistical analysis and interpretation.

9 Running the experiment to confirm results. (7)

Interaction plots are made by average response values (in the Taguchi method these are the SNR values) at each factor level combination. If the lines are parallel there is no interaction between the factors. Non-parallel lines again show interaction presence between the factors. (7)

In the case of injection moulding **control factors** are first chosen for example injection velocity, cooling time, melt temperature, packing pressure and time. The level of the experiment is chosen next. Initial production parameters are chosen according to experience, brainstorming or empirically or by using all of them. The initial parameters are then used to create a range of parameter values that will form the different levels of control factors. (8)

An orthogonal array is selected, and the combinations of factors and levels are made. Then the samples are made, and the measurements for quality are done. **Signal factors** are the output of the process and the quality measurement they can be a specific measurement of the part, strength, warpage or other desired quality characteristics. From the measured values of the signal, the average standard derivation and S/N ratio can then be calculated. The parameter combination with the highest S/N ratio is the best one. (8)

1.3.3.3 Grey relational analysis

Grey relational analysis is a method of measuring approximation degrees between sequences according to Grey relational grade evolution. Because of different units in data sequences preprocessing of data is usually required. It is also needed when the scatter range of the sequence is too large, or if the target of the sequence has different directions. In the data processing, an original sequence is transferred to a comparable sequence. (8)

Grey relational grade indicates the influence degree that the comparability sequence can exert on the reference sequence. A more important comparability sequence is more important to the reference sequence and has a higher grey relational grade. Grey relational analysis can be used to measure approximation correlation between sequences. (8)

A response table in Taguchi method idea can be employed to calculate the average grey relational grade for each factory level. The grey relational grades are first grouped by factory level in the orthogonal array for each column, and then an average is calculated. (8)

1.3.3.4 ANOVA

One way analysis of variance is a statistical technique used to test if three or more means are equal. A significant variable difference in three or more levels of a factor can be tested. The mean within each level of the factor can be calculated in this layout. (9)

For each group/ level a sum and mean is calculated and then all the values are used to get an (x-mean)^2 number, and for these, a sum and a mean is also calculated. (10)

To get a total sum of squares all groups are assembled to one big group and a sum and mean are calculated. This mean is used to get an (x-mean)^2 number for each value. The total sum of squares is the sum of all (x-mean)^2 values. (10)

The sum of squares within groups is calculated by adding together the sums of the (x-mean)^2 values from the smaller level groups. Sum of squares between groups is calculated by subtracting the total sum of squares from the sum of squares within groups. (10)

Total sum of squares = sum of squares between groups + sum of squares within groups *Equation 11*

$$\Sigma\ (\text{observation } - \text{mean})^2 = \text{sum of square of individual group} \qquad \textit{Equation 12}$$

Sum of squares within groups is the sum of the sum of square of all individual groups. (10)

The total sum of squares when all samples are treated as one big group is:

$$Total\ sum\ of\ squares = \Sigma\ (\text{observation } - \text{mean})^2 \qquad \textit{Equation 13}$$

Degrees of freedom for the numerator is the number of groups minus one and degrees of freedom for the denominator is the total amount of observations minus number of groups. (10)

$$\frac{\text{Sum of squares between groups}/_{\text{degrees of fredom}}}{\text{sum f squares within groups}/_{\text{degrees of fredom}}} = F \qquad \textit{Equation 14}$$

(10)

The F is used to get a p-value from a conversion chart or using an online converter. (11)

1.3.4 Quality

Quality management consists of planning inspection and control. Quality planning is done by defining a quality goal, choosing and assessing the characteristics and defining allowable values. Quality inspection consists of inspection planning, inspection and evaluation of data. Inspection of quality finds out if the needs of a quality entity are met. Quality control fulfils quality demands by preventing, supervising and correcting activities. Quality reporting is a part of quality control. (12)

If there is a disturbance in the system, such as wear in equipment or difference in raw material batches the qualities mean value can go out of range. A control chart based on a predetermined number of products from the process are used to set up a control chart. For the samples, an average and a standard deviation are calculated. (12)

Parameters are plotted over time. The dimensions of the part, weight of the part, mechanical properties or optical properties as colour or gloss can be chosen as quality parameters. (12)

Machine Process Capability describes the used machines production accuracy. The sample must consist of 50 continuously produced parts.

Machine Process Capability c_m that must be larger than 1,33 is:

$$C_m = \frac{\mathrm{USL} - \mathrm{LSL}}{8s} \qquad \textit{Equation 15}$$

s= standard deviation

USL= upper specification limit

LSL= lower specification limit (12)

The unit of Machine Process Capability c_m is in parts per million PPM outside the tolerance. The minimal value of 1,33 comes from the Six Sigma philosophy and equals four standard deviations 4S difference between the process and the mean value. Six Sigma requires a PPM of 2. (13)

Process Capability tells if a process runs uniformly over a long-time period and it is influenced by the operator, machine, method, mould and environment. At least ten samples containing five moulded parts are required.

Process Capability c_p is:

$$c_p = \frac{\text{USL} - \text{LSL}}{6\,\sigma} \qquad \textit{Equation 16}$$

where $\sigma = \frac{s}{c_4}$

c_4 quantity depends on the number of samples. (12)

The capability of machine and process is calculated during preliminary production runs. It is not possible in most cases to calculate process value limits from the product quality tolerances. It is important to make sure that the quality of the incoming raw material is inspected and tested. (12)

1.3.4.1 Area measurements from a picture

The area of an object in a picture can be calculated using Equation 17 as the number of pixels in a section are proportional to its area. The area of samples for quality measurements can be calculated using this information. For a successful measurement, a known reference area needs to be used. This can be achieved through putting a square shaped colourful piece of paper next to the sample when the picture for area measurement is taken. (14)

$$\frac{number\ of\ pixels\ in\ sample \times \text{refrence area}\ in\ mm^2}{number\ of\ pixels\ \text{in refrence area}} = \text{Area of sample}\ mm^2 \qquad \textit{Equation 17}$$

1.3.5 Simulation

Computer simulation of injection moulding started with a one-dimensional simulation that was used to do filling time calculations. It has developed through 2D models and a 2,5D Hele-Shaw model to 3D models. (14)

The 2D model uses fluidity to relate pressure and gap wise average velocity are making the filling of a mould cavity a 2D problem. The flow of the molten plastic is assumed to be in a quasi-steady state and due to low Reynolds number the inertia term is neglected. (15)

The Hele-Shaw model is considered to be a 2,5D model as the velocity and temperature profiles are three dimensional while the pressure field is two-dimensional. This model is ideal for thin-walled plastic parts and can be done in two different methods the midplane model or the surface model. (15)

In the midplane model, an arbitrary planar midplane with a defined thickness represents the geometry of the part. The mesh at the centerline of the part is used to solve a 2D pressure field with FEM while the FDM issued for solving of temperature and velocity profiles in 3D. The midplane mesh is complicated to create and is, therefore, limiting the use of the method as 80% of the modelling time would go into mesh creation. (15)

As complex 3D models are used in design, it is more convenient to use the surface model as it uses a skin of mesh on the outside of a 3d part and modelling time is saved in not creating a mid-plane mesh. The shell mesh on two opposite surfaces is used for carrying out Melt flow and temperature calculations using matching and aligned elements on these surfaces. Various stages of injection moulding can be covered with using surface model simulation. (15)

The Hele-Shaw approximation is not accurate in complicated three-dimensional non-thin walled cases of injection moulding. Especially the flow fronts in the filling phase makes simulations complicated. If the shape of the cavity is demanding different wall thicknesses within the part for example or it makes two flow fronts meet it can cause significant changes in stress field. The fountain phenomenon is caused by fluid moving faster at the centre of the stream. With better computers and more research available, full 3D simulations have become a likely and reasonable solution to the problem. (15)

The 3D simulation should be performed on non-thin walled designs. Parts with extreme thickness changes, electrical connectors and thick structural components works well with solid model analysis. Moldflow and later Autodesk Moldflow Adviser and Autodesk Moldflow Insight have become the leading injection moulding simulation software on the market. (15)

The accuracy of the simulation depends on the precision of mathematical model and numerical algorithm. The skill of the user and accuracy of material properties are equally important factors for a successful simulation. How well the geometry used in the simulation match with the real-world part also plays a major role. (15)

1.3.5.1 Process

1 Modelling the geometry of the part is done first. The product is created in a CAD software and then exported and imported into the simulation software in which a mesh is created.

2 The polymer material is selected from the database in the simulation software. A custom material can often also be created. Density is the most important property of the plastic for the simulation.

3 Moulding process conditions are selected so that they represent the real world production process.

4 The simulation is run and results in a numerical graph, and animation format is produced. (15)

1.3.5.2 Mesh

The STL format has become the standard for transferring data from design software to simulation software. STL format describes the three-dimensional geometry using triangle-shaped faces. Accuracy loss from the three-dimensional model due to the lack of surface information in STL causes difficulties in meshing. (15)

A high-quality simulation requires a good mesh. A good mesh has a small ratio between the bases of the triangular faces over the height of them. The faces should have the same size. There should be no errors in the mesh. Common errors are holes or overlapping triangular faces. The opposite surfaces of the mesh need to match or have a high matching rate for the simulation to be successful.

Part thickness is represented by the mesh thickness. Inaccurate mesh thickness has drastic effects on the accuracy of the simulation. Aspect ratio needs to be less than 20 and matching rate more than 80 %. (15)

Mesh density is a major factor as well. It is defined as the number of elements per part surface area. The more elements there is, the longer the simulation will take, but all errors such as weld lines might not show when a low mesh density is used. (15)

1.3.5.3 Results

An animation shows how the melt front moves inside the cavity. From the animation, it can be determined if the entire mould cavity is filled and if the filling is uniform and taking place in an expected way. Gate size, location and number can be variated to get the melt to move in the desired way. (15)

The pressure distribution of the mould cavity is recorded through the whole process. The maximum cavity pressure should not be higher than the pressure limit of the injection moulding machine used. The simulation result of a good design should be 70% of the machine limit. (15)

The temperature of the polymer melt should be as uniform as possible during the filling of the mould. The temperature should not change with more than 5 degrees, but a 20-degree temperature drop during filling is acceptable. Shorter injection time often makes the temperature range smaller. The maximum temperature is determined by the plastic used. (15)

Shear rates and stresses should be below the values expressed as the maximum values for the material used in the material database. The gate is often a problem area for the shear rate. Shear rate problems can be appearance related or cause low mechanical properties in the product. Residual stresses are caused by shear stresses.

For preventing warpage or cracking the shear stress should not be too high. Shear stress should be lower than 1% of the tensile stress of the material. (15)

When flow fronts come together or split and come back together, a weld line can be formed. Mesh density is a factor that greatly affects the weld line simulation result. Therefore, a simulation can show a false weld line or not show a weld line even when it should. Moving or reducing the locations of gates can eliminate or move weld lines. (15)

In a simulation, air traps appear when the material comes to a node from all directions but also on locations that require venting located on the part line. To prevent material from getting burned due to high pressure and temperature air traps should be eliminated.

Air trap analysis is sensitive to mesh thickness. Changing the thickness of the product, changing injection location and changing injection pressure are useful tools to use when trying to eliminate air traps. (15)

The shrinkage percentage of the volume of each unit after the packing phase is relative to the original volume is the shrinkage index. The shrinkage index is used for prediction of trends and locations of sink marks. A uniform shrinkage index reduces chances of warpage. The larger the shrinkage index, the larger the likelihood of a shrink mark. (15)

The aim of cooling analysis is to optimise the cooling of the mould. Heat needs to be extracted uniformly from the part, there should not be a difference in temperature between core and cavity sides of the mould, and the temperature distribution should be even. The placement of cooling channels, mould material and temperature of cooling fluid are the factors that influence the cooling the most. (15)

The reason to warpage is different shrinkage in different parts of the product. Warpage analysis predicts the trend and degree of warpage. Analysis of warpage and prevention of it should be done at an early stage in the product design and mould design process to minimise the costs of the required design changes. (15)

2 METHODS

2.1.1 Preparing recycled material

Large plastic objects were collected based on availability. The items were sledges, a children’s bathtub and baskets for beverage bottles and bakery products. The baskets and sledges cut into pieces are shown in figure 2. The items were cut into pieces that would fit into the sink using a band saw and washed under running warm water with a dish brush. The washed pieces were air dried at least over the night and shredded into flakes using a shredder. In figure 3 the plastic pieces are stacked up for drying, and figure 4 shows the shredded plastic.

Figure 2: Basket used to make the recycled material, and sledges cut into pieces (The author, 2016)

Figure 3: Drying of washed plastic (The author, 2016)

Figure 4: The shredded plastic (The author, 2016)

2.1.2 Starting Parameters

A test injection moulding was done to gain some starting parameters. Starting parameters were acquired by using previous parameters previously used with similar plastics and empirical methods described in the theory part of this thesis on pages 16-20.

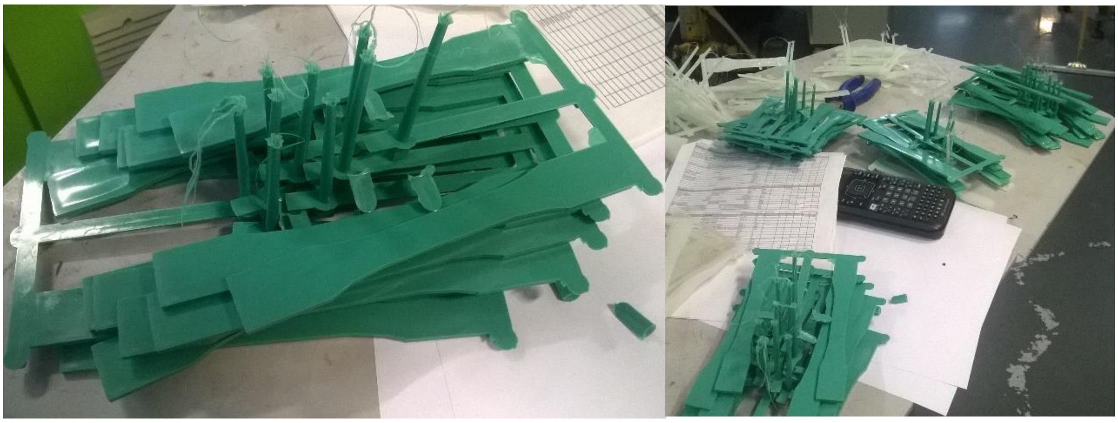


Figure 5: The pieces made in the test injection moulding (The author, 2016)

2.1.3 Machine Process Capability

The starting parameters were used to produce samples for calculations of the machine process capability 50 samples were made from both the recycled and the reference material. The mass of the samples was measured.

For both materials, the masses of the samples were fed into an excel sheet the standard deviation was calculated, upper and lower specification limits were determined the machine process capability was calculated.

2.1.4 Optimization

An optimisation experiment was done using five control factors on five levels. The Control factors/parameters and levels were chosen are listed in Table 1 and Table 2.

Table 1: Control Factors and levels chosen for the reference HDPE

Parameter	**Variable**	**Level 1**	**Level 2**	**Level 3**	**Level 4**	**Level 5**
Nozzle Melt temperature (°C)	X1	220	225	230	235	240
Cooling time (s)	X2	20	22	24	26	28
Holding time (s)	X3	5	7	10	12	14
Holding pressure (bar)	X4	50	55	60	65	70
Injection speed (mm/s)	X5	43	44	45	46	47

Table 2: Control Factors and levels chosen for the recycled HDPE

Parameter	**Variable**	**Level 1**	**Level 2**	**Level 3**	**Level 4**	**Level 5**
Melt temperature (°C)	X1	194	199	204	209	214
Cooling time (s)	X2	20	22	24	26	28
Holding time (s)	X3	5	7	10	12	14
Holding pressure (bar)	X4	25	26	27	28	29
Injection speed (mm/s)	X5	17	18	19	20	21

An L25 Orthogonal array was used to create the combinations of parameters for each run. The created runs are in table 3 and table 4.

