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ANALYSIS OF FLASH IN INJECTION MOLDING USING FLOW SIMULATION AND

DESIGN OF EXPERIMENTS

A Thesis

by

CLAUDIA LIZETTE LOPEZ

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ANALYSIS OF FLASH IN INJECTION MOLDING USING FLOW SIMULATION AND

DESIGN OF EXPERIMENTS

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August 2018

ABSTRACT

Lopez Claudia L., <u>Analysis of Flash in Injection Molding Using Flow Simulation and Design of Experiments.</u> Master of Science Engineering (MSE), August 2018, 158 pp., 7 tables, 35 figures, references, 26 titles.

This study presents a multi-stage experiment to predict and prevent the flash effect on injection molded parts. The latter is accomplished using a mold flow analysis simulation along with the Taguchi method and the full factorial analysis in order to identify the effects of processing parameters over flash. The first stage was to run the design of experiment (DOE) using the injection molding process simulation in the Moldflow analysis software. The second stage was to analyze the results and determine the significant factors by using the Taguchi experimentation, and verify the results with the full factorial design in order to find the most optimal conditions to avoid flash.

This thesis also describes how this experiment was applied to an actual live production molded part to reduce or eliminate the scrap issue that is presently happening on this part. The assumption was that melt temperature and pressure were the major causes of flash. After running the DOE, the results showed that the processing parameters that had the most significant effect were melt temperature and viscosity. Taguchi method and full factorial confirmed that, from these two processing parameters, viscosity had the greatest impact on flash appearance.

DEDICATION

The completion of my studies and this work would not have been possible without our Almighty God, who has given me the strength and the passion to dream big, and the love and support of my family. I dedicate this thesis to my beloved parents, for helping me in every step of the way. Thank you for your unconditional love and unselfish support. Los amo!

To my loving daughter, who has been my inspiration and motivation, and to whom I dream to accomplish far more that what I have accomplished thus far. Thank you for your unyielding love and keeping up with a very busy mom. I love you baby girl! Hasta la luna y de regreso.

To my husband, for his love and patience, and for always helping me and encouraging me to be the best version of myself. For letting me be who and how I am. For sharing my dreams, and for accepting and supporting the sometimes annoying feminist in me. For his willingness to put things on hold for me and for foolishly making me think I am his Wonder Woman. Te amo!

To my amazing brother and sister, to whom I hope I was at least a little help and inspiration in their lives and careers. I hope I was not too hard on you. I love you guys!

To those friends who answer my calls or texts in the middle of the day or night to help without expecting anything in return when I needed you the most. And to all those individuals who have helped me directly or indirectly in any way to complete this milestone in my life. THANK YOU!

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CHAPTER I

INTRODUCTION

Injection Molding

The plastic injection molding process is widely used and of great importance for the manufacturing process production of plastic parts in many applications in many areas such as automotive, sports, electronics and many more endless applications. Injection molding processing has many advantages, such as short production cycles, can be performed with many different types of materials, provides excellent surface of products and facilitates the molding of complicated shapes. The fabrication of plastic products through injection molding used in the manufacturing process consist mainly of three stages: filling and packing, cooling, and ejection. It starts by first feeding the plastic resin (pellets) into the injection machine. These plastic resins are heated to a melting point and then injected into a mold cavity through a screw. Once the melted resin has been injected entirely to the cavity, the mold is clamped under certain temperature and pressure to produce and eject the specified final part. These parameters can significantly affect the quality of the injection molded products.

Temperature and pressure distribution within the mold cavity along with the injection speed are the most critical factors. If the settings of the filling pressure or mold temperature are improper, it could lead to molding defects such as shrinkage, warpage, short shots, sink marks and flashes. This last one being the most important one in this study. The injection molding process will be explained in greater detail in a later section of this thesis.

On the road to identify how, where, and when this flash originates during injection molding, an organized procedure analysis was developed for the mold filling phase of the injection molding process. For this experiment, most processing variables were defined in the mold flow simulation by using the supplier's suggested parameters and all the responses that were obtained from it were also used to find the most optimal result for the molded part. These process parameters can be optimized individually or together using different approaches in order to improve the mechanical performance of final plastic parts.

