AC 2007-611: SIMULATION AS A MEANS TO INFUSE MANUFACTURING EDUCATION WITH STATISTICS AND DOE – A CASE STUDY USING INJECTION MOLDING

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Simulation as a Means to Infuse Manufacturing Education with Statistics and DOE – A Case Study using Injection Molding

Abstract

Modern manufacturing systems continue to evolve and in so doing can produce many unique products using both traditional as well as novel raw materials. This is especially true in the processing of plastic products. In these environments, there is the need to critically examine material compatibility and to optimize methods of manufacture to realize economic success. Key to these endeavors is the ability to conduct product development efforts in a logical fashion. Experimentation is an important component to this process. Graduates of manufacturing engineering and technology programs should thus have knowledge of formal Design of Experiments (DOE) and statistical procedures. But, most undergraduate students are not exposed to these methodologies – only in graduate level statistics classes do engineering and technology students typically receive this type of training. Moreover, implementing formal, hands-on experiments can be problematic in many undergraduate curricula because they can be extremely time and resource consuming. Computer simulation can be one way to effectively implement and achieve these objectives, though. The goal of this paper is to describe how to use simulation software to conduct formal experiments using dedicated injection molding software. This paper will discuss several key topics, including a brief introduction regarding the teaching of statistics and DOE to engineering and technology students, as well as injection molding, a common manufacturing unit operation. An example simulation exercise will then be presented to illustrate the concepts discussed. Educators in manufacturing programs should find this useful as they consider how best to augment laboratory work, student understanding of statistics, as well as to achieve proficiency with computer simulation, as this approach to laboratory experiences transcends injection molding specifically, and has a wide range of applicability with many manufacturing operations.

Introduction

As evidenced by the many presentations at annual ASEE national and regional meetings, educators are constantly developing and implementing improved curricula to meet emerging challenges in the various fields of engineering and technology. Some of these activities encompass developing novel subject matter. Many of these endeavors, however, include teaching fundamental, traditional topics using new methods, approaches, and strategies.

Statistics is a skill that is essential for all engineering and technology professionals, but has not been overly emphasized over the years. Many graduates will frequently need to use these tools once they enter the workforce. This is especially true for those involved in research and development as well as testing and validation activities. Basic and applied statistics is key to analyzing laboratory studies, deciphering what the data mean, and discerning trends and patterns[1]. Even so, the teaching of statistics to engineers has been the subject of only a few studies in recent years[2-4]. Essential statistics topics should include independent and dependent variables, factorial experimental designs and coding schemes, summarizing collected data with estimates of central tendency (i.e., means) and estimates of observed error (i.e., standard deviation), main effects due to the independent variables, and treatment combination effects, due to simultaneously altering the levels of the independent variables.

Additionally, the ability to conduct experiments is also a crucial skill set for students – thus formal training in Design of Experiments (DOE) is also very important. For most engineering and technology programs, at least at the undergraduate level, however, this is not a subject which is typically taught. Rather, it is generally left up to either the individual or their employer to provide this training. As further evidence of this curricular need, this topic has been discussed by only a few recent studies[5-7].

One way to address this is to infuse courses with statistics and DOE components – not full-blown training in all of the techniques available, but rather an introduction to the common "tools of the trade". Logical places would be to interject these components in either a manufacturing processes course or an experiential learning environment. According to Lin et al.[8], injection molding is one potential avenue that can be used for such curricular development, as it lends itself to formal hands-on laboratory experiences.

Injection Molding

In fact, injection molding in educational settings has been discussed by several authors. For example, prior studies have examined raw products[9], analysis methods[10], process changes[11], and effects on final products[12]. Partnerships between academic institutions and industrial partners have also been discussed[13].

Traditional injection molding was first conceptualized in 1868 by John Wesley Hyatt to make a billiard ball from a cellulose formulation. In 1946, James Hendry marketed his screw injection machine, which replaced the plunger system. Screw machines are the predominate injection molding machine used today[14]. Basically, molten plastic is forced into a closed cavity of a specific, desired geometry.

Various processing parameters influence molding success. These include melt temperature, mold temperature, injection pressure, injection time, dwell time, freeze time, and dead time[15]. The inclusion of fillers, however, will alter material properties, which will thus affect processing behavior and final product quality. These altered properties can include thermal properties, such as conductivity and specific heat, as well as rheological behavior. Rheological properties include viscosity, and the empirical parameters which are used to quantify the effects of shear rate and temperature.

Computer-aided engineering (CAE) software provides powerful analysis of product designs and manufacturing parameters. Three dimensional (3-D) computer-aided designs (CAD), such as solid models, provide a starting point to evaluate heat transfer and structural integrity of injection molded products. Flow analysis is a member of the CAE software family. Injection mold analysis can either be 2-D or 3-D. The 3-D flow analysis, while more computationally intense, performs better for most injection mold cavity studies[14]. As inputs, these software programs use part geometry, processing parameters, thermal properties, and material flow characteristics. Most software programs break the model into small entities, and each of these small units is studied in relation to its neighbors. This technique is called finite element analysis (FEA). The output of these programs can include various quality characteristics, including strength, knit lines, fill patterns, fill time, sink marks, etc.[15]. There are many studies where authors use these computational flow analysis programs[16-23]. With mathematical modeling, the practitioner can attempt to optimize the parameters for desired results. Several authors suggest methods for optimization[24]. Taguchi methods[25-26] have been used, as well as neural networks[27-29]. Others have studied composite injection molding with dedicated flow analysis software[30-32].

Laboratory injection molding can be an expensive proposition if a department does not have the appropriate equipment, or sufficient resources with which to procure them. The use of software in the classroom to simulate injection molding operations can be tremendously advantageous in this regard. Its use can also be a route to simultaneously teaching simulation, design of experiments, and statistics. An example of this type of approach, which the authors have successfully used in their own experience, follows.

Statistical Education Framework

Investigators in many fields use experimentation to learn about their products and processes. Statistical methods provide a structured approach to understanding effects of various factors. This comprehension yields better products and more efficient processes. At one time statistical analysis was very specialized. With cross functional teams and improved computing tools, students graduating today will be expected to perform statistically based analyses.

Guidelines for designing experiments have been discussed elsewhere.[33] First the investigator must recognize and define the problem. Second, chose the factors and the levels that will be run during experimentation. Third, select the response variables to be measured or observed. Fourth, determine the appropriate experimental design. Fifth, run the experiment based on the experimental design. Then, execute the statistical analysis. Finally, draw practical conclusions which likely will involve iterative confirmation runs.

Further, researchers are encouraged to use nonstatistical understanding of the systems being studied.[33] An appropriate level of common sense improves the analysis. Simple experimental designs are useful. In other words, add complexity only when necessary. It is tempting for naïve students to over emphasize statistical differences when in practicality there is no useful case for making a differentiation.

Before students embark on learning design experimentation, they should have a grasp of basic statistical concepts. This goes beyond the ability to calculate a mean and standard deviation of a sample. Students are expected to be able to make practical inferences about differences in means. Without the ability to phrase hypothesis testing results in concise and statistically sound language, students will be lost and will fail to grasp experimental designs.

Therefore, we suggest a review of the following statistical concepts before embarking on a designed experimentation exercise. First, given two sample populations (about 20 observations) calculate the mean and standard deviation. Second, graph a dot diagram of the two sample populations – Figure 1 provides an example of this. Third, create a box and whisker plot (Figure

2 provides an example of this). Ask each student to study the statistics and graphs. Using this information, the students should be able to suggest if there is a difference between the two populations and explain in a straightforward manner why this is the case. For this example, the students should be able to see the difference between the two recipes.