Table 3: Test runs for the reference HDPE

Run	**Nozzle temperature X1 (°C)**	**Cooling time X2 (s)**	**Holding time X3 (s)**	**Holding pressure X4 (bar)**	**Injection speed X5 (mm/s)**
1	220	20	5	50	43
2	220	22	7	55	44
3	220	24	10	60	45
4	220	26	12	65	46
5	220	28	14	70	47
6	225	20	7	60	46
7	225	22	10	65	47
8	225	24	12	70	43
9	225	26	14	50	44
10	225	28	5	55	45
11	230	20	10	70	44
12	230	22	12	50	45
13	230	24	14	55	46
14	230	26	5	60	47
15	230	28	7	65	43
16	235	20	10	55	47
17	235	22	14	60	43
18	235	24	5	65	44
19	235	26	7	70	45

20	235	28	10	50	46
21	240	20	14	65	45
22	240	22	5	70	46
23	240	24	7	50	47
24	240	26	10	55	43
25	240	28	12	60	44

Table 4: Test runs for the recycled HDPE

Run	**Nozzle temperature X1 (°C)**	**Cooling time X2 (s)**	**Packing time X3 (s)**	**Packing pressure X4 (bar)**	**Injection speed X5 (mm/s)**
1	194	20	5	25	17
2	194	22	7	26	18
3	194	24	10	27	19
4	194	26	12	28	20
5	194	28	14	29	21
6	199	20	7	27	19
7	199	22	10	28	21
8	199	24	12	29	17
9	199	26	14	25	18
10	199	28	5	26	19
11	204	20	10	29	18
12	204	22	12	25	19

13	204	24	14	26	20
14	204	26	5	27	21
15	204	28	7	28	17
16	209	20	10	26	21
17	209	22	14	27	17
18	209	24	5	28	18
19	209	26	7	29	19
20	209	28	10	25	20
21	214	20	14	28	19
22	214	22	5	29	20
23	214	24	7	25	21
24	214	26	10	26	17
25	214	28	12	27	18

Surface area, mass and tensile strength were chosen as control factors because they can be clearly measured using available equipment.

The surface of the samples was measured by hanging a digital camera from a drill and taking pictures of the samples of a run then removing the memory card from the camera and inserting it into a memory card reader and saving the pictures into a run specific folder. The camera hanging setup is shown in figure 6. The samples were numbered after the pictures were taken. The process was repeated on all the runs of both the reference and the recycled material.

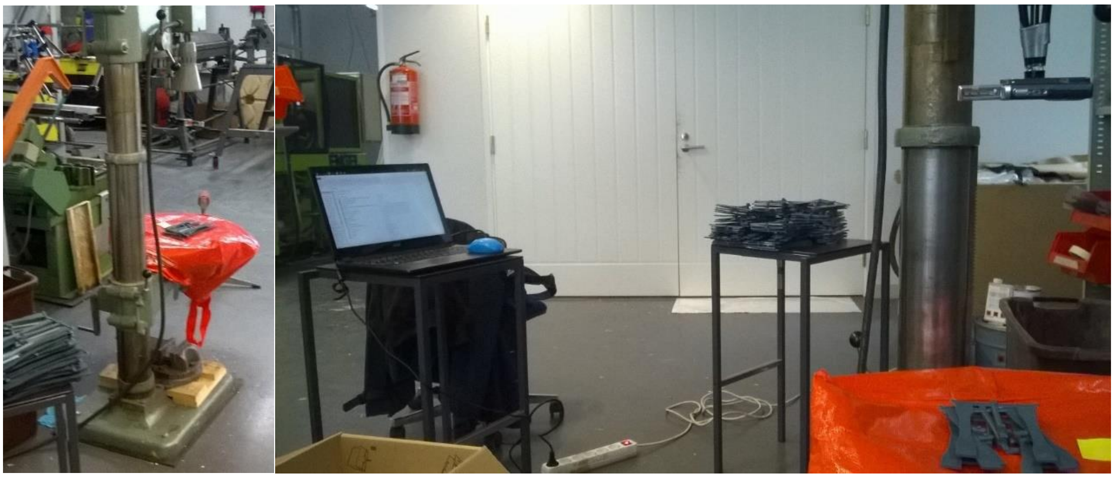


Figure 6: The surface area measurement setup (The author, 2016)

The pictures taken of the samples had yellow post-it notes in them on a red background. Figure 7 and Figure 8 shows how the pictures for area measurement looked. The pictures of a run were opened in the Photoshop software. The yellow post-it notes were marked, and then the histogram tool was used to determine the number of yellow pixels. Next, the note was unmarked and the colour of the sample was marked, and the pixel amount in it was determined using the histogram tool. The marked sample and the histogram tool can be seen in figure 9.

The amounts of pixels were written into an excel file. The area of the samples was calculated using Equation 17 on page 26. The average, the standard deviation and the nominal the best S/N ratio was computed for each of the runs.

The mass of the samples was measured. For both materials, the masses of the samples were fed into an excel sheet, and the average, the standard deviation and the larger, the better S/N ratio was calculated for each of the runs.

The tensile tests were done using a Testometric tensile testing machine, and the ASTM D 638-67T standard was used. The test speed was 51mm/min.

Figure 7: A surface area measurement picture of the reference HDPE (The author, 2016)

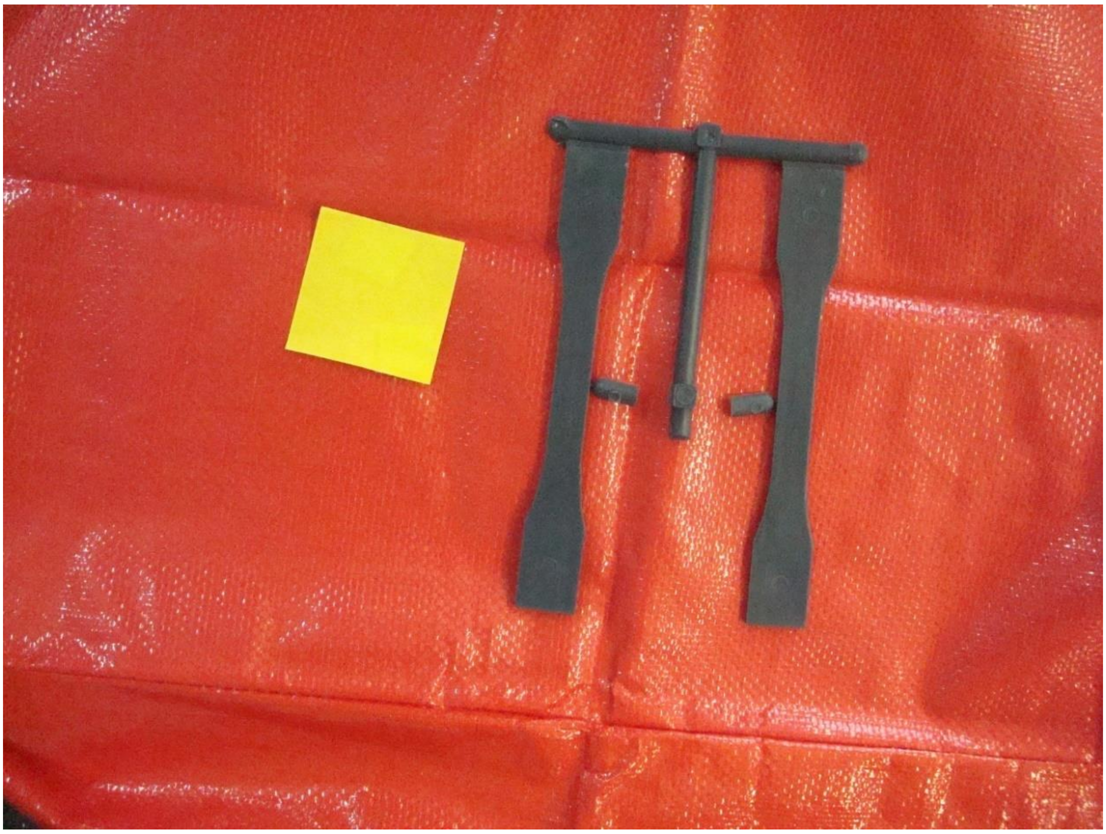
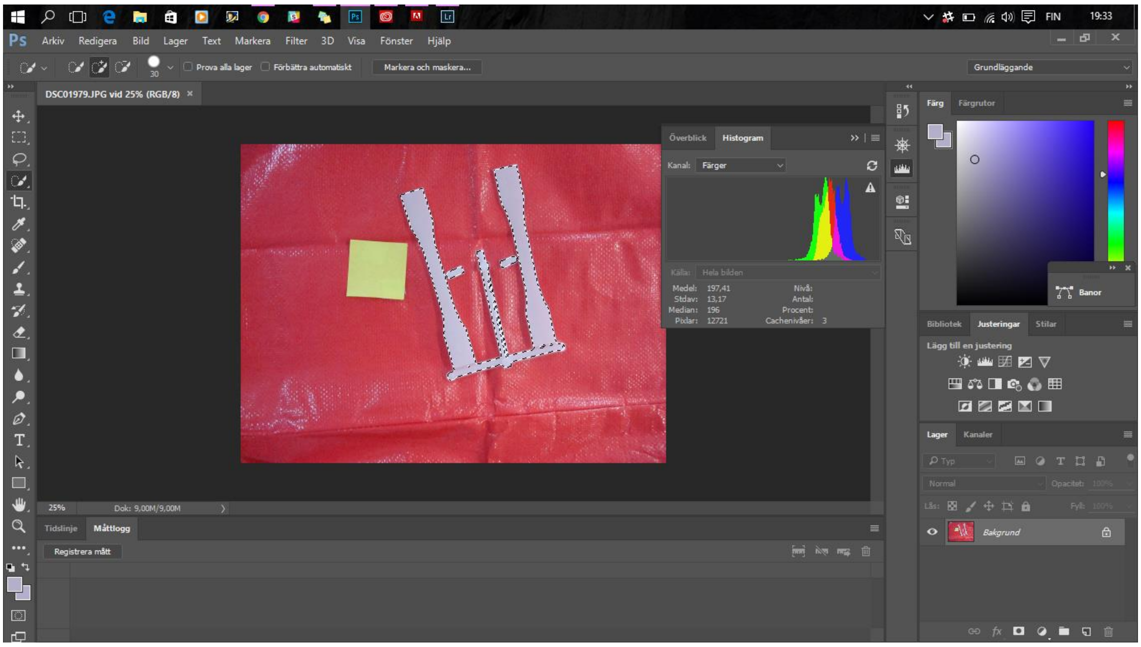


Figure 8: A surface area measurement picture of the recycled HDPE (The author, 2016)



Kanal: Färger

Källa: Hela bilden

Medel: 197,41
Stdav: 13,17
Median: 196
Pixlar: 12721
Nivå:
Antal:
Procent:
Cachenivåer: 3

Figure 9: A screen cut of the surface area measurement (The author, 2016)

2.1.5 Taguchi method

Nominal the best was chosen for the surface area measurements, and Equation 9 on page 24 was used for the calculation. The larger, the better was chosen for mass, and tensile measurements and Equation 10 on page 25 was used for the calculations. The S/N ratios were calculated in Microsoft Excel software and then ranked from highest to lowest S/N ratio value using the sort function in the software.

2.1.6 ANOVA

A one-way ANOVA vas done for each of the parameters for mass, area and tensile quality measurements for both materials, this gives a total of 30 calculations done in the same way. The test runs were first grouped into five groups so that runs that had the specific parameter on the same level were in the same group. Equations 11-14 on page 28 were used to get an F value for each calculation. The numerator was determined to be 4 and the denominator to be 120. The F was used to get a P-value using an online calculator from (12). A significance level of 0,05 was chosen.

2.1.7 Simulation

Simulations were done using both Autodesk Moldflow and SolidWorks Plastics. For SolidWorks, the HDPE DuPont Engineering Polymers / Alathon 7030 with 220 °C melt temperature was chosen, and the ambient temperature was determined to be 25 °C. For Moldflow Escorene HD-6706,19 data was used as it also had a melting temperature of 220 °C and the material data measurements had been done by Moldflow.

3 RESULTS

3.1 Starting parameters

The starting parameters gained from the empirical methods test run are in Table 5.

Table 5: Starting parameters

Parameter	**Reference**	**Recycled**
Melt temperature (C°)	230	204
Cooling time (s)	24	24
Holding time (s)	10	10
Holding pressure (bar)	60	27
Injection speed (mm/s)	45	19
Injection pressure (bar)	72	72
Plasticizing stroke (mm)	47	47

3.2 Machine Process Capability

The results from the Machine process capability test are displayed in Table 6. As a Cm of 1,3 is the equivalent of 4S quality, it can be determined that the machine is doing a quite nice job.

Table 6: Machine Process Capability

Plastic	**Standard deviation**	**USL (g)**	**LSL (g)**	**Cm (PPM)**
HDPE	0,014	22,1	21,9	1,746
RHDPE	0,026	23,0	22,6	1,899

3.3 Optimization

The results of the surface measurement can be seen in Table 16 and Table 17. Table 18 and Table 19 contains the results of the mass measurement. The tensile strength Force at yield measurement results is displayed in Table 20 and Table 21. Tables 16-21 can be found in the appendices.

3.3.1 Taguchi method results

The S/N ratios for the reference material can be found in Table 22, and the S/N ratios for the recycled material can be accessed in Table 24.

The ranking of the top 5 S/N ratios of the reference material can be viewed in Table 7. The S/N ratio ranking of the top 5 recycled material is displayed in Table 8. The complete S/N ratio rankings can be found in Tables 23 and 25. Table 7 and 8 are on the next page while the other tables mentioned previously can be found in the appendices.

Run 5 occurred twice in the top four runs in both materials. Run 21 occurred twice in the top five of the RHDPE material and once in the reference material. Run 25 occurred twice in the top three of the RHDPE material and twice in the top six of the reference material. Run 5 and 25 both has X2 cooling time on level 5 28 seconds. Run 5 and 21 both have X3 Packing time on level 5 14 seconds and X1 melt temperature on level 5.

In the HDPE reference material runs 11, 17 and 19 occurred twice in the list of top 6 runs. For the RHDPE material run 12 occurred twice in the top two while runs 11 and 17 occurred once.

Runs 11 and 12 both had X1 melt temperature on level 3 which was 204 °C for the RHDPE material. Runs 11 and 21 had X2 cooling time on level 1 at 20 seconds while runs 12 and 17 had the same parameter on level 2 of 22 seconds.

Runs 5 and 25 for the reference HDPE had the X4 Packing pressure on level 5 this was 70 bar while runs 17 and 19 both had X1 melt temperature on level 4. Runs 12, 19 and 21 all had X5 Injection pressure on level 3 this was 45 bar for the reference material and 19 bar for the recycled material.

Table 7: Reference HDPE S/N ratios top 5

Run area	**S/N area**	**Run mass**	**S/N mass**	**Run tensile**	**S/N tensile**
9	42,1720	11	2,6941	11	5.9179
24	41,4955	8	2,6930	19	5.9079
14	40,5900	21	2,6921	17	5.9033
22	38,6230	5	2,6908	5	5.8966
25	38,4224	19	2,6839	16	5.8939

Table 8: Recycled HDPE S/N ratios top 5

Run area	**S/N**	**Run mass**	**S/N mass**	**Run tensile**	**S/N tensile**
10	44,1958	21	2,6674	12	6.0635
12	41,8682	5	2,6642	25	5.9909
5	41,6697	25	2,6633	24	5.9904
3	41,6387	17	2,6628	16	5.9870
7	41,1677	11	2,6626	21	5.9860

3.3.2 ANOVA method results

In the mass measurement in Table 9 of the HDPE reference material X3 holding time and X4 holding pressure were significant. In Table 10 for reference material area measurement X1 cooling time and X4 holding pressure was significant. In the reference material, tensile measurements in Table 11 X1, X3 and X4 were significant.