To achieve this goal, a multi-stage experiment to predict and prevent the flash effect on injection-molded parts was performed. The first stage was to simulate the injection molding process of the molded part in the mold flow analysis software, and perform the design of experiment (DOE) by using the injection molding process simulation from Moldflow analysis software. The second stage was to analyze the results and determine the significant factors by using the Taguchi experimentation, and verify the results with the full factorial design in order to find the most optimal conditions to avoid flash. It is very important to use these two important tools together for better modeling and analysis of the manufacturing processes. DOE has been a very useful tool to analyze complicated industrial design problems. It helps us to understand process characteristics and to investigate how processing parameters affect responses based on statistical principles [1]. In this case, the experiment and analysis procedure developed would be an invaluable tool for both the design engineer in the industry who must approve the new critical input parameters for given design targets, as well as for the production engineer who has to optimize and monitor the production stage to successfully implement the new route that would be taken [2].

Leap Chair Ribbon

The problem that was investigated in this thesis, was also found on a Steelcase conference chair, the *Leap* chair. Because of its great ergonomic design and its remarkable features, it makes this chair one of Steelcase's most popular chairs in the market. However, throughout the years of its successful history in the field, some issues have been encountered along the way. One of the biggest issues that have risen is the scrap factor generated in the powder coating paint line by the defects appearing on the Leap Chair Ribbon (LCR) Fig 1. Because the root cause of why these defects are appearing on the molded part is still unknown, this part would be used as the testing sample on this experiment in order to find a possible solution that would eliminate or minimize the flash defect that is becoming a big concern in the injection molding process of this part.

Figure 1. Steelcase Leap Chair Ribbon (LCR)

These defects were quantified for the past three years, and they exceed $100,000 USD in less than three years, taking into account that fiscal year of 2018 for the company does not end until February 27 of 2019, and its monetary contribution because of the defects found is of $29,634 USD as shown in Figure 2.
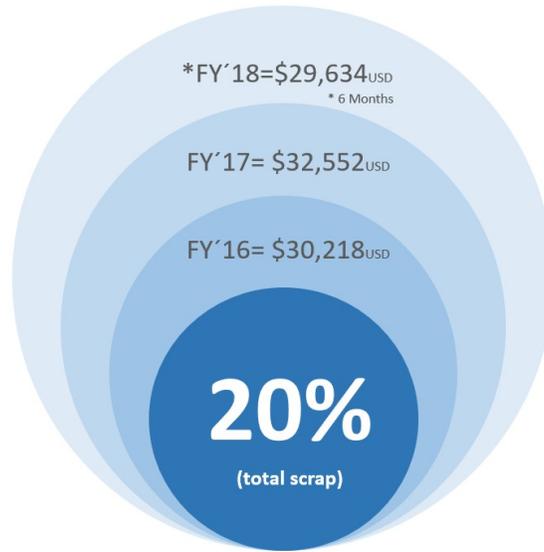
Figure 2. Leap ribbon yearly scrap factor

Leap Chair Injection Mold

Seeking for a solution that will solve the problem and find the real root cause to eliminate the issue, one step further was taken and the injection molding was evaluated as well. By doing this, it was found that the defect was in deed coming from the injection molding process. The injection mold had suffered wear and tear from the years of use and lack of preventative maintenance performed throughout the years of its working life cycle. Figure 3 shows the actual mold that is used to inject the LCR.

Figure 3. Steelcase Leap Ribbon Injection Mold

Two options were proposed in order to be evaluated and take a decision on which of them would be the best solution for the problem. Because of the noticeable damage on the injection mold, one of the suggested options was to create a completely new mold design with the old design as a baseline but adding newer and better technology that would avoid the problems the injection mold is currently having. The second option that was evaluated was to modify the existing injection molding resin that is currently in use (OMNI Plastics-Omnilon PA6 GR43 EF LV NA) to make it more efficient, and avoid having the defect appearing on the molded parts because of the resin properties' variables. This latter option allows us to keep the current mold design which would markedly lower the cost compared to the amount of money that would be expended if the whole mold is redesigned. So, the main goal to be achieved is to attempt to obtain better injection molding parts by keeping the current design and just monitor the most influential factors in the equation. The latter allowed for the experiment to be reproduced on this specific molded part using the same mold and the results obtained were very promising.