Once students have demonstrated this proficiency, it is reasonable to proceed with learning designed experiments. Keep in mind, this case study best fits students working on an internship or special topics where adequate background knowledge can be learned such as injection molding process. Further, mentoring students throughout this process is very beneficial. For example, follow-up on student progress through the exercise over a period of a couple weeks will build confidence and emphasize the iterative nature of research.

Simulation – A Case Study of Implementation

The objective of this exercise was to simulate the processing behavior of a modified plastic formulation when subjected to injection molding. The rheological and thermal properties of the plastic were parametrically altered, and processing behavior and final product quality were then examined using typical statistical analysis, including determining means, standard deviations, and examining main effects and treatment combination effects due to alterations in the levels of the independent variables.

The addition of fillers to thermoplastics can substantially alter the physical characteristics of these composite materials, which will impact behavior during the injection molding process, and thus final product quality and performance. Using polypropylene as a benchmark material for this case study, a 3D model of a typical "dog-bone" specimen (Figure 3) was constructed according to ASTM Method D790[34]. This model was used in a series of simulated experiments.

To simulate the effects of adding fillers, or otherwise altering the chemical composition, several physical parameters were systematically altered in this study. Thermal properties included thermal conductivity and specific heat. For the base polypropylene, the values of thermal conductivity and specific heat were, respectively, 0.164 (W/m·C) and 2740 (J/kg·C). Rheological properties altered in this study included various parameters used to define the viscosity relationship. For thermoplastics, which are classified as shear-thinning materials, viscosity can be defined using the Cross-WLF model:

$$\eta = \frac{\eta_o}{1 + \left(\frac{\eta_o \gamma}{\tau *} \right)^{1-n}}$$

where:

$$\eta_o = D1 \exp\left[\frac{-A1(T - T*)}{A2 + (T - T*)} \right]$$

where: η is the viscosity (Pa·s), γ is the shear rate (1/s), T is the temperature (K), T* is D2+D3·P (K), P is the pressure (Pa), A2 is A2*+D3·P (K), while n, τ^*, D1, D2, D3, A1, and A2* are regression coefficients based upon empirical data. For the base polypropylene used in this study, the values of these coefficients were, respectively, 0.2751 (-), 24200 (Pa·s), $4.66x10^{12}$ (Pa·s), 263.15 (K), 0 (K/Pa), 26.12 (-), and 51.6 (K).

Using polypropylene as the baseline, a formal experiment was then designed to include five factors (thermal conductivity, specific heat, τ^*, D1, and n), each at two levels (+/- 25% from the base values). This resulted in a 2^5 experiment (32 treatments), which was implemented factorially. Additionally, a center point (i.e., the unaltered polypropylene) was also included in the design. This resulted in 33 total treatment combinations. The coded experimental design that was used is provided in Table 1, while the experimental design with actual variable values is given in Table 2.

Simulations of the injection molding process were conducted with Moldflow Part Advisor (version 7.2) software, using a mold temperature of 40°C, a maximum injection pressure of 180 MPa, and a shot volume of 8.57 cm^3. Processing conditions determined via the simulations included fill time (s), injection pressure (Pa), pressure drop (Pa), flow front temperature (C), surface temperature (C), freeze time (s), confidence of mold fill (-), required clamping force (tonnes), and total cycle time (s). Final quality of the molded products included cooling quality, quality prediction, locations of weld lines, locations of air traps, locations of sink marks, and skin orientations.

Because polypropylene was the baseline material used for this study, an examination of the simulation results for this benchmark, as a prelude to all the results from the various treatment combinations, is useful. Overall, the resulting processing conditions for the polypropylene were quite good. Fill time of the specimen (Figure 4) was 1.68 s. Injection pressure (Figure 5) varied from 0 to 3.88 MPa, depending on location within the sample. The pressure drop (which is the inverse of injection pressure) was also determined (Figure 6), which also varied from 0 to 3.88 MPa. Temperature of the flow front (Figure 7) varied from 239.24 to 240.00°C, depending on location within the sample. The flow temperature during processing was high throughout the sample, but was slightly cooler near the ends of the mold. Variations in surface temperature (Figure 8), on the other hand, ranged from -5.67 to 2.54°C. Throughout the specimen, temperature variation was most at the center and least at the edges and ends. Variations in freeze time (Figure 9) ranged from -0.28 to 0.14 s, and were least near the edges throughout, and at the center. Confidence of mold fill (Figure 10) was good throughout the extent of the mold.

Considering all quality parameters calculated, the final molded polypropylene specimen was determined to be very good. Cooling quality was good throughout (Figure 11), and overall predicted quality was also excellent (Figure 12). No weld lines were present in the specimen (Figure 13), and neither were air traps (Figure 14). No sink marks were present throughout the product either (Figure 15). Skin orientation results illustrate the flow lines throughout the product, which radiate from the injection (i.e., center) point (Figure 16).

Considering only the main treatment effects (i.e., not the treatment combination effects), and pooling the data appropriately produced "pseudo-replications" for each main factor (n=16 for each main effect) because the independent variables had two levels each. Results of this analysis are provided in Table 3. As shown, various trends were evident. As thermal conductivity and specific heat increased, injection time increased. On the other hand, as the rheological parameters increased, it appeared that no trends for injection time were evident. Injection pressure increased as each of the factors increased. Clamping force did not show any trends as each of the factors was increased, though. Cycle time decreased as thermal conductivity increased, but increased as specific heat increased.

Comparing the results from all the simulation runs, it became apparent that the graphical results appeared very similar for all treatment combinations (data not shown for brevity). In-depth examination of the numerical results, however, provided several interesting insights. Altering the rheological and thermal properties produced definite changes in processing conditions and final product properties. In order to see where specific differences occurred, treatment combination effects (i.e., results from each specific run) were compared (Table 4). Some treatment combinations produced either increased, or decreased, values compared to the unaltered polypropylene. Moreover, some factor levels had a more drastic effect than others, as evidenced by the calculated change (%) versus the unaltered polypropylene for each combination. Pure polypropylene had an injection time of 1.68 s, and a cycle time of 25.15 s. Those treatments with a low thermal conductivity and a high specific heat produced greater injection and cycle times. On the other hand, those treatments with high thermal conductivity and low specific heat produced decreased injection and cycle times compared to polypropylene. The required injection pressure for pure polypropylene was 3.88 MPa. Most treatment combinations resulted in a decreased pressure, although some factor combinations did require greater pressure. A few, however, resulted in a minimal change. The clamping force required for polypropylene was 0.58 tonnes. The results show that most of the treatment combinations required less force, although a few did require an increase. Ultimately, these observed behaviors were due to the trade-offs between the thermal and rheological properties of the plastic during molding.

The range of potential bulk property changes that were considered in the simulated exercise should, at least as a starting point, provide a range of potential variations that could be expected when actually altering the chemical composition of the thermoplastic under consideration. Results clearly show differences between final products, which were due to the parameter alterations that were established when formally designing the experiment.