Table 9: ANOVA results HDPE mass

HDPE Mass	**DF**	**Sum of squares within groups**	**Total sum of squares**	**Sum of squares between groups**	**F**	**P-value**
X1	4	16.4922	16.369184	0.123016	0.223771237	.924722
X2	4	16.4922	16.30888	0.18332	0.33346673	0.33
X3	4	16.4922	7.579904	8.912296	16.21183832	.00001
X4	4	16.4922	9.742096	6.750104	12.27872085	.00001
X5	4	16.4922	16.332176	0.160024	0.291090334	.883339

Table 10: ANOVA results HDPE area

HDPE Area	**DF**	**Sum of squares within groups**	**Total sum of squares**	**Sum of squares between groups**	**F**	**P-value**
X1	4	10877453.32	6797669.249	4079784.074	11.25203838	0.00001
X2	4	10877453.32	10270808.88	606644.445	1.673124472	0.16
X3	4	10877453.32	10572784.57	304668.7511	0.84027596	.502299
X4	4	10877453.32	9905591.67	971861.6535	2.680392987	.034874
X5	4	10877453.32	10488101.77	389351.55	1.073830993	.372589

Table 11: ANOVA results HDPE tensile

HDPE Tensile	**DF**	**Sum of squares within groups**	**Total sum of squares**	**Sum of squares between groups**	**F**	**P-value**
X1	4	63420.28329	56036.0659	7384.217389	3.492991677	.009792
X2	4	63420.28329	62425.14494	995.1383488	0.470735054	0.75
X3	4	64923.71972	55499.40838	9424.311341	4.354792692	.002529
X4	4	63420.28329	47474.66702	15945.61627	7.542831145	.000019
X5	4	63420.28329	62145.81822	1274.465069	0.602866308	.661349

In the recycled material mass measurement Table 12 holding time X3 was significant. Area measurement in Table 13 of the RHDPE has X1 and X3 as significant factors. The tensile test of the recycled material in Table 14 had no significant values.

X3 Holding time occurred as significant four times while X1 melt temperature and X4 holding pressure both occurred three times.

Table 12: ANOVA results RHDPE mass

RHDPE Mass	**DF**	**Sum of squares within groups**	**Total sum of squares**	**Sum of squares between groups**	**F**	**P-value**
X1	4	6.1436832	6.092664	0.0510192	0.249130033	.909718
X2	4	6.1436832	6.038376	0.1053072	0.514221827	.725409
X3	4	6.1436832	0.349464	5.7942192	28.29354482	.00001
X4	4	6.1436832	6.064904	0.0787792	0.384683898	.819302
X5	4	6.1436832	6.10764	0.0360432	0.176001263	.950368

Table 13: ANOVA results RHDPE area

RHDPE Area	**DF**	**Sum of squares within groups**	**Total sum of squares**	**Sum of squares between groups**	**F**	**P-value**
X1	4	5191579.831	3602565.155	1589014.676	9.18226086	.00001
X2	4	5191579.831	5035363.177	156216.6548	0.902711659	.464775
X3	4	5191579.831	4627034.049	564545.7828	3.262277386	.014063
X4	4	5191579.831	5018178.117	173401.7143	1.002017035	.40938
X5	4	5191579.831	5042279.971	149299.8601	0.862742354	.488558

Table 14: ANOVA results RHDPE tensile

RHDPE Tensile	**DF**	**Sum of squares within groups**	**Total sum of squares**	**Sum of squares between groups**	**F**	**P-value**
X1	4	78185377.13	75727715.61	2457661.523	0.943013238	.441662
X2	4	78185377.13	75740657.46	2444719.669	0.938047404	.444483
X3	4	78171473.28	75549254.67	2622218.612	1.006333321	.407099
X4	4	78185377.13	75725640.21	2459736.922	0.943809576	.441212
X5	4	78185377.13	75682392.81	2502984.321	0.960403753	.431949

3.4 Simulation

3.4.1 Autodesk Moldflow

According to the shot weight xy plot over 70 percent of the shot weight goes into the mould cavity within the three first seconds of injection. Some air traps are forming at the ends of the cavity. Fill time was 3,003 seconds and the speed at flow front was 465,8 cm/s.

The bulk temperature of the plastic reached 40,56 °C after 32,97 seconds. The bulk temperature at the end of fill was 225,2 ° C. The flow front had a 215-220 ° C temperature variation with the cooler temperature at the end of the cavities. Ejection temperature was reached in about 20 seconds.

20 MPa was the pressure at the end of fill in the test piece part to the mould cavity the pressure in the runners was higher. Switchover pressure was 48,47 MPa. The max pressure at injection location was almost 50 MPa. The maximum clamp force used was a little bit more than 2,5 tonne.

A deflection off all components shoves a slight bending of the test pieces. There is a bit more than 20 MPa residual stress in the sample pieces while the runners had up to 35 MPa of residual stress. The orientation at the core is perpendicular to the flow while the orientation at the skin is in the same direction as the flow. There were no weld lines. Graphics generated by the software can be found in Enclosure Figure 1- 16 in the appendix.

3.4.2 SolidWorks Plastics

The maximum inlet pressure was 50.08 MPa, and the required injection pressure was 49.12 MPa. The pressure at the end of fill was 49,12 MPa while pressure at packing switch time was 48,49 MPa. The pressure at the end of packing was 30,15 MPa.

The inlet flow rate was 16,21 cm^2/s, maximum clamping force used 25,8 tonne and cycle time was measured to be 23,64 seconds. Fill time was 3,3 s.

The bulk temperature at the end of fill was varying between 60-222 ° C. The flow front central temperature was 180-225 ° C. The bulk temperature at the end of packing was 50-100 ° C.

Total displacement shows a little bit of bending in the middle of one of the test pieces. Graphics generated by the software can be found in Enclosure Figure 17- 26 in the appendix.

4 DISCUSSION

4.1 Optimization

Comparing the results from Taguchi and ANOVA methods the best melt temperature for the RHDPE appears to be 214 °C as it occurs twice in the top S/N ratio list. For the reference material, 230 °C seems to be the best temperature as run 11 that has this temperature is at the top of the list for S/N ratio in both mass and tensile measurements, Run five with a temperature of 220 °C is next runner up so a temperature profile in this range would probably work.

For X3 holding time, the only reoccurring level was level five in runs 5 and 21 for both materials and run 17 for the reference material. Holding pressure X4 had level 5 in run 5 for both materials and runs 11 and 19 for the reference material.

Cooling time was probably not significant in any of the quality measurements due to all times used being long enough to cool the product. Therefore, the shortest cooling time can be chosen as it will make production faster. Even though X5 injection speed was not significant the most occurring level in the S/N ratio comparison was level 3 which is the middle value.

Table 15: Optimisation experiment results

Variable	RHDPE	HDPE
Melt temperature (°C)	Level 5: 214	Level 2-3: 220-230
Cooling time (s)	Level 1: 20	Level 1: 20
Holding time (s)	Level 5: 14	Level 5: 14
Holding pressure (bar)	Level 5: 29	Level 5: 70
Injection speed (mm/s)	Level 3: 19	Level 3: 45

4.2 Simulation

Both simulations had surprisingly close results in Switchover pressure (approximately 50 MPa) and fill time (3 seconds). They both also showed bending of the test pieces' which is a thing that sometimes happens with the mould used, so that is also quite accurate.

A lot of the simulation results were expressed in entirely different ways and are therefore hard to compare flow speed is one of the measurements that cannot be compared as they are measured as flow front speed in Autodesk Moldflow and inlet flow rate in solid works plastics, so the units are entirely different.

The flow front temperature had the largest difference. The maximum clamp forces used has a difference of a factor of ten. It was surprising that the Moldflow simulation indicated different orientation for the skin and core layers. The animation in SolidWorks had a nicely and uniformly moving melt front, and this is backed up by Autodesk Moldflow showing no weld lines.

5 CONCLUSION

It is worth noting that the starting parameters that were gained were good and that the difference between the levels of the parameters was small therefore the difference in S/N ratios were low as well.

When comparing the results from the experiment and the simulations the first thing that is noticeable is the 20 second cooling time from the experiment and the Autodesk simulation stating that the ejection temperature cam is reached in 20 seconds, the same cooling time was also the result of the optimisation work done. The simulations do not optimise melt temperature as it is determined by the material data materials chosen for both simulations had a 220 ° C melting temperature.

The XY plot of pressure at injection location shows a steady holding pressure of about 40 MPa. It is not very close to 19 or 70 bars, but on the other hand holding pressure has not been analysed it is expressed as a pressure at the end of fill value instead. The software had chosen to hold the pressure on for like 13 seconds; this can be read off from the pressure at injection location xy plot. It is quite close to the 14 seconds' result from the experiment.

The software's does not do an injection speed analysis either as they are more focused on pressure and flow speed as these less dependent on specific properties of the nozzle and screw and barrel of the injection moulding machine.

Using the tensile strength as a quality factor for the recycled plastic did not work in the ANOVA analysis as the material was so uniformly weak that not one of the factors could be determined as significant.

Time spent on doing the calculations is worth doing them in the long run as it then would be possible to work out a way to incorporate the calculations into the ongoing production procedure and make them a routine. It is far less work to fill in pre-done worksheets that do the calculations than to do new ones each time.

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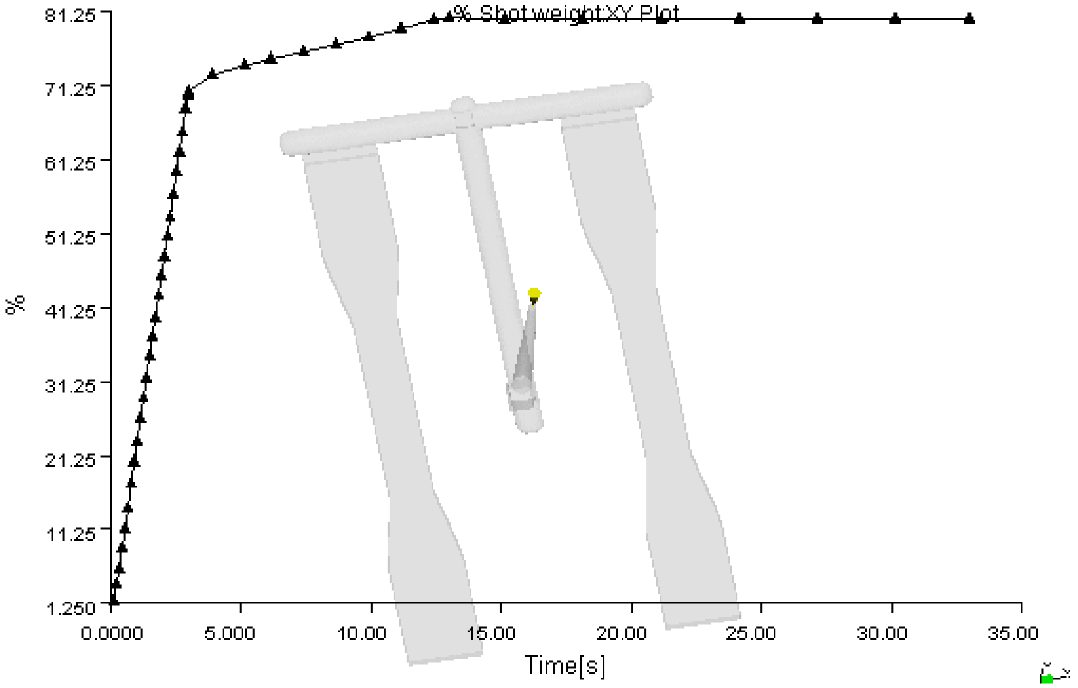
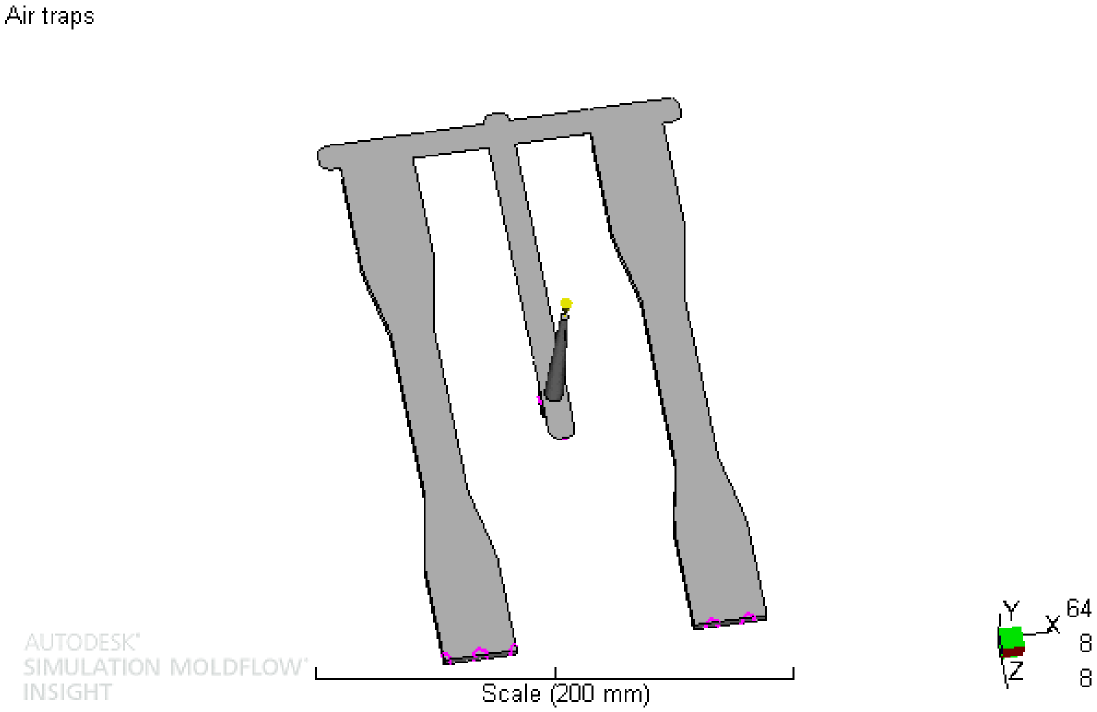
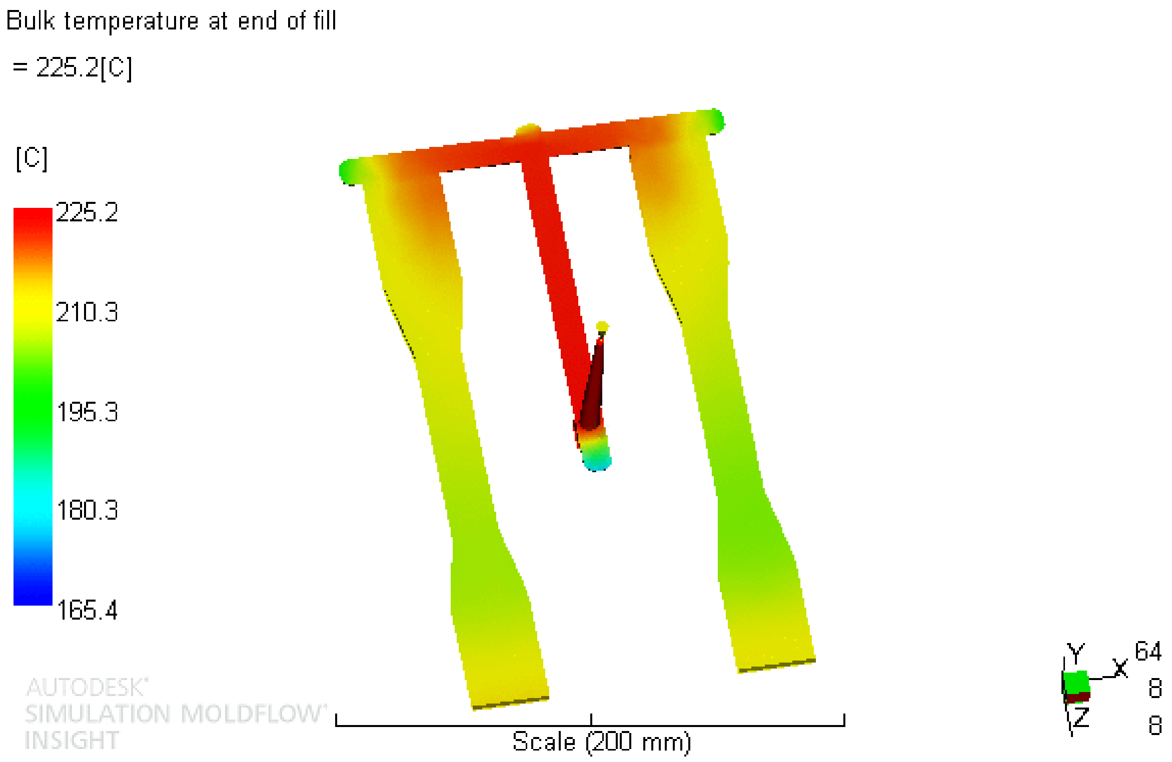
APPENDICES