CHAPTER II

LITERATURE REVIEW

Overview

It is important to understand what has been done for similar problems and how it was analyzed in order to minimize flash. From here, the selected solution should fulfill the requirements stated earlier in this thesis. The purpose is to present the reader a few examples regarding filling, packing, and other analyses to compare and contrast their behavior, which were based on utilizing computer simulation packages, such as Autodesk Moldflow, and then compare them with and verify the results obtained with the design of experiment (DOE), to choose the best optimal solution for the presented problem [3]. The modern computational and simulation tools for injection molding process have advanced to a point where they can provide substantial insight into the process metrics and can be efficiently utilized to help improve the design of injection-molded components. Computer simulation like Moldflow has made a major impact on the design and manufacturing related to the injection molding process. Combining DOE and Moldflow to take advantage of both techniques is important when numerous factors affect the quality of the manufacturing process. It is necessary to look for optimal conditions because nowadays the competitive conditions force manufacturers to produce faster and cheaper with higher quality. Not to mention that when the process parameter settings are not suitable they can cause many

production problems such as product defects, which results in long lead times, and as consequence the higher cost of the products [1].

Injection Molding Process

Injection molding has been a common processing technique to produce plastic components. The cycle starts with the injection or filling phase during which the injection screw moves forward carrying molten material to be injected into the mold cavity. When the cavity is nearly filled, the packing phase commences by forcing further molten material into the cavity to compensate for the shrinkage of the part. When the packing is finished and no pressure is further maintained, the cooling phase commences. Although heat loss from the melt may occur from the onset of the cycle, during this phase, the remaining (largest amount of) heat from the material is removed until it is sufficiently solid to be ejected from the mold [3]. With the closure of the mold, the new injection molding cycle begins.

The number of products per time unit determines the yield of the process. Therefore, a shorter cycle time is often an objective. Thinner parts need shorter cooling time, which contribute to the trend of the miniaturization of components but need significantly higher injection speed.

Higher injection speeds are needed because during the injection of polymer melt into the cavity, the melt quickly solidifies when it comes in contact with the colder mold surface [4], which contributes to several types of defect, flash being one of those defects.

In Injection molding, flash is defined as additional unwanted material on the finished part, typically forming at the parting lines of injection molded parts where melt flows from the cavity into thin gaps between parting surfaces of the injection molding tool. To avoid the formation of potential flash issues, it is necessary to ensure that the mold plates fitting is correct

and also by making sure the mold is sealing properly and without any obstructions. To achieve this, the mold plates should have adequate surface area that seal off at the parting line, evenly distributing the clamp force during molding. By reducing the injection and packing pressure, it directly reduces the clamp force requirement. Reducing the injection pressure reduces the tendency for the material to produce flash.

Previous studies showed that controlling pressure and injection velocity are the most influential parameters with a direct effect for the materials. However, other research has shown that for certain materials, the injection speed and packing pressure were the most influential parameters for increasing the amount of flash formation. Higher melt and mold temperature settings were less influential parameters for increasing the flash amount when molding these tested materials.

The factors that were most investigated by researchers have been mainly: melt and mold temperature, injection velocity, holding pressure and holding time. Each study has found a different set of significant parameters. The latter is probably due to the fact that different experimental investigations have employed tools with different mould design features (i.e., sprue and runner dimensions, gate design, cooling/heating layout, etc.) as well as different cavity geometry design [5].

Injection Mold

In a typical injection molding machine, the polymer feedstock, in the form of loose granules, is fed into the barrel from the hopper as shown in Figure 4. Initially, it is pushed by the rotating screw and moves along the barrel in an Archimedian manner toward the mold where it is heated and melted. From the entry of feedstock to the nozzle, the barrel and screw will contact, respectively, with solid polymer and semi-molten and molten polymers. Abrasive wear can occur as hard fillers in the polymer are pressed and slid against the barrel and screw surface. The