Conclusions and Implications

Progressive engineering and technology curricula demand the ongoing development of new educational methods and tools. Unfortunately, this does not always agree with the need to reduce the cost of that education. Computer simulation may offer the potential to achieve both goals simultaneously. Thus, the objective of this paper was to discuss the use of injection molding simulation software to demonstrate the concepts of statistics and Design of Experiments as well as data analysis. This method could be used to bolster manufacturing laboratory curricula. A case study was conducted to demonstrate this approach, with a series of simulations to determine the effects of parametrically altering the thermal and rheological properties of polypropylene. This simulation case study provides a pattern that could be a useful reference base from which to work for further simulation exercises and curriculum development. And, this approach to using simulation software as means to infuse statistics and DOE concepts into manufacturing curricula is not limited to injection molding – we have discussed a general approach that could be used for many manufacturing operations, as long as the simulation software is available.

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Table 1. Factorial experimental design with coded variables.[a]

RUN	τ^*	D1	n	Thermal Conductivity	Specific Heat
1	-1	-1	-1	-1	-1
2	-1	-1	-1	-1	1
3	-1	-1	-1	1	-1
4	-1	-1	-1	1	1
5	-1	-1	1	-1	-1
6	-1	-1	1	-1	1
7	-1	-1	1	1	-1
8	-1	-1	1	1	1
9	-1	1	-1	-1	-1
10	-1	1	-1	-1	1
11	-1	1	-1	1	-1
12	-1	1	-1	1	1
13	-1	1	1	-1	-1
14	-1	1	1	-1	1
15	-1	1	1	1	-1
16	-1	1	1	1	1
17	1	-1	-1	-1	-1
18	1	-1	-1	-1	1
19	1	-1	-1	1	-1
20	1	-1	-1	1	1
21	1	-1	1	-1	-1
22	1	-1	1	-1	1
23	1	-1	1	1	-1
24	1	-1	1	1	1
25	1	1	-1	-1	-1
26	1	1	-1	-1	1
27	1	1	-1	1	-1
28	1	1	-1	1	1
29	1	1	1	-1	-1
30	1	1	1	-1	1
31	1	1	1	1	-1
32	1	1	1	1	1
33	0	0	0	0	0

[a] τ^*, D1, n are empirical regression coefficients used to define viscosity.

Table 2. Factorial experimental design with actual variable values.[a]

RUN	τ*	D1	n	Thermal Conductivity	Specific Heat
1	3.495E+12	18150	0.2063	0.123	2055
2	3.495E+12	18150	0.2063	0.123	3425
3	3.495E+12	18150	0.2063	0.205	2055
4	3.495E+12	18150	0.2063	0.205	3425
5	3.495E+12	18150	0.3439	0.123	2055
6	3.495E+12	18150	0.3439	0.123	3425
7	3.495E+12	18150	0.3439	0.205	2055
8	3.495E+12	18150	0.3439	0.205	3425
9	3.495E+12	30250	0.2063	0.123	2055
10	3.495E+12	30250	0.2063	0.123	3425
11	3.495E+12	30250	0.2063	0.205	2055
12	3.495E+12	30250	0.2063	0.205	3425
13	3.495E+12	30250	0.3439	0.123	2055
14	3.495E+12	30250	0.3439	0.123	3425
15	3.495E+12	30250	0.3439	0.205	2055
16	3.495E+12	30250	0.3439	0.205	3425
17	5.825E+12	18150	0.2063	0.123	2055
18	5.825E+12	18150	0.2063	0.123	3425
19	5.825E+12	18150	0.2063	0.205	2055
20	5.825E+12	18150	0.2063	0.205	3425
21	5.825E+12	18150	0.3439	0.123	2055
22	5.825E+12	18150	0.3439	0.123	3425
23	5.825E+12	18150	0.3439	0.205	2055
24	5.825E+12	18150	0.3439	0.205	3425
25	5.825E+12	30250	0.2063	0.123	2055
26	5.825E+12	30250	0.2063	0.123	3425
27	5.825E+12	30250	0.2063	0.205	2055
28	5.825E+12	30250	0.2063	0.205	3425
29	5.825E+12	30250	0.3439	0.123	2055
30	5.825E+12	30250	0.3439	0.123	3425
31	5.825E+12	30250	0.3439	0.205	2055
32	5.825E+12	30250	0.3439	0.205	3425
33	4.660E+12	24200	0.2751	0.164	2740

[a] τ*, D1, n are empirical regression coefficients used to define viscosity.

Table 3. Main effects due to injection molding process conditions.

Parameter	Injection Time (s)			Injection Pressure (MPa)			Clamping Force (tonnes)			Cycle Time (s)		
	Mean	Change (%)	St. Dev.	Mean	Change (%)	St. Dev.	Mean	Change (%)	St. Dev.	Mean	Change (%)	St. Dev.
Tau* (Pa·s)												
3.495E+12	1.71	1.53	0.60	3.21	-17.17	0.85	0.36	-37.18	0.09	26.29	4.54	7.71
4.660E+12	1.68	-	-	3.88	-	-	0.58	-	-	25.15	-	-
5.825E+12	1.74	3.68	0.60	3.91	0.76	1.13	0.49	-15.01	0.18	26.33	4.70	7.48
D1 (Pa)												
18150	1.70	1.12	0.61	3.00	-22.63	0.79	0.34	-40.84	0.08	26.27	4.46	7.69
24200	1.68	-	-	3.88	-	-	0.58	-	-	25.15	-	-
30250	1.75	4.06	0.59	4.11	5.90	0.99	0.51	-11.56	0.17	26.35	4.78	7.50
n (-)												
0.2063	1.70	1.23	0.61	2.94	-24.26	0.66	0.34	-40.73	0.08	26.29	4.52	7.72
0.2751	1.68	-	-	3.88	-	-	0.58	-	-	25.15	-	-
0.3439	1.75	3.96	0.59	4.17	7.43	1.01	0.51	-11.66	0.17	26.34	4.72	7.47
Thermal Conductivity (W/m·C)												
0.123	2.16	28.31	0.51	3.22	-16.96	0.86	0.39	-33.30	0.13	31.55	25.43	6.72
0.164	1.68	-	-	3.88	-	-	0.58	-	-	25.15	-	-
0.205	1.32	-21.53	0.30	3.90	0.56	1.12	0.47	-18.66	0.17	21.39	-14.96	4.02
Specific Heat (J/kg·C)												
2055	1.34	-20.31	0.34	3.86	-0.48	1.13	0.46	-20.58	0.17	21.15	-15.91	4.04
2740	1.68	-	-	3.88	-	-	0.58	-	-	25.15	-	-
3425	2.09	24.23	0.55	3.30	-14.95	0.92	0.40	-30.63	0.15	31.17	23.95	6.68

Table 4. Treatment combination effects due to injection molding process conditions.