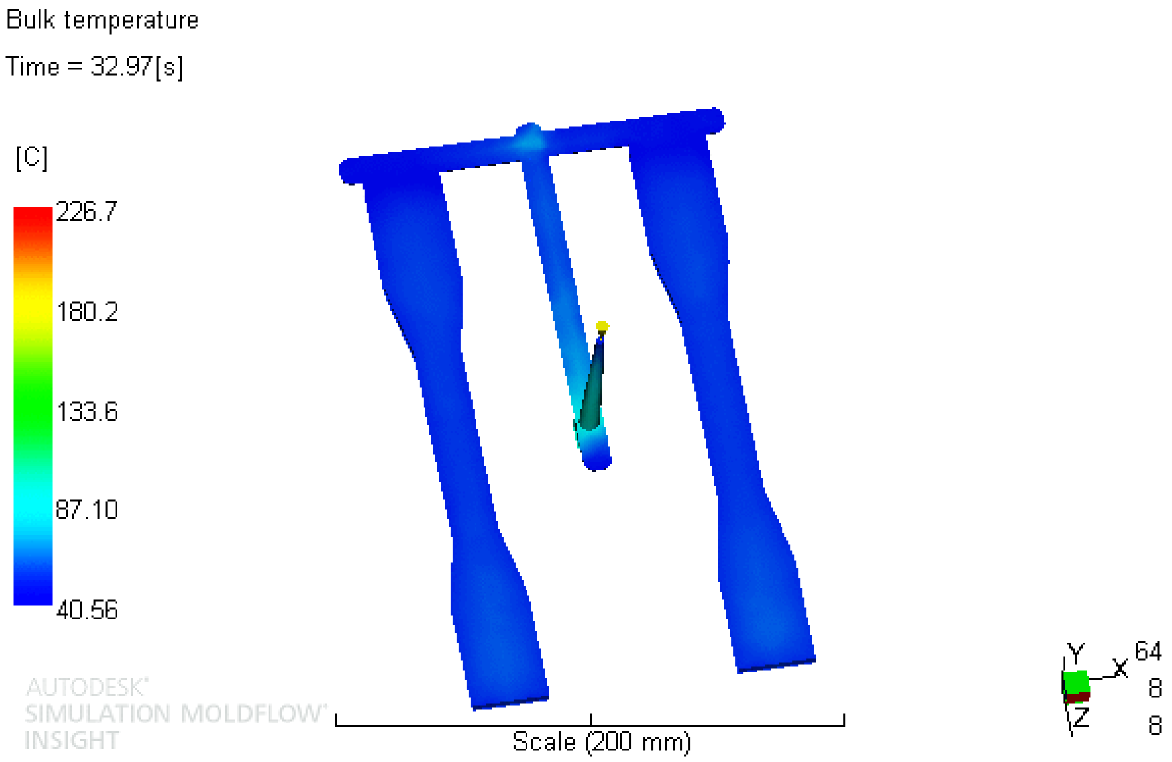
Enclosure Figure 1: Autodesk Moldflow Shot weight XY plot



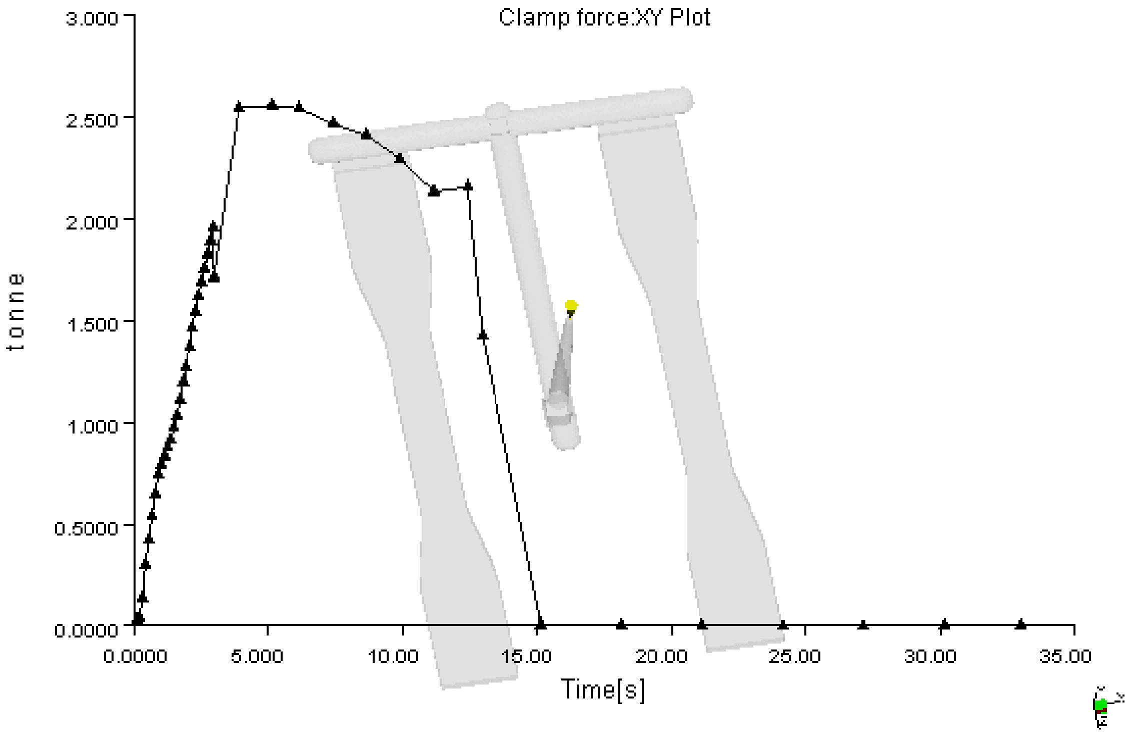
Enclosure Figure 2: Autodesk Moldflow Air traps



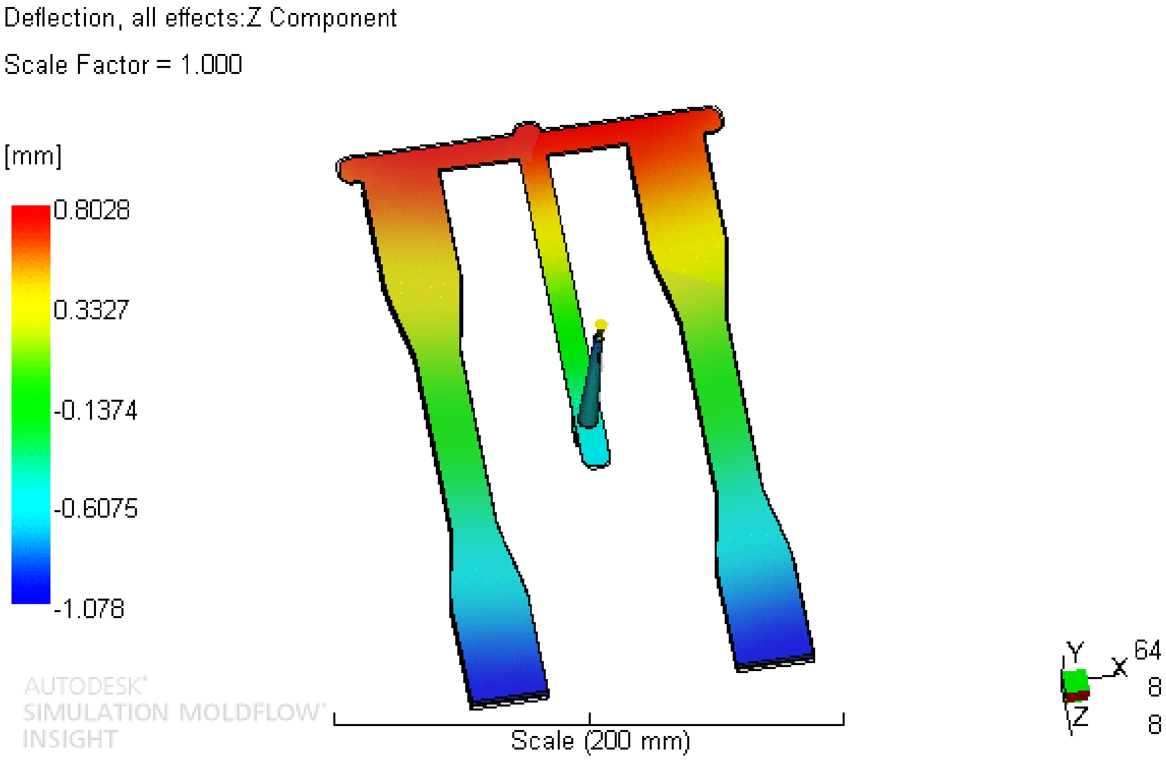
Enclosure Figure 3: Autodesk Moldflow Bulk temperature at the end of fill



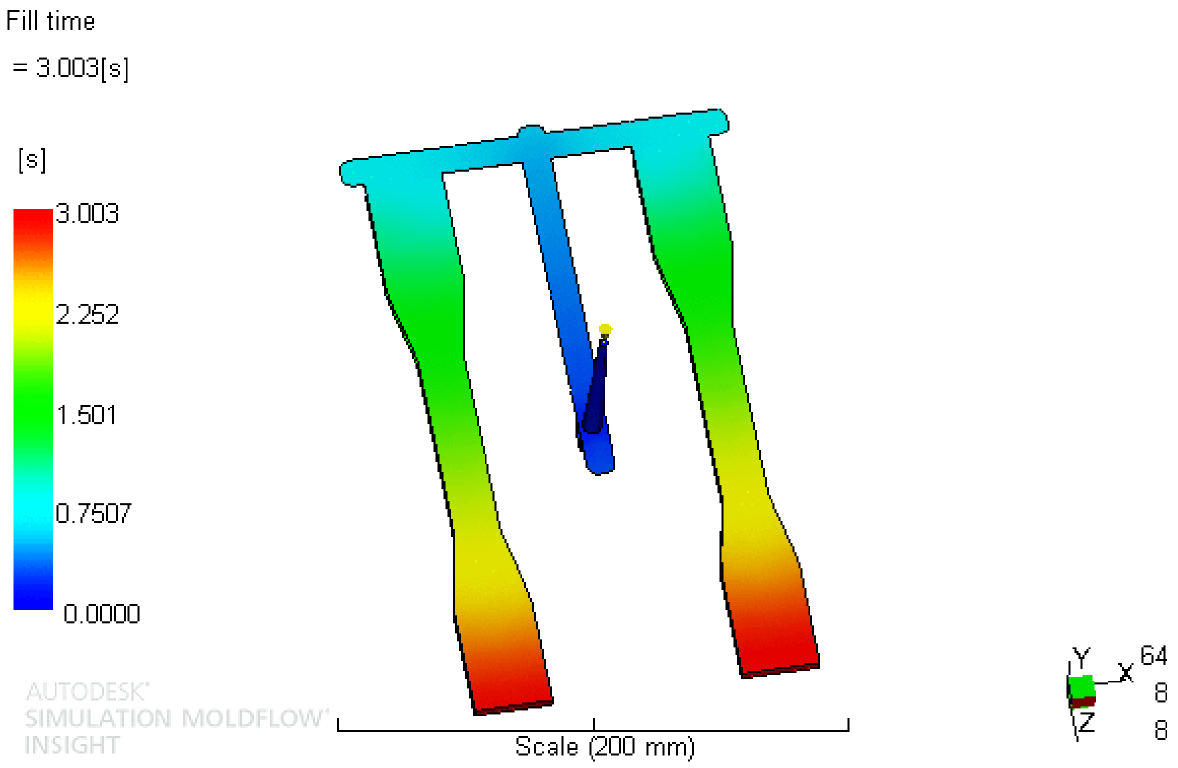
Enclosure Figure 4: Autodesk Moldflow Bulk temperature



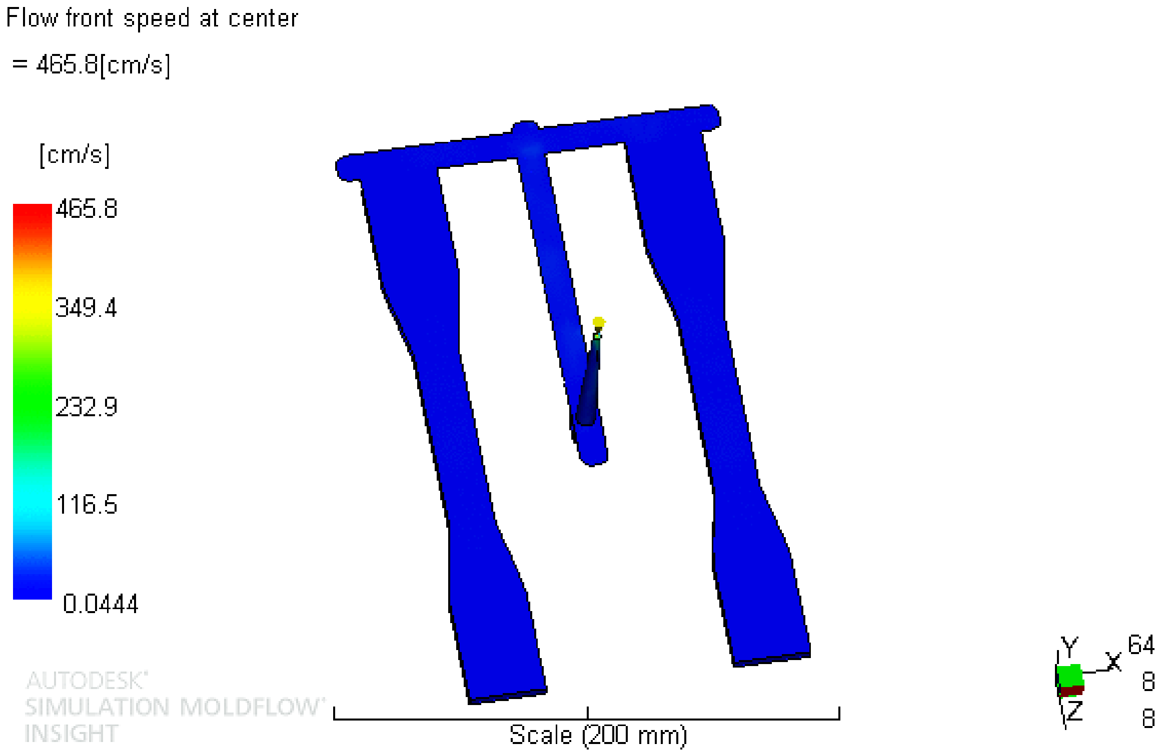
Enclosure Figure 5: Autodesk Moldflow Clamp force XY plot