features of this abrasion may change due to the different contacting situations along the barrel. In addition, the screw may also vibrate in the barrel leading to metal-to-metal contact between them, so that impact wear and adhesive wear may occur. Attack by corrosion is possible from the polymer matrix or any other additives, especially as temperatures can increase up to 250°C near the nozzle depending on the polymer being processed [6].
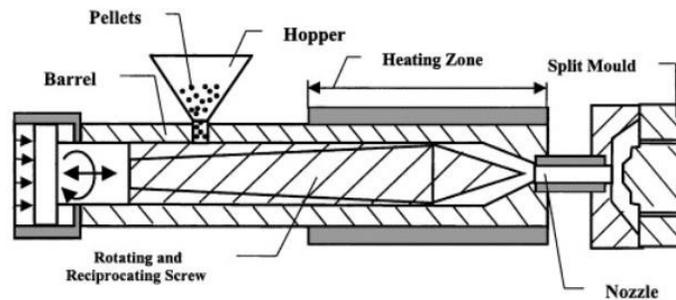

Figure 4. Schematic of an Injection Molding Machine

Moldflow

MoldFlow is a finite element software in computer-aided engineering (CAE) which can simulate injection mold flow conditions. The processing parameters that affect the quality of injection molding products include cooling time, injection pressure, injection speed, injection time, filling time, melt temperature, ejecting pressure, mold temperature, mold geometry shape, material property of melt, melt speed, and heat transfer action of flow field. It was suggested on previous papers that filling time, melt temperature, mold temperature and injection pressure are the significant control factors that can affect flash and mechanical properties. In this study, the software is employed to predict the flash coming from pressure and fill time of the component. In the MoldFlow analysis, only the injection time, melt temperature, mold temperature and injection pressure are imported to the MoldFlow software. The plastic materials are taken as the

material being injected. The parameters of processing conditions and plastics have a numerous values. This study used the Taguchi method and full factorial design of experiments (DOE) to acquire the optimal results [7].

Research Methods

The methodology presented in this thesis includes two DOEs: Taguchi's method and a full-factorial design of experiments. These two DOEs were used to find the most significant factors to develop a regression model in order to find the most optimal solution along with the Moldflow analysis.

The Taguchi' method has been used broadly in engineering analysis to optimize the performance characteristics through setting of important processing and design parameters. Taguchi's method consists of three stages including system, parameters, and tolerance designs. The system design involves the application of scientific and engineering knowledge required in the manufacturing of a product. This method is used to find optimal process values and for the improvement of the quality of the product. The tolerance design is used for analyzing the tolerances associated with optimal settings that were initially recommended by the parameter design phase. Taguchi's method is usually used to identify the significant factors for quality characteristics of the products.

A full factorial design is employed to reduce the total number of experiments in order to achieve the best overall optimization of the process. The principal steps of statistically designed experiments are determination of response variables, factors and factor levels, choice of the experimental design, and statistical analysis of the data. Once the analysis is completed, the user determines which factors have important effects on a response as well as how the effect of one

factor varies with changes in the level of the other factors. The determination of interactions of factors can be important for successful system optimization.

The regression analysis has the purpose of determining the quantitative relations between the investigated values and the variables that directly influence them to assess the results of their activity and to predict the behavior of the investigated variables. Regression analysis is also one of the most commonly used statistical tools because it provides simple methods for establishing functional relationship among variables. It can be used to develop a more suitable model to predict the dependent variables from a set of independent variables [2].

Summary

With a better understanding of what this experimental design involves, it is now easier to picture what the problem is and what steps are needed to be taken in order to solve it. It was explained earlier how the injection molding of parts occurs, what problems can be encountered within the process, and how to find a solution that would work for each specific problem. In this study, the solution that was explored was to take advantage of the MoldFlow analysis simulation and combining it with other analysis such as Taguchi's method and full-factorial DOE in order to determine the optimal injection molding conditions different resin materials in order to avoid flash in the finished molded parts. Hence, the best material chosen to test and approve was the one selected based on the results obtained from the most significant value of viscosity, which had the greatest effect on pressure and time and subsequently on flash.