Run	Injection Time		Injection Pressure		Clamping Force		Cycle Time	
	(s)	Change (%)	(MPa)	Change (%)	(tonnes)	Change (%)	(s)	Change (%)
1	1.55	-7.74	2.25	-42.01	0.26	-55.17	24.78	-1.47
2	2.61	55.36	1.94	-50.00	0.26	-55.17	37.80	50.30
3	0.93	-44.64	2.57	-33.76	0.30	-48.28	17.17	-31.73
4	1.56	-7.14	2.25	-42.01	0.26	-55.17	25.04	-0.44
5	1.66	-1.19	3.16	-18.56	0.35	-39.66	24.89	-1.03
6	2.58	53.57	2.56	-34.02	0.28	-51.72	38.05	51.29
7	1.04	-38.10	3.88	0.00	0.44	-24.14	17.28	-31.29
8	1.56	-7.14	3.22	-17.01	0.36	-37.93	25.04	-0.44
9	1.66	-1.19	3.18	-18.04	0.36	-37.93	24.89	-1.03
10	2.59	54.17	2.71	-30.15	0.31	-46.55	38.05	51.29
11	1.04	-38.10	3.68	-5.15	0.42	-27.59	17.28	-31.29
12	1.56	-7.14	3.22	-17.01	0.37	-36.21	25.04	-0.44
13	1.66	-1.19	4.14	6.70	0.46	-20.69	24.89	-1.03
14	2.69	60.12	3.29	-15.21	0.36	-37.93	38.16	51.73
15	1.04	-38.10	5.15	32.73	0.57	-1.72	17.28	-31.29
16	1.56	-7.14	4.22	8.76	0.47	-18.97	25.04	-0.44
17	1.66	-1.19	2.57	-33.76	0.30	-48.28	24.89	-1.03
18	2.59	54.17	2.27	-41.49	0.26	-55.17	38.06	51.33
19	0.93	-44.64	2.91	-25.00	0.34	-41.38	17.17	-31.73
20	1.56	-7.14	2.58	-33.51	0.30	-48.28	25.04	-0.44
21	1.65	-1.79	3.93	1.29	0.44	-24.14	24.89	-1.03
22	2.70	60.71	3.20	-17.53	0.36	-37.93	37.91	50.74
23	1.04	-38.10	4.76	22.68	0.54	-6.90	17.28	-31.29
24	1.56	-7.14	3.98	2.58	0.44	-24.14	25.04	-0.44
25	1.67	-0.60	3.72	-4.12	0.47	-18.97	24.89	-1.03
26	2.70	60.71	3.21	-17.27	0.37	-36.21	38.16	51.73
27	1.04	-38.10	4.22	8.76	0.49	-15.52	17.28	-31.29
28	1.56	-7.14	3.74	-3.61	0.43	-25.86	25.04	-0.44
29	1.79	6.55	5.19	33.76	0.74	27.59	26.25	4.37
30	2.73	62.50	4.23	9.02	0.61	5.17	38.17	51.77
31	1.06	-36.90	6.47	66.75	0.89	53.45	17.28	-31.29
32	1.69	0.60	5.60	44.33	0.82	41.38	25.15	0.00
33	1.68	-	3.88	-	0.58	-	25.15	-

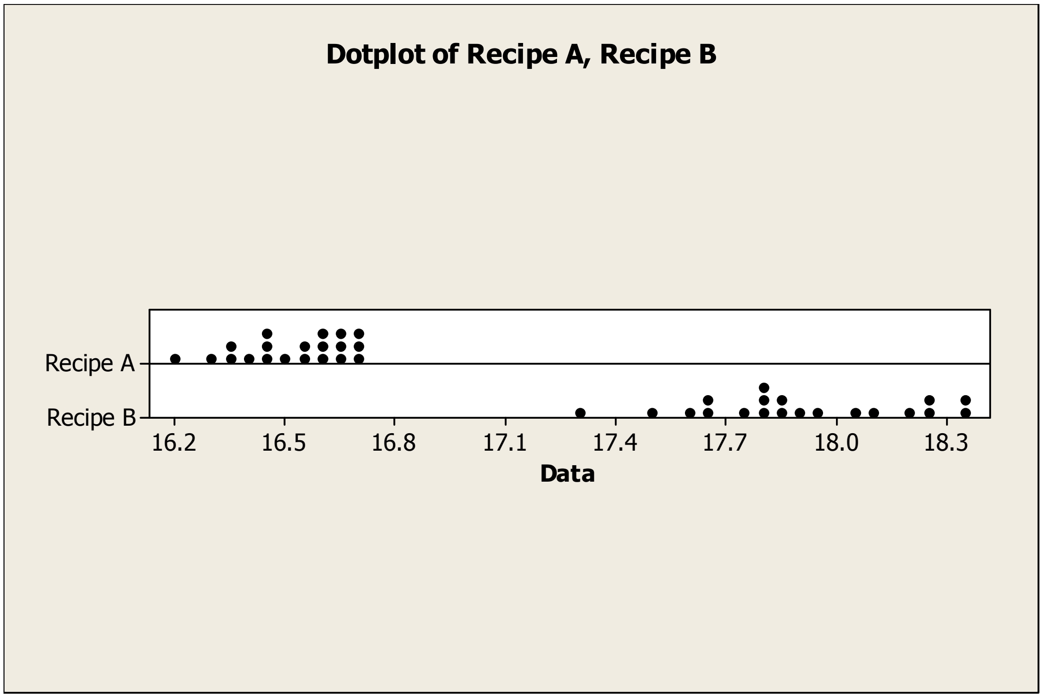

Figure 1. A dot plot of an example data set produced from two different recipes.

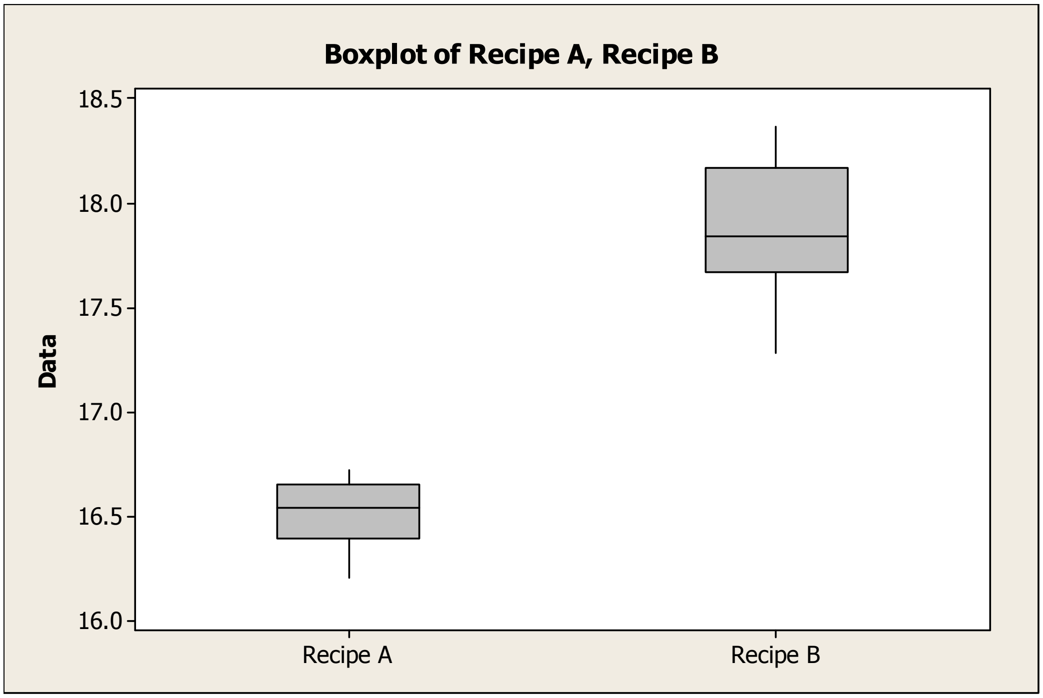

Figure 2. A box plot of an example data set produced from two different recipes.