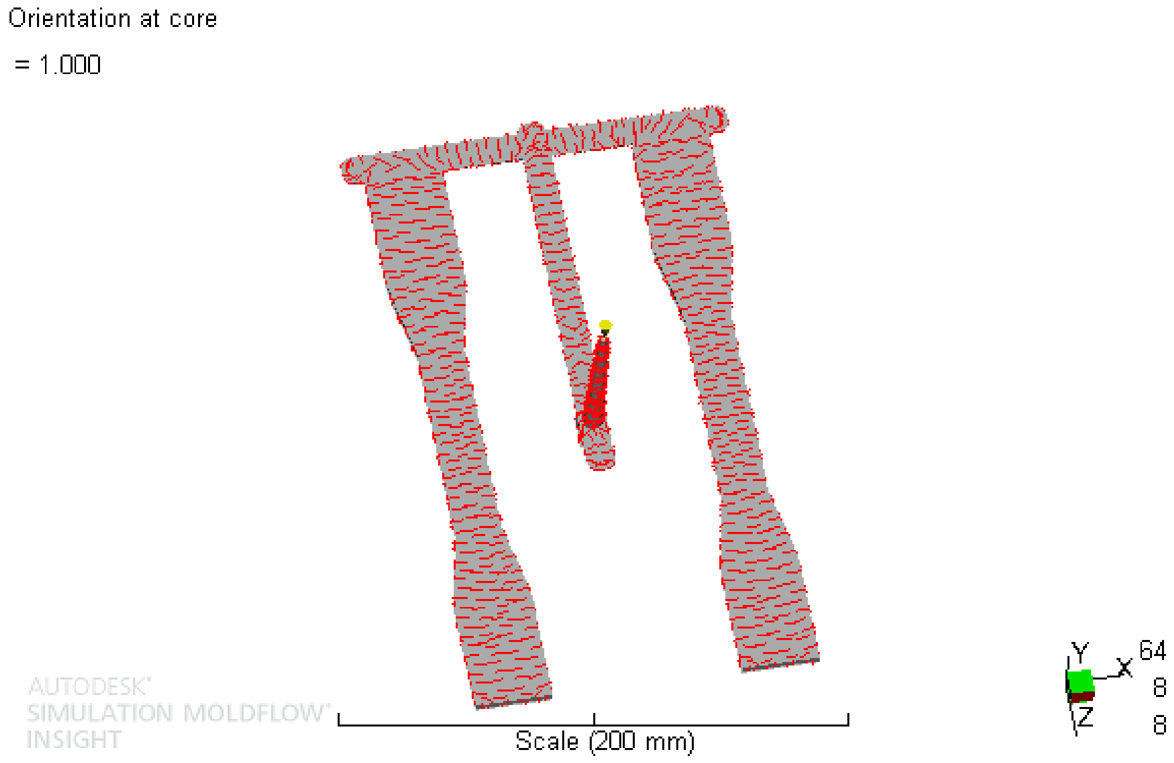
Enclosure Figure 6: Autodesk Moldflow Deflection Z component



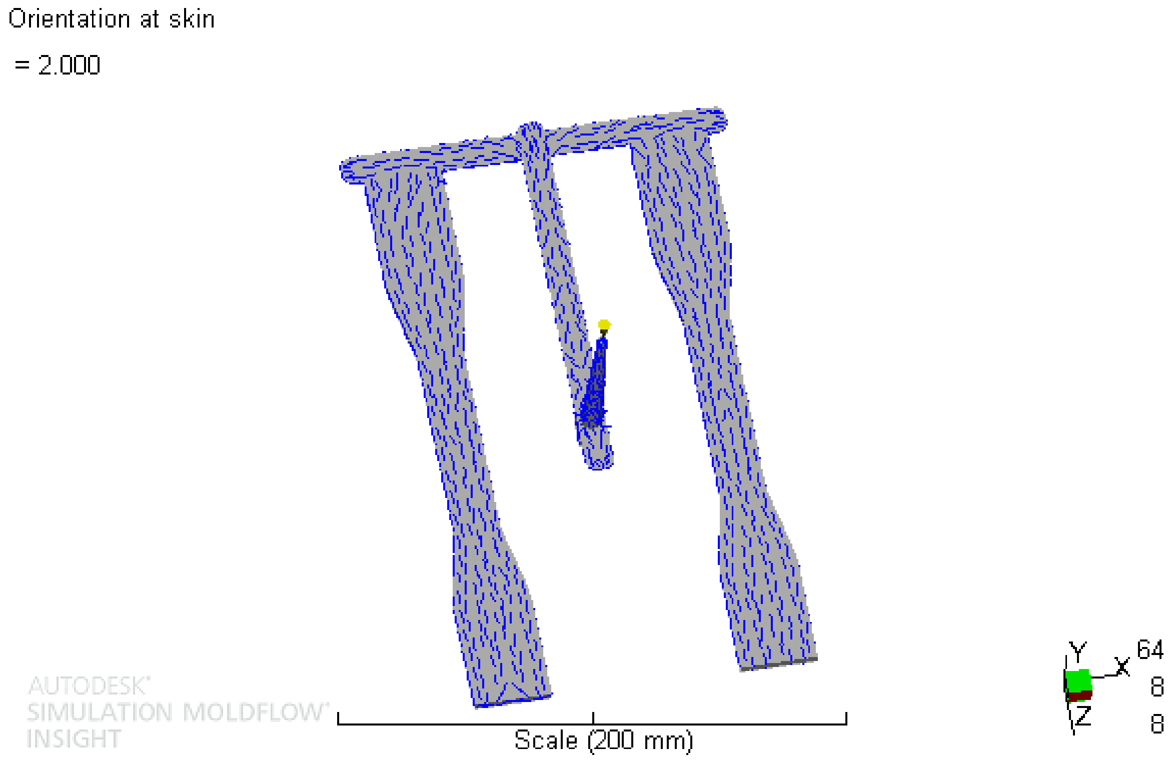
Enclosure Figure 7: Autodesk Moldflow Fill time



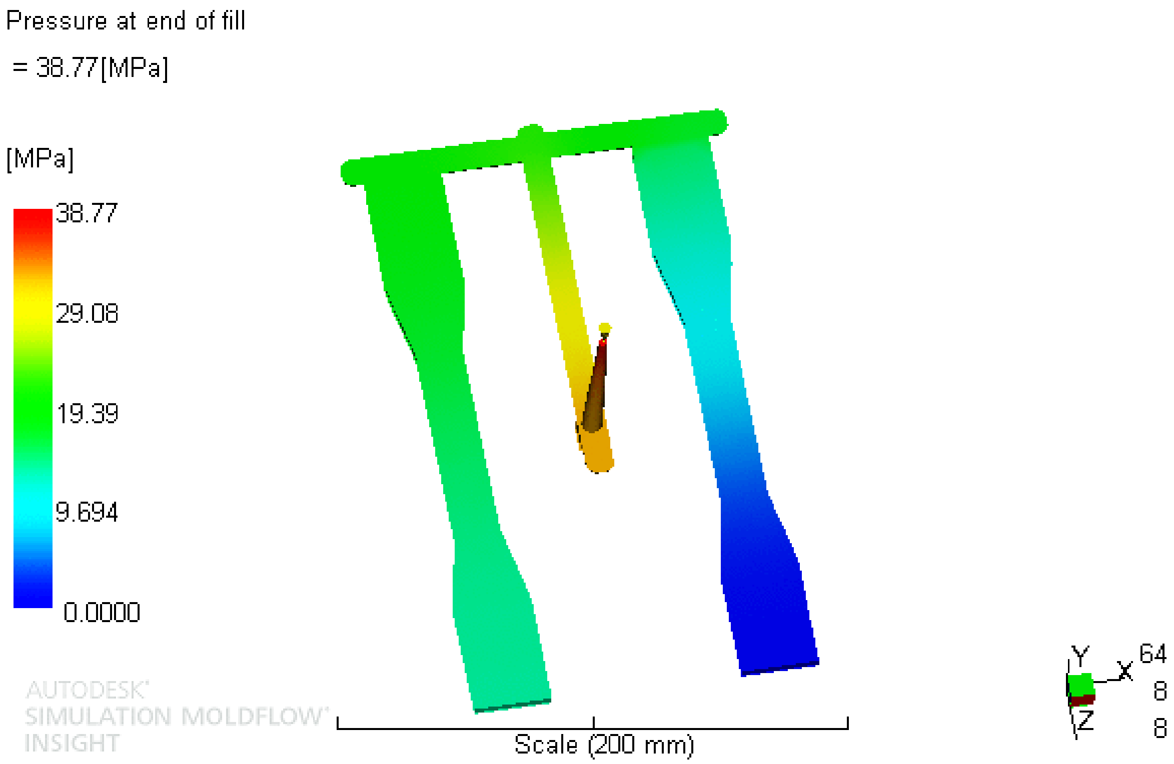
Enclosure Figure 8: Autodesk Moldflow Flow front speed



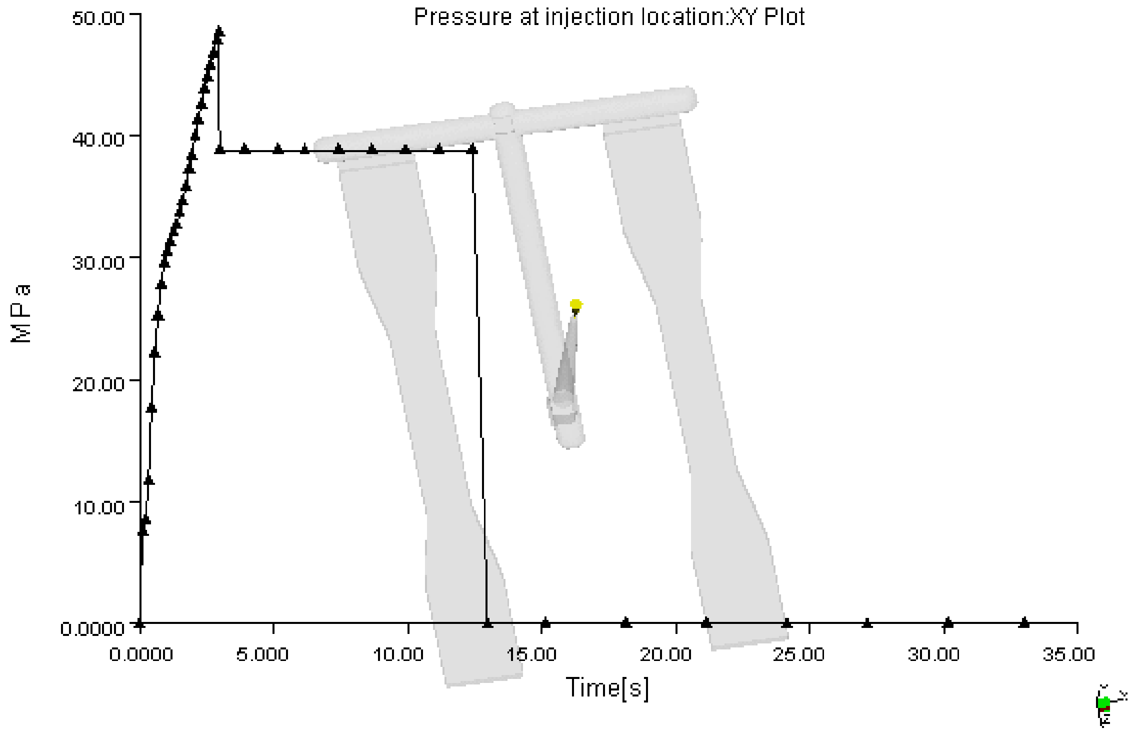
Enclosure Figure 9: Autodesk Moldflow Orientation at core



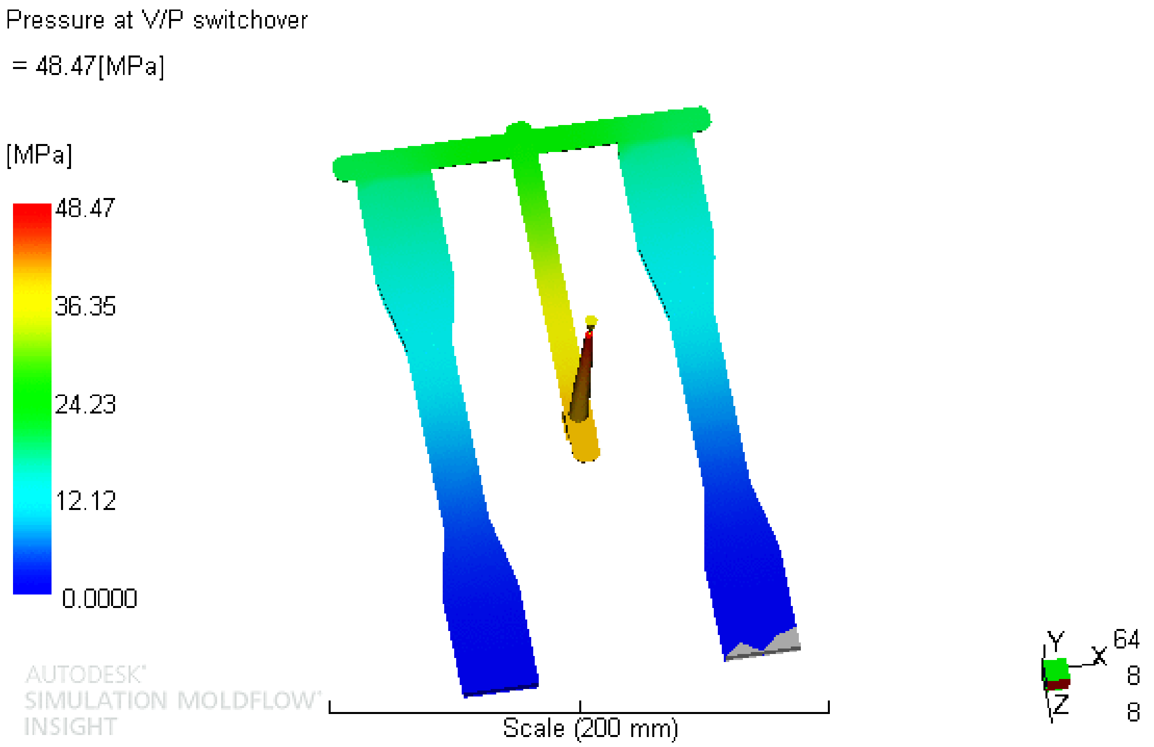
Enclosure Figure 10: Autodesk Moldflow Orientation at skin



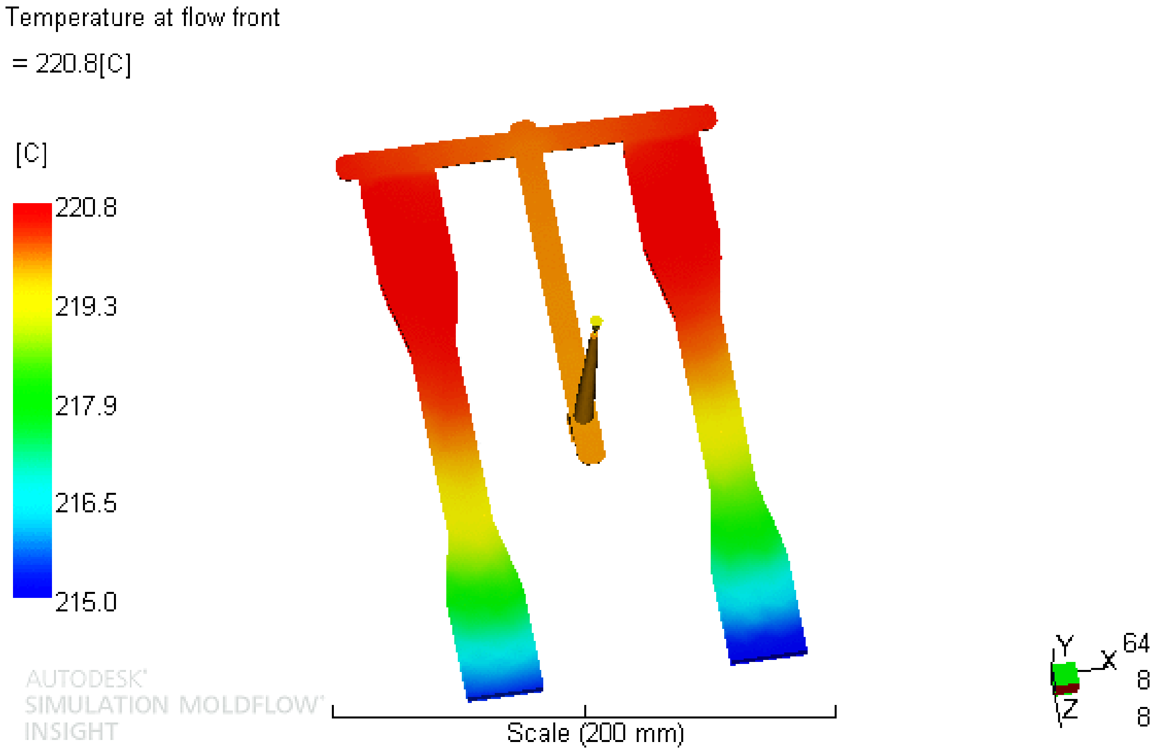
Enclosure Figure 11: Autodesk Moldflow Pressure at the end of fill