CHAPTER III

METHODOLOGY AND FINDINGS

Setup

For this study, it was decided to focus on modifying the existing mold resin used in the real LCR, and to find the most optimum resin from the results obtained from the different methods of analysis in order to eliminate or reduce the flash issue. The type of processing variables to evaluate are the ones mentioned previously; i.e. temperature, pressure, mold temperature, melt temperature, viscosity, and injection speed or fill time. Warpage, shrinkage, and other properties will also be considered during this experiment in order to decide what would be the best and most cost effective solution. It will also be necessary to examine the changes occurring in the experiment in order to decide on the optimal resin that would be selected to replace the one currently in use. Changing the viscosity of the resin would permit us test the effect of rheological parameters of the specimens and how it will affect the other variables that are being monitored in this experiment. As mentioned earlier, the objective of this study is to obtain the optimal temperature and pressure data with the acquired modeling correlations, and to confirm the accuracy and the improvement in the data from the numerical simulation for the injection-molding process in the Mold flow software in order to implement in the future production LCR.

The properties of the following polymers: Akulon K224-HG6U BK223 J-3/30/HS BK223 (sample I), Unitika Nylon6 FR-RUNG50LWJ (sample II), and Novamid-1040H2 (sample III), shown in Table 1, will be measured and tested through both the online testing mold and a conventional testing method in order to obtain more accurate data. Moldflow software simulations were carried out, and the results for the temperature and pressure obtained were examined and compared with the actual simulation of the actual prototype mold that was designed for this testing experiment.

Table 1. Specimen Sample Conditions

	Sample I	Sample II	Sample III
Family name	POLYAMIDES (NYLONS, PPA, …)	POLYAMIDES (NYLONS, PPA,…)	POLYAMIDES (NYLONS, PPA,…)
Trade name	Akulon K224-HG6U BK223 (J-3/30/HS BK223)	Unitika Nylon6 FR-RUNG50LWJ	Novamid-1040H2
Manufacturer	DSM EP (Americas)	Unitika	DSM Japan Engineering Plastics
Link			
Family abbreviation	PA6	PA6	PA6
Material structure	Crystalline	Crystalline	Crystalline
Data source	Moldflow (Formerly C-Mold) :pvT-Measured: mech-Measured	Manufacturer (Unitika) : pvT-Supplemental : mech-Measured	Manufacturer (DSM Japan Engineering Plastics) : pvT-Measured: mech-Supplemental
Data last modified	11-Oct-05	13-Sep-11	15-Sep-11
Date tested	7-Apr-98	28-Oct-09	
Data status	Non-Confidential	Non-Confidential	Non-Confidential
Material ID	6526	13849	2987
Grade code	CM6526	CM13849	CM2987
Supplier code	DSMEPA	UNITIKA	MITSUBI
Fibers/fillers	33% Glass Fiber Filled	50% Glass Fiber Filled	Unfilled

These polymers were chosen because of their similarity to the current resin used to mold the LCR plastic part. More information on their properties such as rheological properties, thermal properties, pvT properties, mechanical properties, and shrinkage properties can be found in the Appendix A of this thesis.

Moldflow Analysis

Moldflow plastic injection molding simulation software helps designers and engineers improve plastic parts, compression molds, and injection mold designs. Mold Flow Analysis is the process whereby a part, tool design and material is modeled in a computer and the molding process is then simulated. Mold flow and simulation is a critical aspect of efficient mold design and build operations, which helps in identifying problems and improvements before the mold is built. This methodology allows the engineer to experiment with the part and/or tool design to determine the most optimal process that will yield the best results [8].

With the three different materials already chosen, the next step was to carry out the analysis for the fill time, pressure, and temperature in order to compare the calculated results to the ones given by the Mold flow software. The temperature of the molded parts at the time of ejection is a complex function of the molded part design, cooling line design, material properties, and processing conditions. While high heat transfer rates are desired, an overly aggressive cooling system design can actually cause quality problems. This latter is one of the main reasons why many different combinations of melt temperature and mold temperature had to be considered for this experiment. As the cooling lines approach the mold cavity surface, the heat transfer path between the surface and the cooling line becomes more direct. As a result, there can be a great variation in the temperature across the cavity surface unless the cooling lines are also

placed very close together. When flash occurs in the molded parts due to variations in parameters, especially temperature parameters, the molder often has no choice but to run longer cycle times and use the mold as a cooling fixture. Because of this, and in order to find the most optimal conditions, the more experimental runs that can be completed, the better the results acquired.