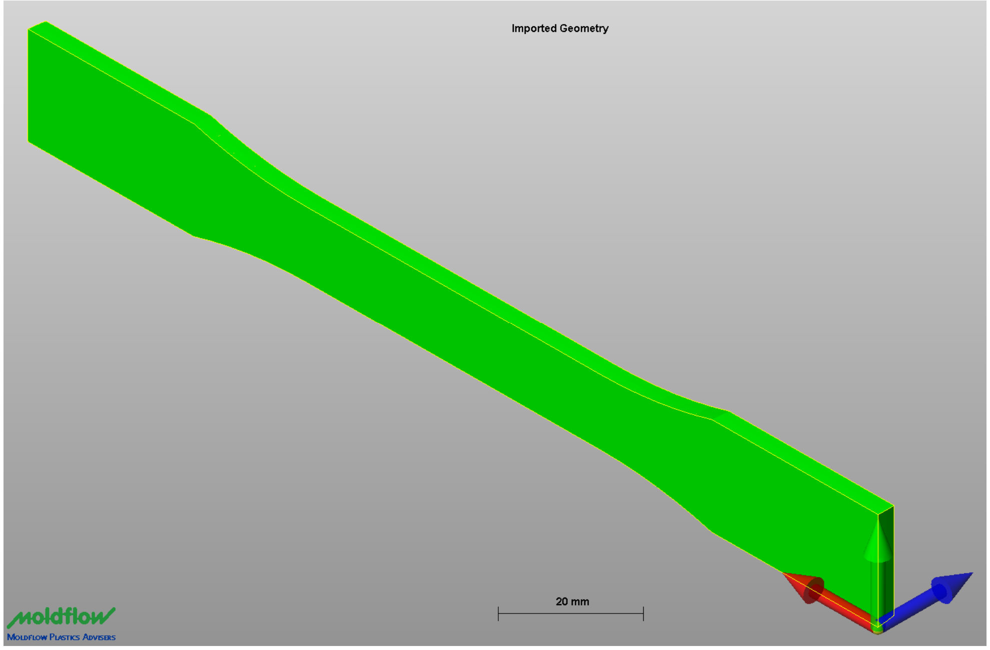

Figure 3. Standard “dog-bone” solid model used for all simulations.

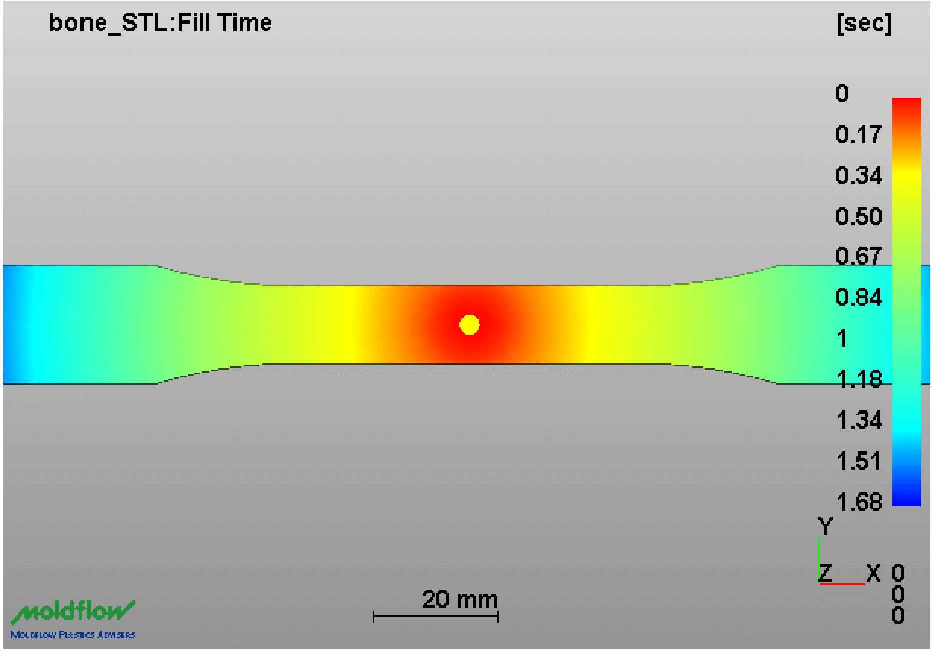

Figure 4. Fill time results for pure polypropylene (Treatment 33).

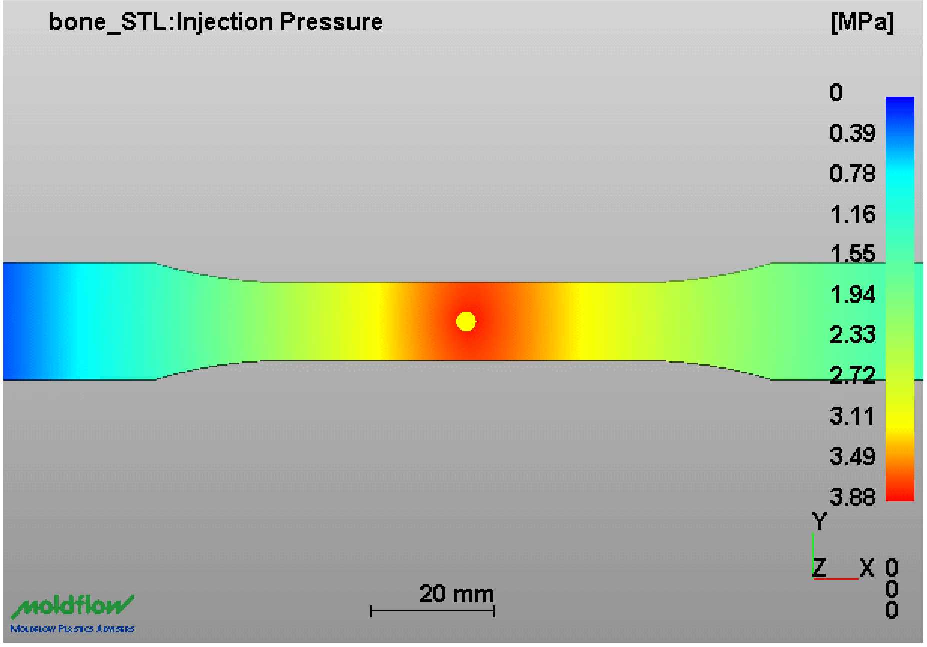

Figure 5. Injection pressure results for pure polypropylene (Treatment 33).

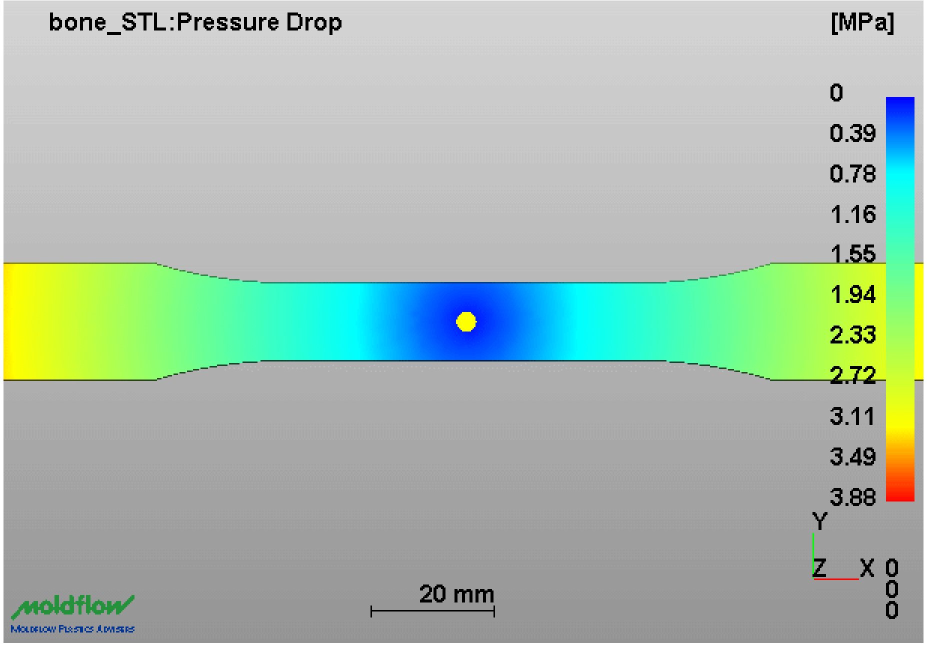

Figure 6. Pressure drop results for pure polypropylene (Treatment 33).