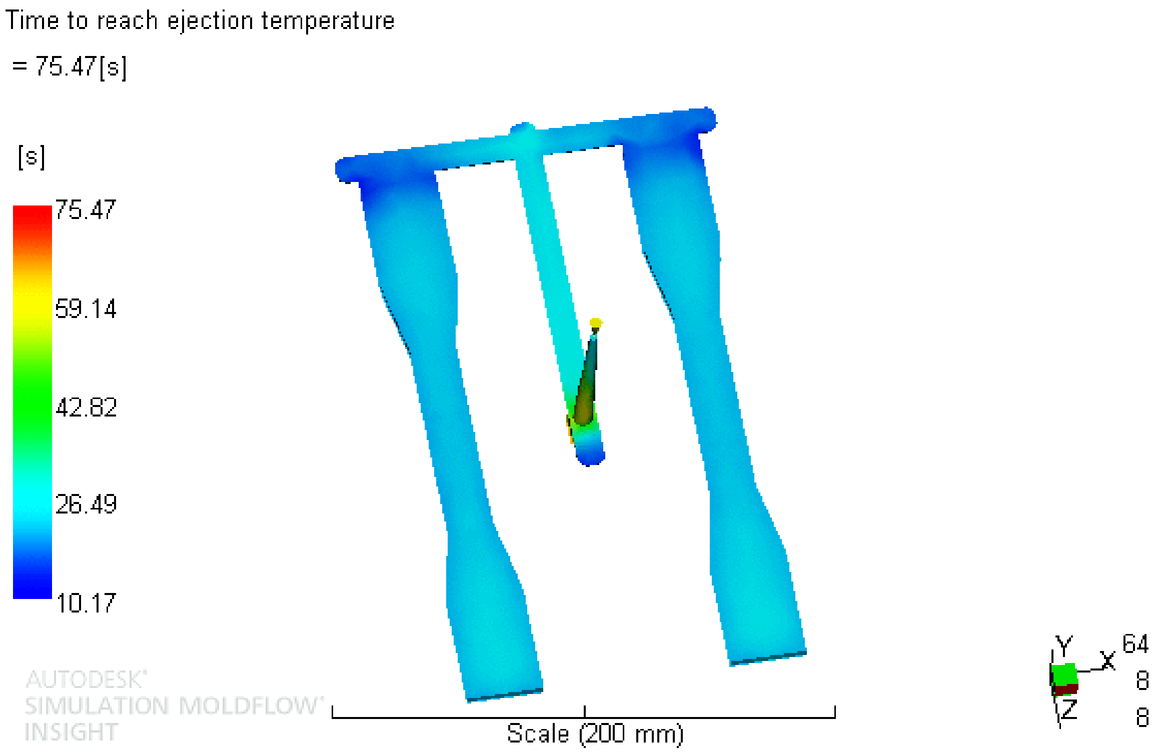
Enclosure Figure 12: Autodesk Moldflow Pressure at injection location



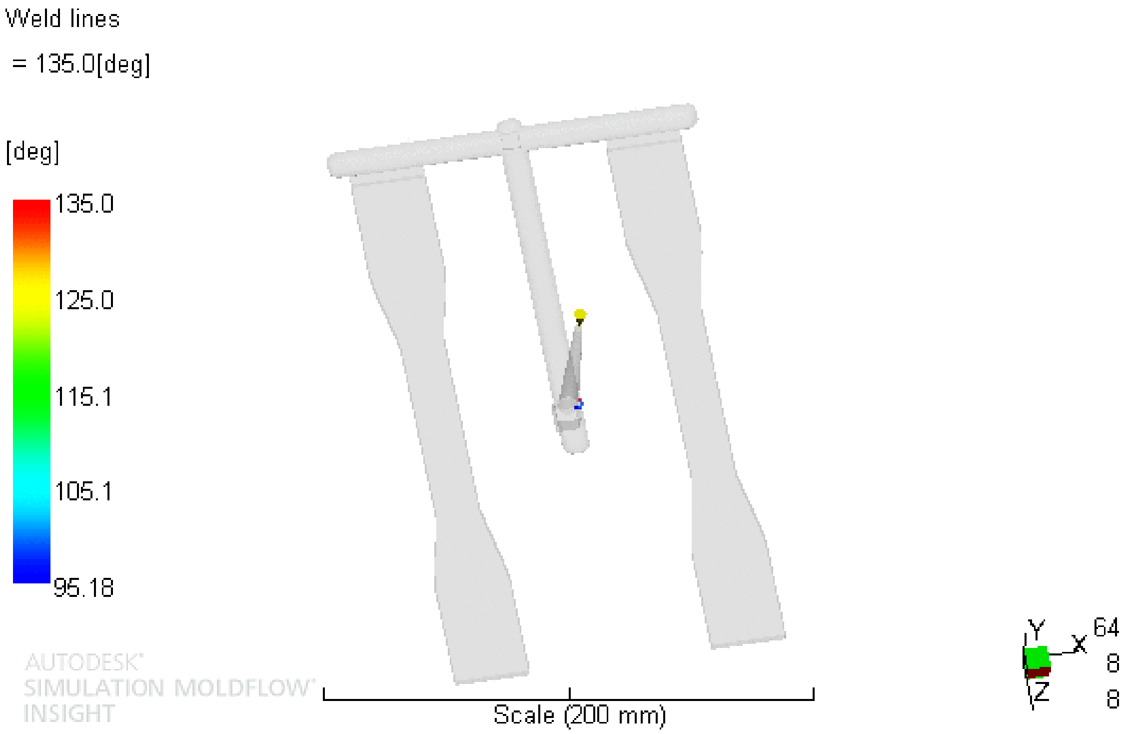
Enclosure Figure 13: Autodesk Moldflow Switchover pressure



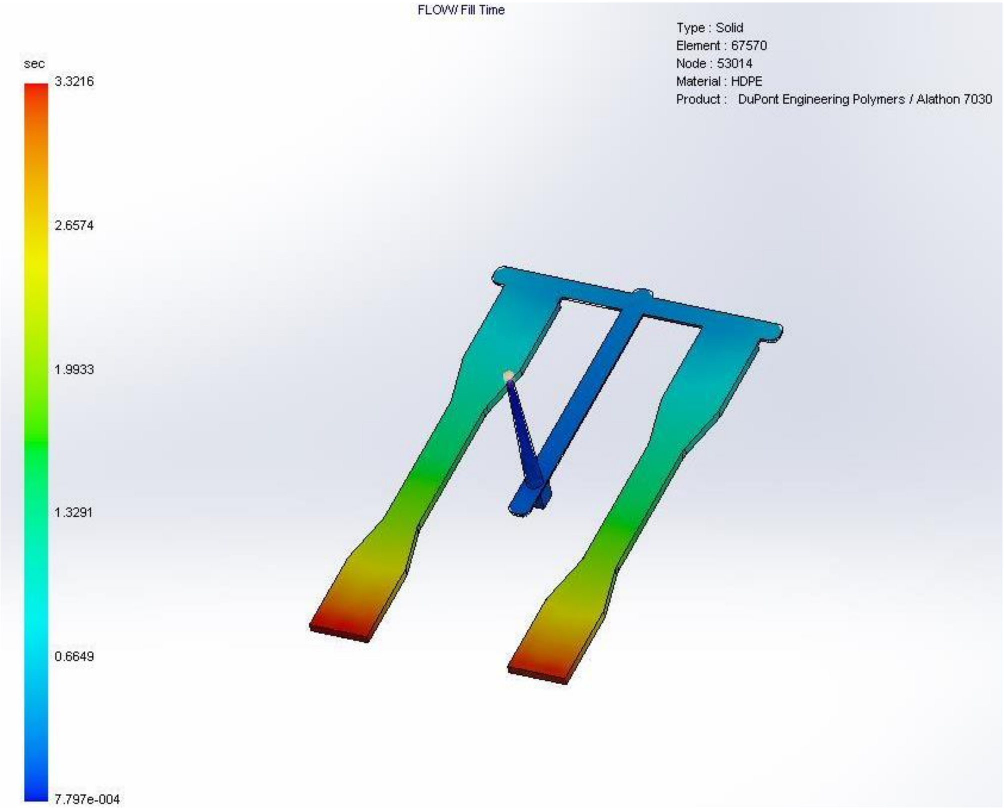
Enclosure Figure 14: Autodesk Moldflow Flow front temperature



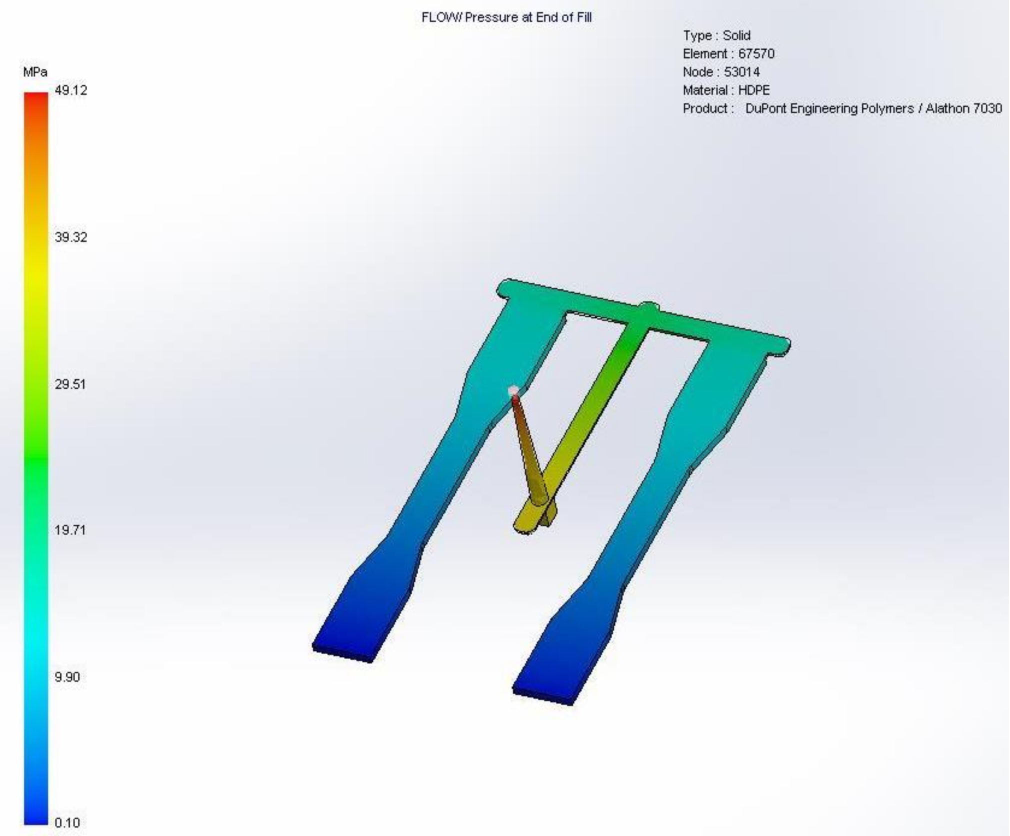
Enclosure Figure 15: Autodesk Moldflow Time to reach ejection temperature



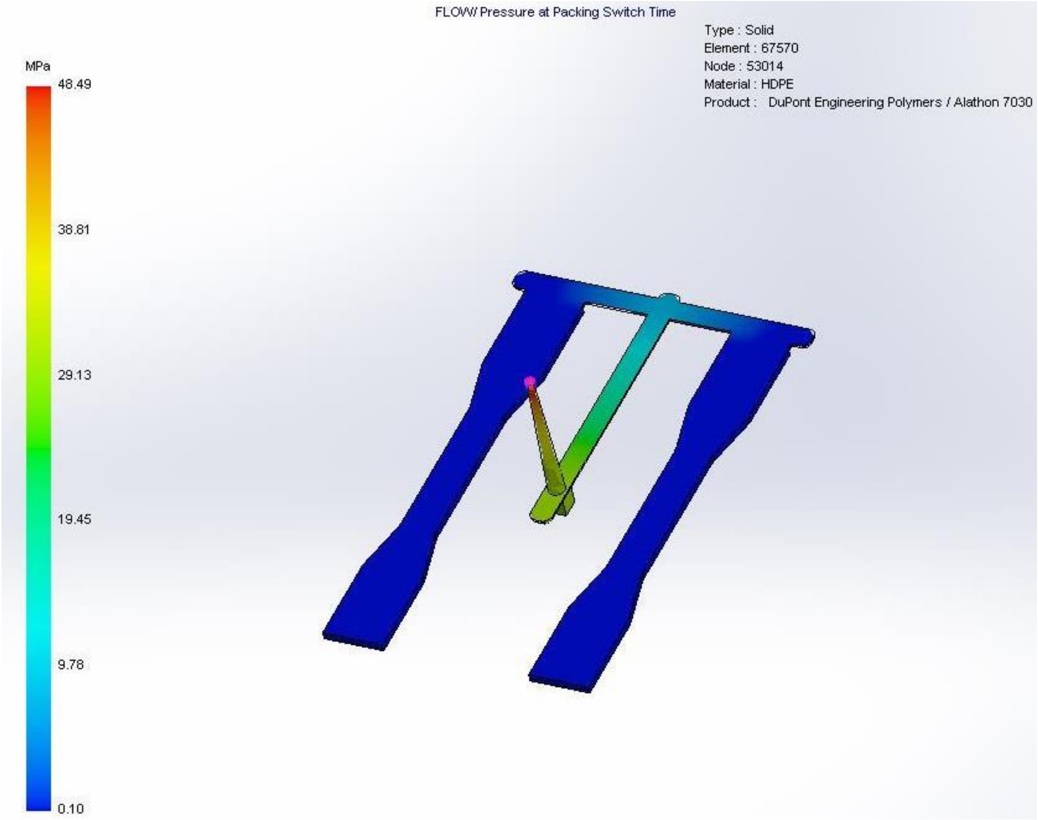
Enclosure Figure 16: Autodesk Moldflow Weld lines



Enclosure Figure 17: SolidWorks Plastics Fill time

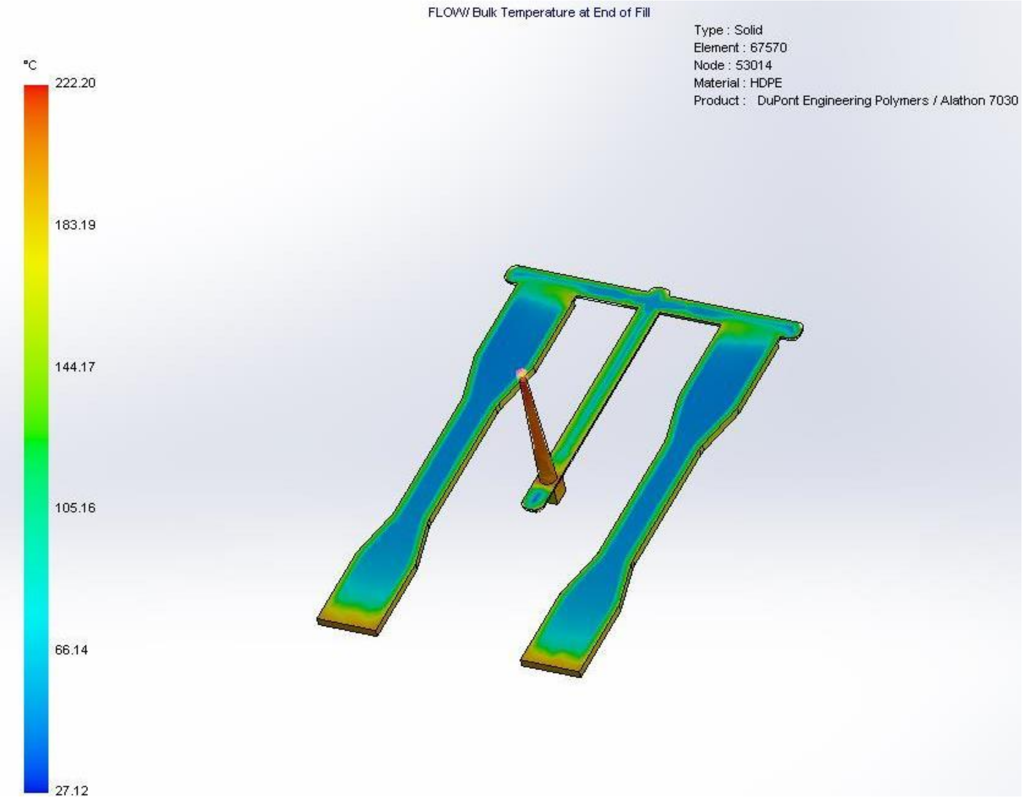


Enclosure Figure 18: SolidWorks Plastics Pressure at the end of fill



Type : Solid
Element : 67570
Node : 53014
Material : HDPE
Product : DuPont Engineering Polymers / Alathon 7030