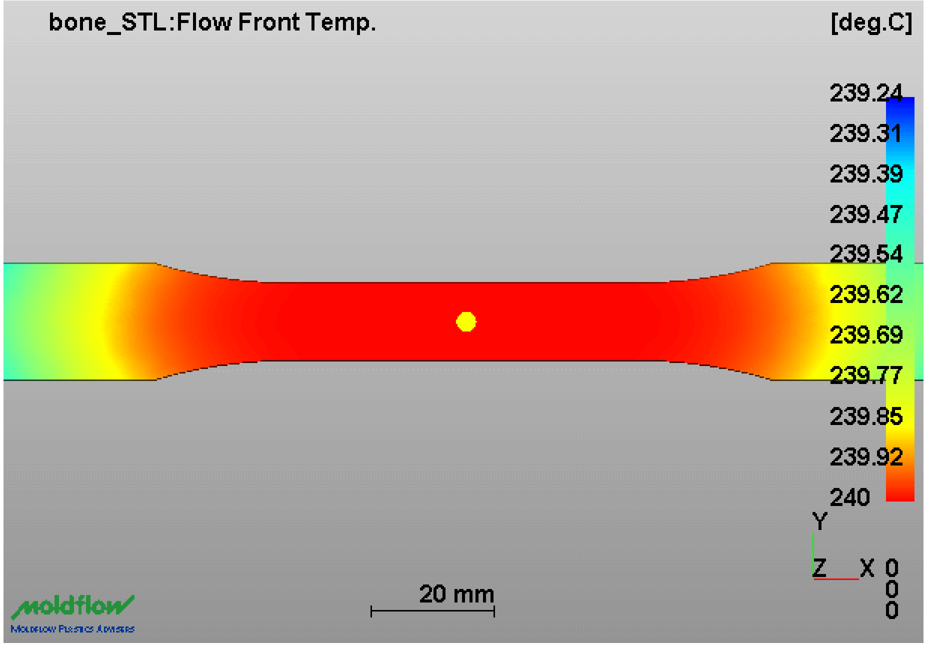

Figure 7. Flow front temperature results for pure polypropylene (Treatment 33).

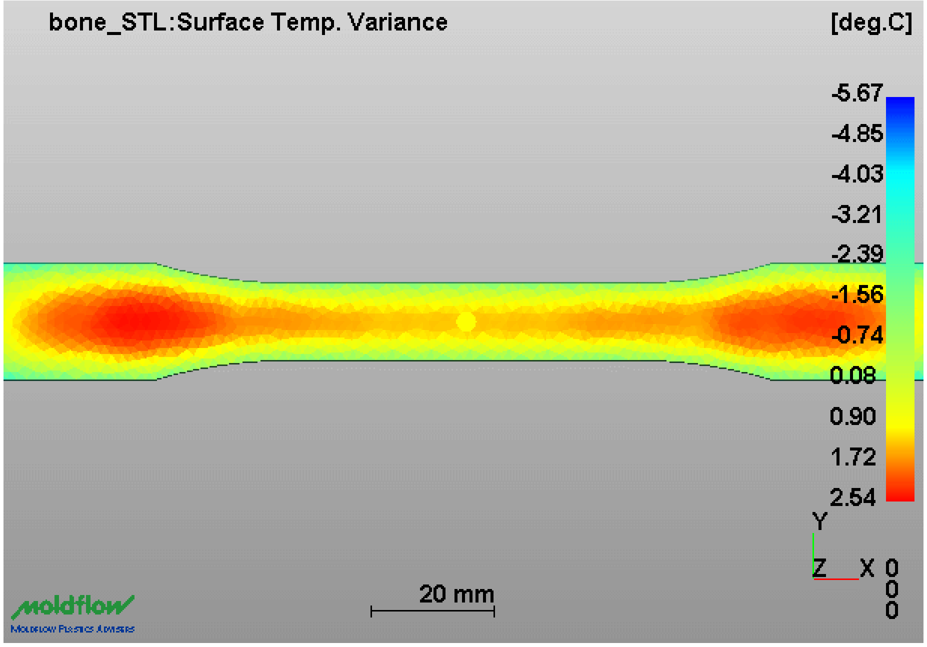

Figure 8. Surface temperature variance results for pure polypropylene (Treatment 33).

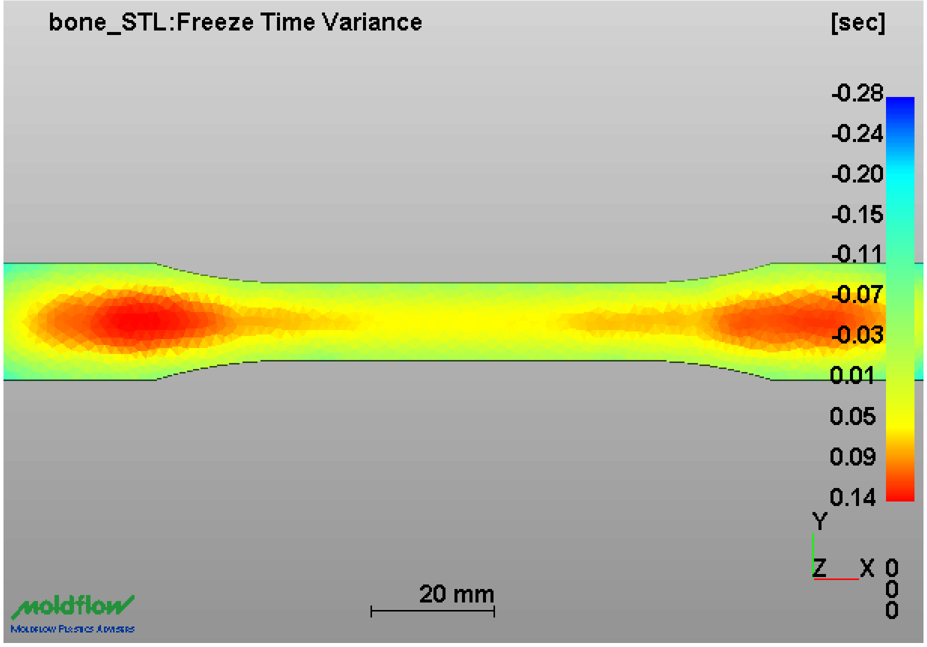

Figure 9. Freeze time variance results for pure polypropylene (Treatment 33).