Enclosure Figure 19: SolidWorks Plastics Pressure at switch time



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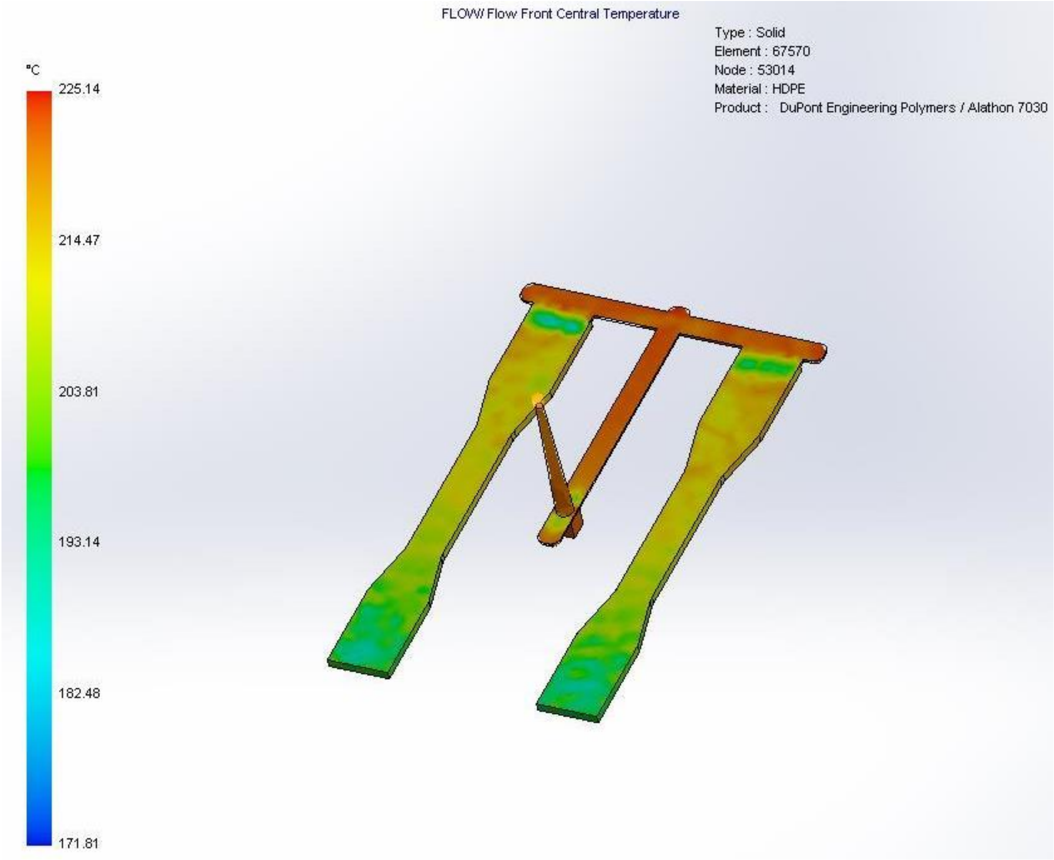
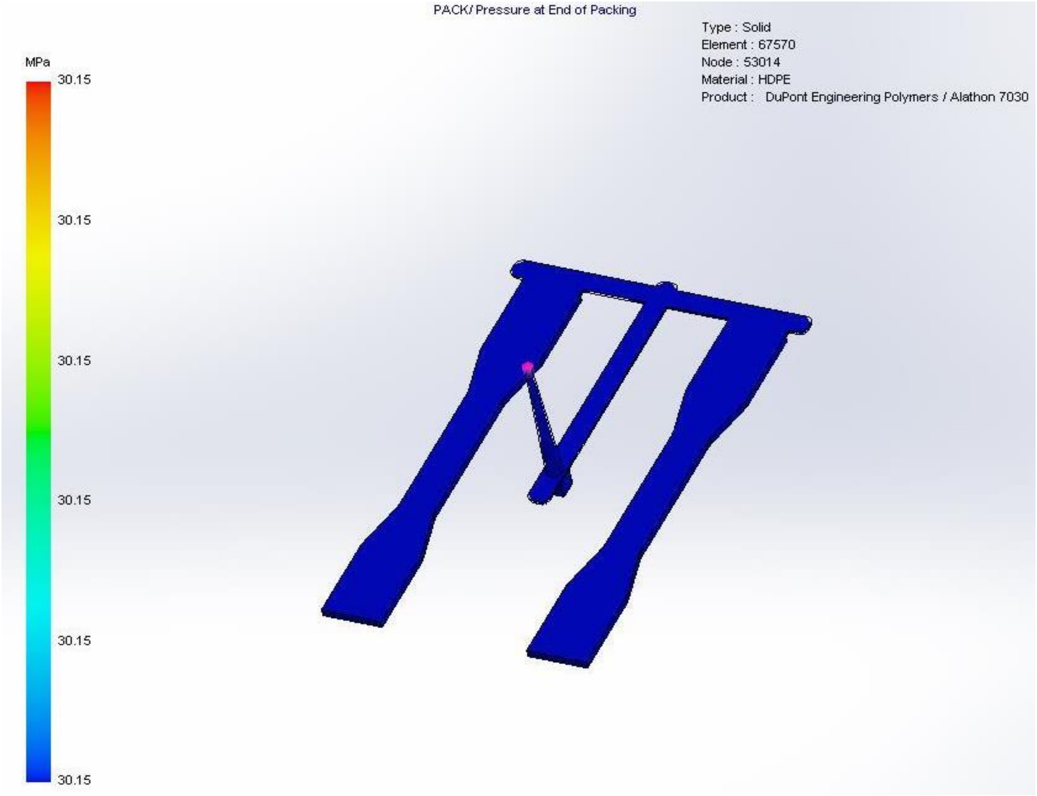
Node : 53014
Material : HDPE
Product : DuPont Engineering Polymers / Alathon 7030

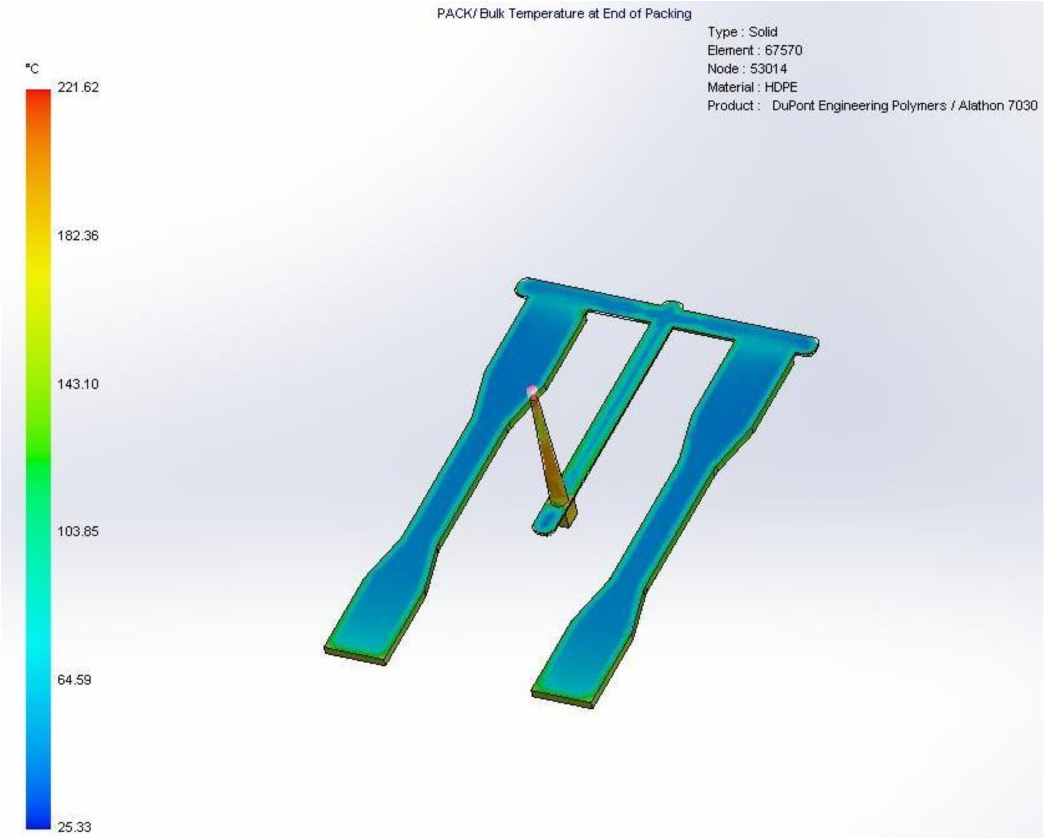
Enclosure Figure 20: SolidWorks Plastics Temperature at the end of fill



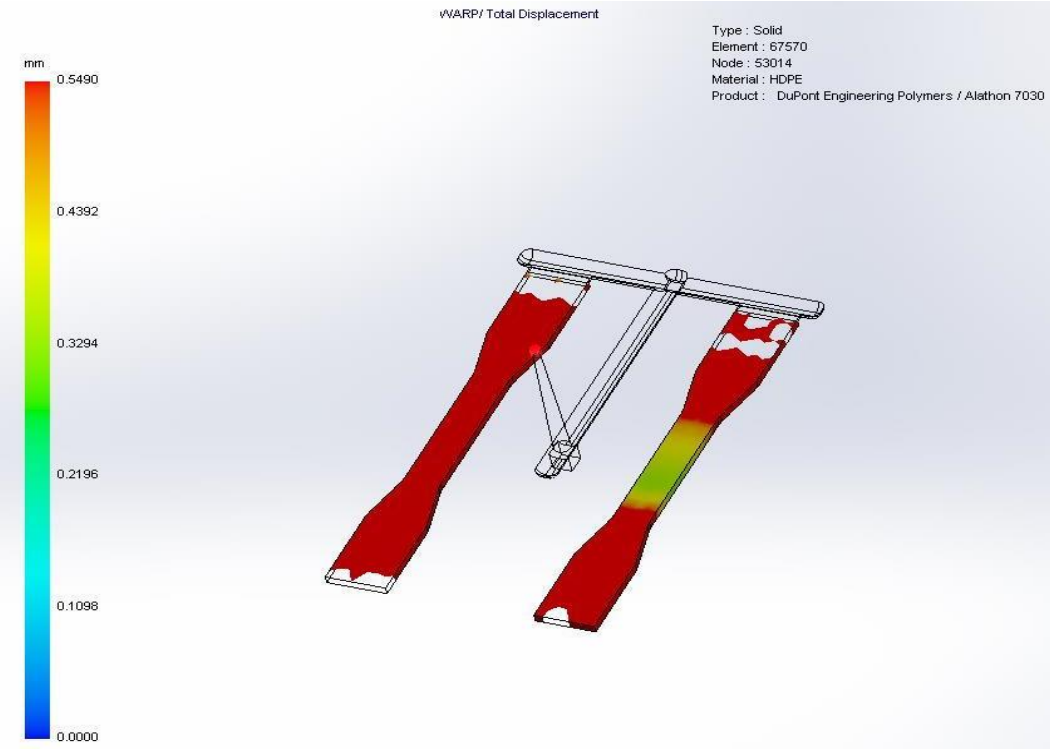
Enclosure Figure 21: SolidWorks Plastics Flow front temperature



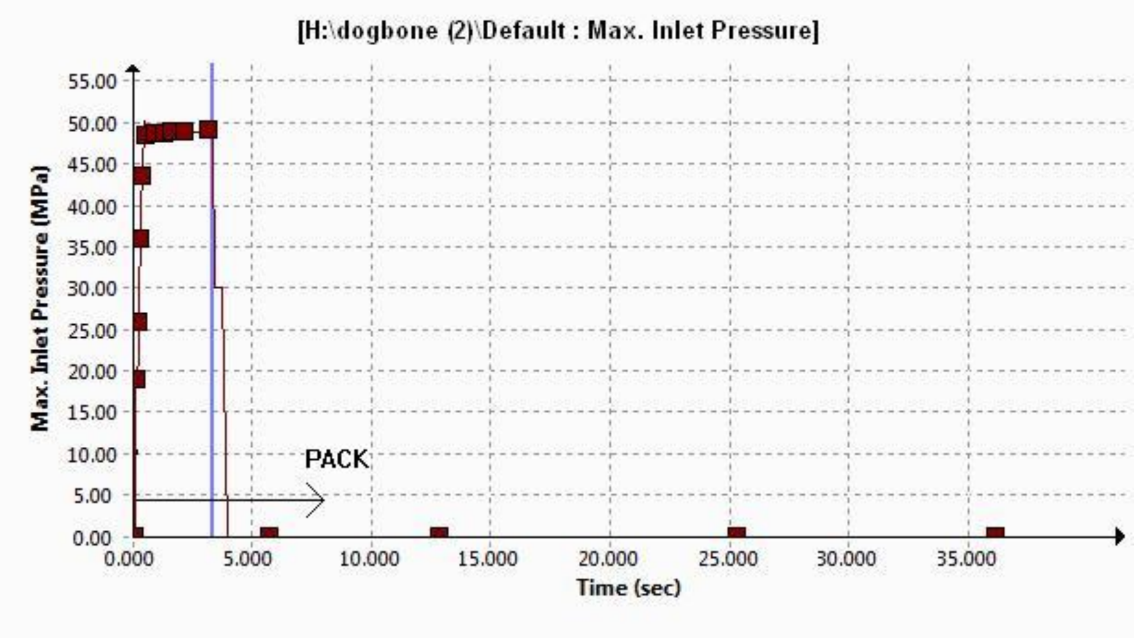
Enclosure Figure 22: SolidWorks Plastics Pressure at the end of packing



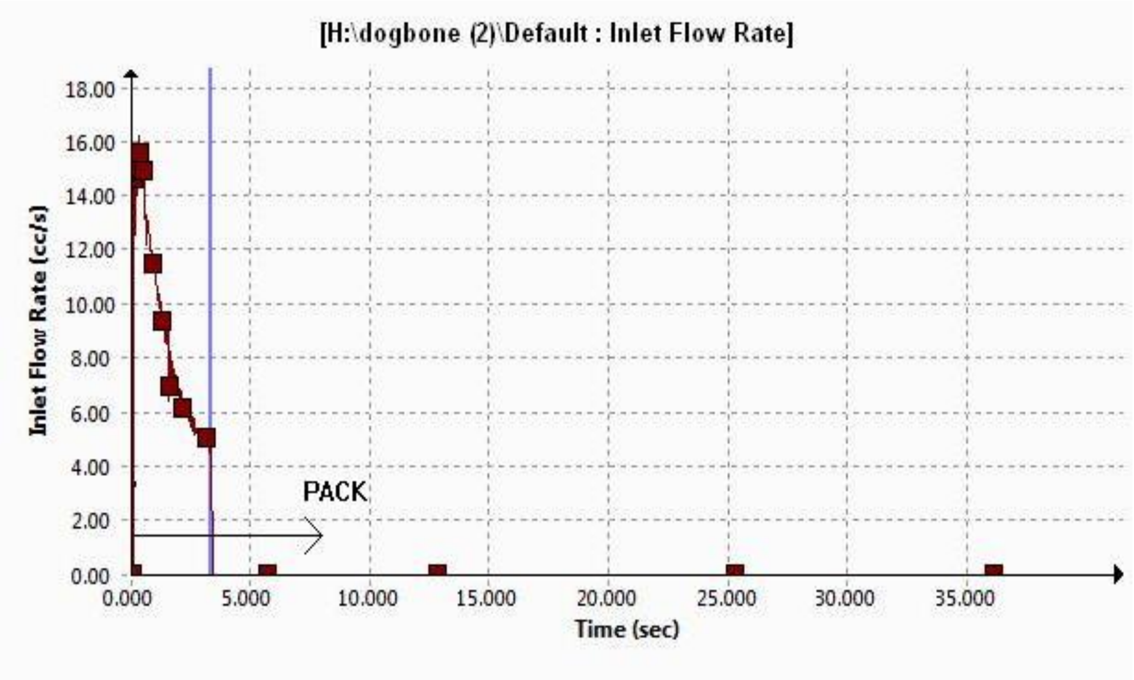
Enclosure Figure 23: SolidWorks Plastics Temperature at the end of packing



Enclosure Figure 24: SolidWorks Plastics Total displacement



Enclosure Figure 25: SolidWorks Plastics Inlet pressure



Enclosure Figure 26: SolidWorks Plastics Inlet flow rate

Table 16: Reference HDPE surface area results

Run	**Sample 1**	**Sample 2**	**Sample 3**	**Sample 4**	**Sample 5**
1	6404.53	6448.347	7236.208	6865.025	6603.52
2	6875.168	6753.005	6994.103	7021.341	7105.611
3	7182.618	6503.323	6716.976	6751.263	6846.815
4	6952.195	6755.621	6447.666	6983.575	6737.971
5	6738.515	6262.47	7115.689	7137.515	6989.951
6	6412.394	6874.624	6811.019	6695.136	6407.517
7	6871.076	6329.833	6800.324	6658.031	6938.029
8	7183.252	6931.299	7136.077	7382.68	7159.8
9	7158.995	7191	7278.759	7240.71	7145.176
10	6993.331	6917.427	7240.312	7354.346	7196.316
11	6799.608	7172.138	7415.851	7669.093	7259.704
12	7481.312	7090.133	7387.566	6747.323	6797.067
13	7032.654	7113.427	7304.452	7341.995	7378.835
14	7240.242	7159.37	7302.432	7223.321	7331.237
15	7226.633	7085.464	7206.789	7556.863	7107.384
16	7384.992	7329.547	7175.172	7028.13	7147.84
17	7098.304	7163.987	7308.447	7083.69	7172.964
18	7168.596	7379.232	7415.141	7256.618	7344.522
19	7523.517	7253.431	7538.379	7146.015	7600.089
20	7468.957	7507.243	7312.611	7104.942	6961.157
21	6869.901	6928.635	7292.761	7113.605	7105.454
22	7563.302	7448.421	7652.91	7554.436	7669.459
23	7217.706	7179.446	7002.395	6943.816	7088.115
24	7292.248	7189.792	7343.108	7252.96	7215.064
25	7387.196	7192.903	7245.881	7331.103	7189.979

Table 17: Recycled HDPE surface area results

Run	**Sample 1**	**Sample 2**	**Sample 3**	**Sample 4**	**Sample 5**
1	6811.477	7135.114	7184.851	6845.359	7000.474
2	7126.595	6967.679	7236.051	6979.266	7162.954
3	7158.11	7083	7207.837	7146.856	7062.031
4	7065.629	6886.84	7066.498	7106.807	7259.753
5	7149.067	7126.887	7031.498	7049.177	7158.11
6	7035.006	7066.246	7183.393	7009.236	7285.179
7	7146.48	7110.074	7095.627	7013.32	7177.62
8	7075.688	6925.676	6992.02	7225.69	7093.534
9	7041.206	7283.024	6959.692	7322.387	7016.521
10	6971.659	7022.363	7045.526	6945.211	7034.058
11	7140.721	7309.425	7173.419	6461.449	6843.569
12	6694.562	6679.981	6725.666	6808.353	6776.188
13	6595.689	6769.391	6694.991	6870.173	6421.219

14	6679.458	6597.851	6396.859	6765.504	6743.726
15	7086.001	6821.598	6945.859	6679.726	7152.471
16	7122.876	7029.407	6897.936	6917.233	7192.944
17	6838.268	6715.239	6923.93	6779.884	6738.42
18	7219.665	7185.545	6989.211	7292.353	6452.698
19	7079.045	7295.681	7107.572	7186.694	7175.367
20	7120.912	7253.963	7042.276	6965.553	7100.883
21	7025.277	7110.122	7026.033	7266.806	6660.536
22	7038.196	6907.236	6999.176	7013.084	7126.151
23	7257.556	7090.374	7130.415	7125.627	7263.998
24	7014.547	7054.253	7142.446	7345.069	6841.095
25	7493.97	7142.208	6989.237	7099.749	7055.887

Table 18: Reference HDPE mass results

Run	**Sample 1**	**Sample 2**	**Sample 3**	**Sample 4**	**Sample 5**
1	20.96	20.95	21	20.95	20.99
2	21.32	21.35	21.32	21.32	21.32
3	21.62	21.6	21.63	21.65	21.64
4	21.82	21.81	21.83	21.86	21.82
5	22.11	22.12	22.13	22.2	22.2
6	21.4	21.43	21.46	21.44	21.4
7	21.81	21.8	21.79	21.82	21.84
8	22.24	22.2	22.25	22.18	22.18
9	21.57	21.57	21.56	21.56	21.57
10	21.01	20.96	21	20.96	20.98
11	22.2	22.29	22.28	22.18	22.23
12	21.52	21.51	21.52	21.54	21.52
13	21.67	21.67	21.67	21.69	21.69
14	21.08	21.04	21.04	21.08	21.07
15	21.58	21.56	21.57	21.57	21.52
16	21.6	21.6	21.58	21.59	21.59
17	21.74	21.72	21.7	21.72	21.73
18	21.19	21.22	21.16	21.25	21.24
19	22.02	21.91	22.02	21.95	21.99
20	21.49	21.48	21.49	21.47	21.47
21	22.21	22.16	22.23	22.23	22.1
22	21.16	21.54	21.55	21.52	21.54
23	21.21	21.24	21.24	21.18	21.22
24	21.65	21.62	21.66	21.63	21.63
25	21.86	21.83	21.84	21.86	21.88

Table 19: Recycled HDPE mass results

Run	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5
1	20.97	20.97	20.94	21.01	20.95
2	21.23	21.26	21.2	21.23	21.23
3	21.41	21.35	21.41	21.35	21.35
4	21.42	21.43	21.47	21.45	21.43
5	21.49	21.5	21.48	21.46	21.49
6	21.2	21.23	21.24	21.23	21.23
7	21.41	21.41	21.41	21.41	21.41
8	21.44	21.43	21.46	21.44	21.44
9	21.37	21.37	21.38	21.38	21.38
10	20.87	20.89	20.88	20.87	20.89
11	21.44	21.44	21.46	21.45	21.44
12	21.37	21.37	21.36	21.37	21.36
13	21.45	21.43	21.42	21.42	21.43
14	20.85	20.85	20.85	20.88	20.84
15	21.18	21.17	21.17	21.2	21.17
16	21.39	21.38	21.37	21.37	21.38
17	21.45	21.46	21.46	21.44	21.44
18	20.88	20.88	20.85	20.88	20.88
19	21.18	21.15	21.16	21.16	21.16
20	21.33	21.34	21.32	21.33	21.32
21	21.56	21.55	21.57	21.59	21.55
22	20.86	20.82	20.82	20.83	20.84
23	21.05	21.05	21.07	21.05	21.05
24	21.37	21.37	21.36	21.36	21.38
25	21.47	21.46	21.45	21.47	21.46

Table 20: Reference HDPE tensile strength results

Run	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5
1	811.2	841.2	851.3	841.1	842.6
2	816.3	855.1	857	863.6	854.6
3	831.4	883.5	877.7	876.9	876.7
4	840.7	878.1	876.1	883	877.2
5	871	898.8	894.4	894.1	881.8
6	831.6	857.9	859.2	853.8	859.2
7	843.1	879.4	864.9	864.1	865.7
8	862.7	880.2	882.9	890.8	896.8
9	826.8	869.3	880	874.8	871.5
10	823.5	845.5	851	856.2	846.1
11	862.8	920.9	914.6	935.6	920.9
12	836.2	879.4	869	863.5	867.6
13	839.6	875.8	863.33	866.6	880.5

14	827.6	859.3	859	853.5	849.9
15	838	864.5	867.1	861.7	871.5
16	874.3	886.2	880.2	892.5	892.5
17	889.5	901.2	895.5	893.9	893.3
18	841.4	875.8	866.5	878.3	882.7
19	881.5	905.2	917.6	902.6	891.6
20	847.2	865.4	866.2	863.9	878.3
21	866.2	870.3	885.6	896.8	881
22	817.7	867.9	882.1	875	875.3
23	826.5	855.9	858.1	861.9	849.3
24	832.2	862.4	858.6	871.4	879.6
25	853.7	859.7	857.3	879.9	884

Table 21: Recycled HDPE tensile strength results

Run	**Sample 1**	**Sample 2**	**Sample 3**	**Sample 4**	**Sample 5**
1	911	945.9	948.1	941.9	941.9
2	921.9	983.1	964.6	967	976.5
3	920.6	969.2	957.1	966.4	968.1
4	947.9	959.4	983	971.8	964.9
5	944.9	988.5	981.7	966.4	964
6	937.5	986.6	986.6	986.6	984.5
7	957.7	980.6	977.3	969.4	973.5
8	946.8	980.7	973	972.4	976.6
9	955.8	1000.8	989.9	986.9	966.2
10	952.5	973	957.4	965.4	960.2
11	949.8	974.6	973.8	972.7	978.1
12	930.9	9844.1	975.5	969.4	980.6
13	940.3	994.2	976.2	981.1	980.6
14	922.7	956.3	951.1	947.3	955.5
15	943.5	975.8	992.1	962.8	982
16	945.7	1003.2	995.9	983.9	1000.6
17	936.4	983.4	988.6	987	980.7
18	937.5	958.5	967.2	960.5	968.3
19	929.7	970.9	995.4	985.3	987.8
20	938.6	993.5	984.2	1005.2	982
21	954.5	989.7	1009	980.1	989.4
22	914.9	955.5	963.5	957.2	958.8
23	936.9	961.2	975.2	974.3	985.8
24	965	999.1	989.3	991.3	1001.7
25	974.3	989	988.2	992.3	1005.4

Table 22: Reference HDPE S/N ratios

Run	**Area**	**Mass**	**Tensile**
1	25.798985	2.643195558	5.845592233
2	34.07166568	2.657818398	5.857612657
3	28.763908	2.670031897	5.877623818
4	29.99597381	2.678027082	5.879638163
5	25.48643898	2.690821704	5.896671182
6	29.60431437	2.661880657	5.861021184
7	28.89593363	2.677390168	5.872225553
8	32.98906265	2.693094794	5.891379822
9	42.17206731	2.667539135	5.87284133
10	31.94792278	2.643692534	5.852925924
11	27.10194605	2.69410842	5.917967293
12	26.5694663	2.665764984	5.871788749
13	33.53857738	2.672038158	5.873841598
14	40.59007586	2.64699823	5.858443481
15	31.65507348	2.667296278	5.869314635
16	33.99136126	2.668585587	5.893940025
17	38.11487427	2.673799133	5.903311912
18	37.29862116	2.653160061	5.877594556
19	31.38722254	2.683971434	5.907951721
20	29.82217161	2.664068328	5.873055203
21	32.48809086	2.692151374	5.888744671
22	38.62302087	2.663274702	5.871620199
23	35.76262712	2.653407453	5.858892393
24	41.49550482	2.670433632	5.869381891
25	38.42246148	2.679061048	5.875689607

Table 23: Reference HDPE S/N ratios ranking

Area		**Mass**		**Tensile**	
run	S/N	run	S/N ratio	run	S/N ratio
9	42.17207	11	2.69410842	11	5.917967293
24	41.4955	8	2.693094794	19	5.907951721
14	40.59008	21	2.692151374	17	5.903311912
22	38.62302	5	2.690821704	5	5.896671182
25	38.42246	19	2.683971434	16	5.893940025
17	38.11487	25	2.679061048	8	5.891379822
18	37.29862	4	2.678027082	21	5.888744671
23	35.76263	7	2.677390168	4	5.879638163
2	34.07167	17	2.673799133	3	5.877623818
16	33.99136	13	2.672038158	18	5.877594556
13	33.53858	24	2.670433632	25	5.875689607

8	32.98906	3	2.670031897	13	5.873841598
21	32.48809	16	2.668585587	20	5.873055203
10	31.94792	9	2.667539135	9	5.87284133
15	31.65507	15	2.667296278	7	5.872225553
19	31.38722	12	2.665764984	12	5.871788749
4	29.99597	20	2.664068328	22	5.871620199
20	29.82217	22	2.663274702	24	5.869381891
6	29.60431	6	2.661880657	15	5.869314635
7	28.89593	2	2.657818398	6	5.861021184
3	28.76391	23	2.653407453	23	5.858892393
11	27.10195	18	2.653160061	14	5.858443481
12	26.56947	14	2.64699823	2	5.857612657
1	25.79898	10	2.643692534	10	5.852925924
5	25.48644	1	2.643195558	1	5.845592233

Table 24: Recycled HDPE S/N ratios

Run	**Area**	**Mass**	**Tensile**
1	32.43338652	2.643112311	5.94390221
2	35.62633476	2.653898948	5.966241935
3	41.63873289	2.659769148	5.96067389
4	34.52429021	2.662448656	5.969220772
5	41.66971246	2.664229768	5.97241493
6	35.77364619	2.653735787	5.978681745
7	41.16777964	2.661233335	5.974976724
8	35.88543643	2.662530311	5.973252784
9	32.65993937	2.659852813	5.982011333
10	44.19586103	2.63946075	5.966009949
11	26.28567049	2.662692422	5.973218491
12	41.86827169	2.65944638	6.063563031
13	31.78518751	2.662044002	5.977083029
14	32.97029064	2.638378188	5.952087097
15	31.13528829	2.651769493	5.974258357
16	34.81228642	2.659933986	5.987010216
17	38.1671067	2.662854367	5.977657705
18	26.29271912	2.639210927	5.962915645
19	38.61684272	2.651113141	5.97617399
20	36.46193211	2.657900104	5.982358925
21	29.97158518	2.667458019	5.986039678
22	39.00861181	2.637544648	5.954957902
23	38.9335835	2.646669049	5.970164007
24	31.67941469	2.65952759	5.99040944
25	31.19945379	2.663340223	5.990998847

Table 25: Recycled HDPE S/N ratios ranking

Area		**Mass**		**Tensile**	
run	S/N	run	S/N ratio	run	S/N ratio
10	44.19586	21	2.667458019	12	6.063563031
12	41.86827	5	2.664229768	25	5.990998847
5	41.66971	25	2.663340223	24	5.99040944
3	41.63873	17	2.662854367	16	5.987010216
7	41.16778	11	2.662692422	21	5.986039678
22	39.00861	8	2.662530311	20	5.982358925
23	38.93358	4	2.662448656	9	5.982011333
19	38.61684	13	2.662044002	6	5.978681745
17	38.16711	7	2.661233335	17	5.977657705
20	36.46193	16	2.659933986	13	5.977083029
8	35.88544	9	2.659852813	19	5.97617399
6	35.77365	3	2.659769148	7	5.974976724
2	35.62633	24	2.65952759	15	5.974258357
16	34.81229	12	2.65944638	8	5.973252784
4	34.52429	20	2.657900104	11	5.973218491
14	32.97029	2	2.653898948	5	5.97241493
9	32.65994	6	2.653735787	23	5.970164007
1	32.43339	15	2.651769493	4	5.969220772
13	31.78519	19	2.651113141	2	5.966241935
24	31.67941	23	2.646669049	10	5.966009949
25	31.19945	1	2.643112311	18	5.962915645
15	31.13529	10	2.63946075	3	5.96067389
21	29.97159	18	2.639210927	22	5.954957902
18	26.29272	14	2.638378188	14	5.952087097
11	26.28567	22	2.637544648	1	5.94390221