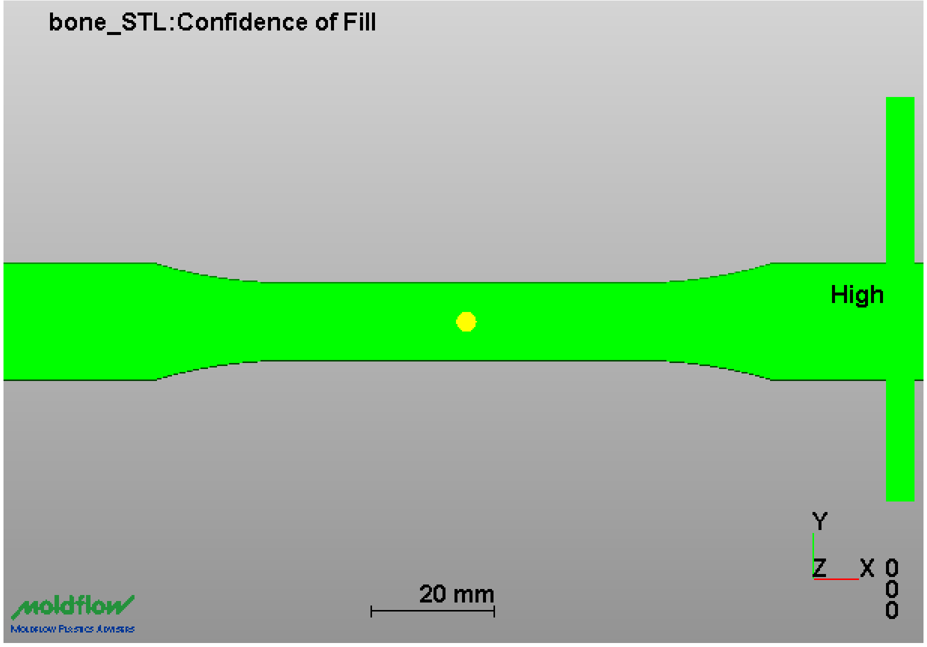

Figure 10. Confidence of fill results for pure polypropylene (Treatment 33).

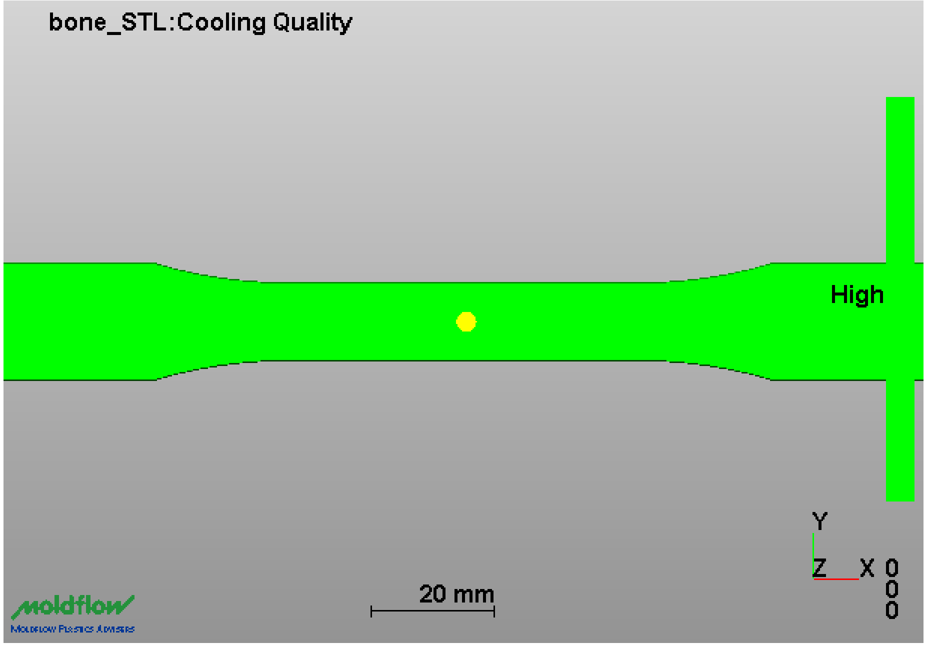

Figure 11. Cooling quality results for pure polypropylene (Treatment 33).

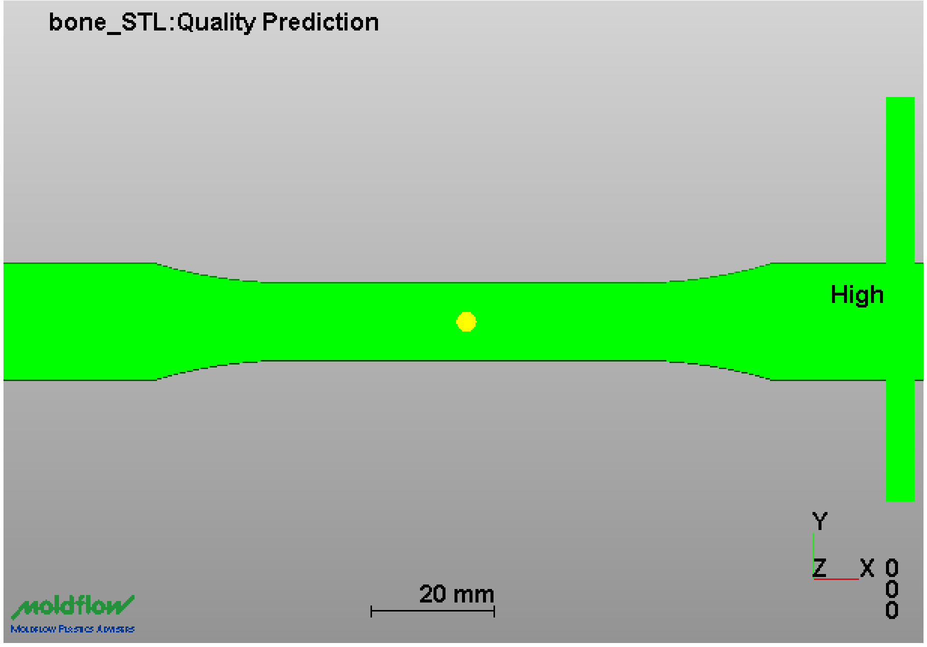

Figure 12. Quality prediction results for pure polypropylene (Treatment 33).

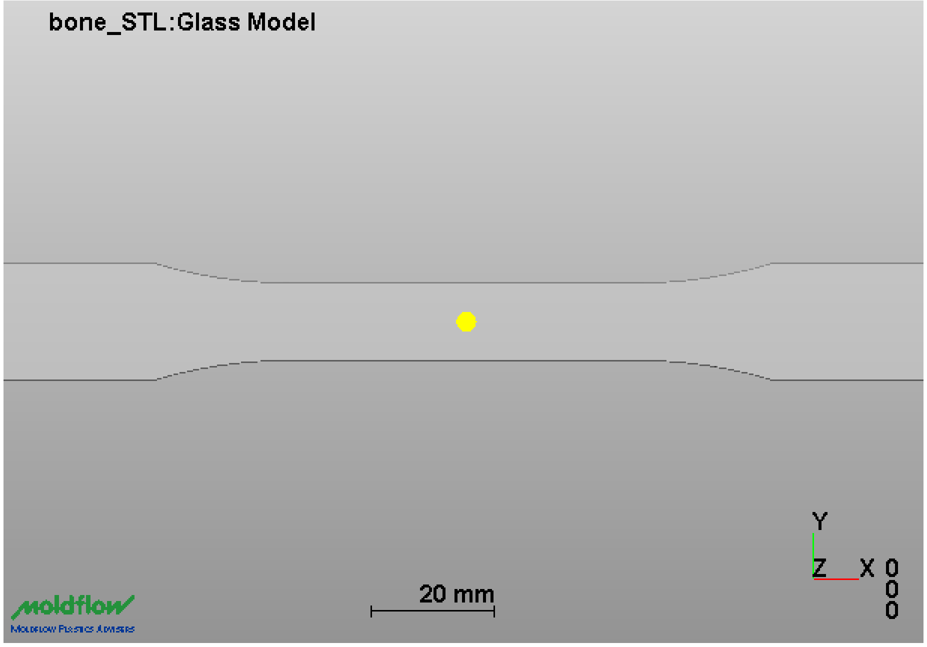

Figure 13. Weld lines results for pure polypropylene (Treatment 33).

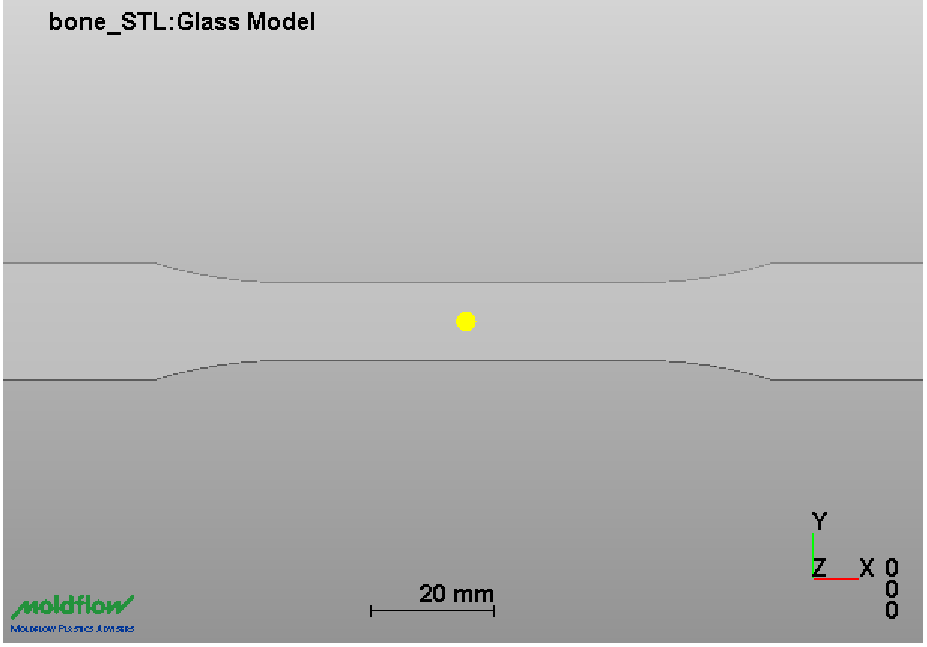

Figure 14. Air traps results for pure polypropylene (Treatment 33).

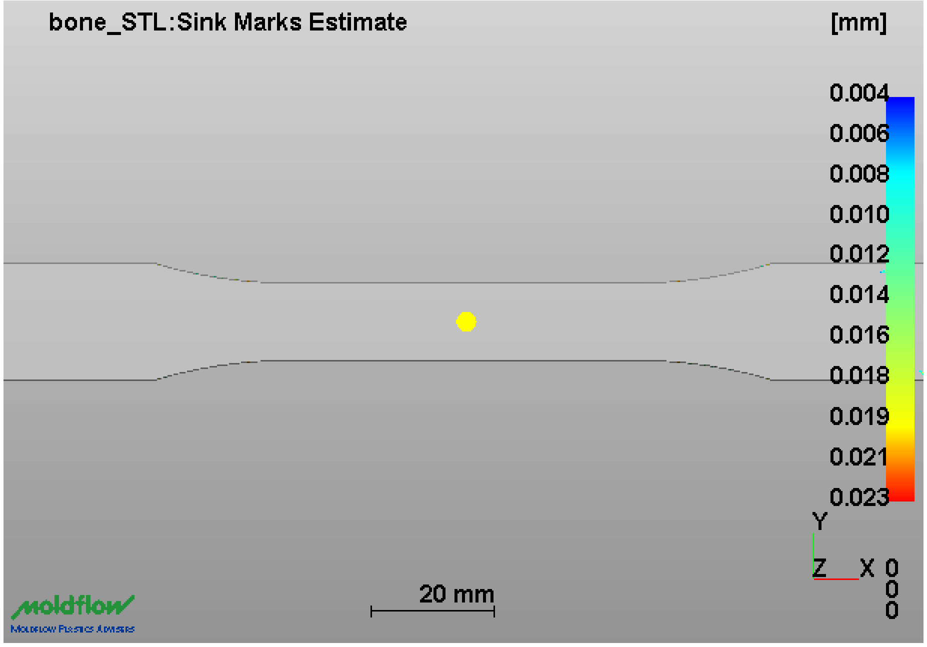

Figure 15. Sink marks estimate results for pure polypropylene (Treatment 33).

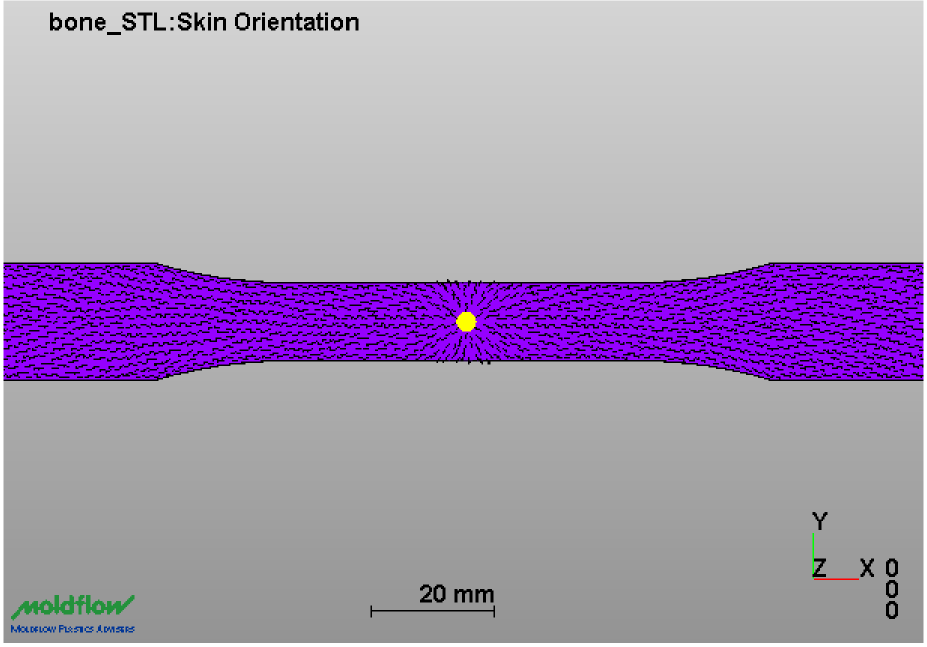

Figure 16. Skin orientation results for pure polypropylene (Treatment 33).