The flash of molded plastic parts is governed primarily by the temperature and viscosity of the plastic, the compressibility of the plastic at packing pressures, and by the poor condition of the mold metal cavities. Sub-optimal molding conditions due to material viscosity, injection rate, and the runner system can reduce pressures and shot size to the minimum required. Ideally, a shot size would equal 50% of the capacity of the barrel. However, this depends on the material being used. As this ratio drops the time of residence for the material in the barrel, the pressure increases, and the material gets hotter. It will flow much easier and enter areas where it could not at its normal viscosity. It would be necessary to reduce the injection and packing pressure to reduce the clamp force requirement. If too much pressure is used, the press may not be able to hold the mold closed. By reducing the injection pressure, the tendency for the material to flash is reduced. Also, reducing the area where the two mold halves are touching will focus the clamp-force and allow less clamp tonnage to be used [11].

Moreover, once the pressure drop through the feed system is analyzed, it is possible to adjust the feed system design to improve the performance. Multiple repetitions of design and analysis in moldflow must be conducted to obtain a design that provides a low pressure drop while consuming very little material in order to find the optimal formula that would help find the answer to avoid flashing on the plastic molded parts. Multivariate optimization is a numerical technique that can be employed to simultaneously minimize the pressure drop while minimizing

the runner volume. However, this approach requires time to implement and validate while suppressing the details of the analysis from the designer [12].
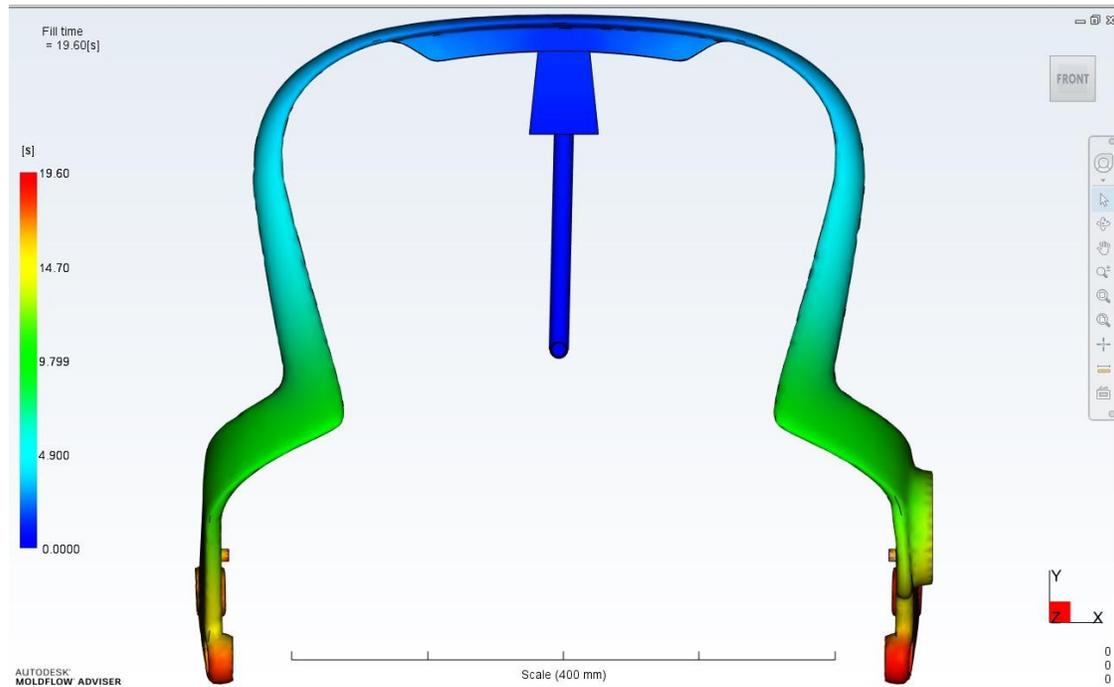
Figure 5. Sample #1 Tested in Moldflow

Figure 5 shows the results of the fill time obtained from running the leap ribbon's first trial (sample #1) with low mold temperature, low melt temperature, low viscosity and low injection speed. As shown in the figure, the results display how the fill time goes from 0.00 to 19.60 seconds, which will be compared to all the other remaining eighty samples in order to discover which sample will be the most adequate to replace the current resin used in Royal Plastic Technologies to mold the LCR plastic parts.
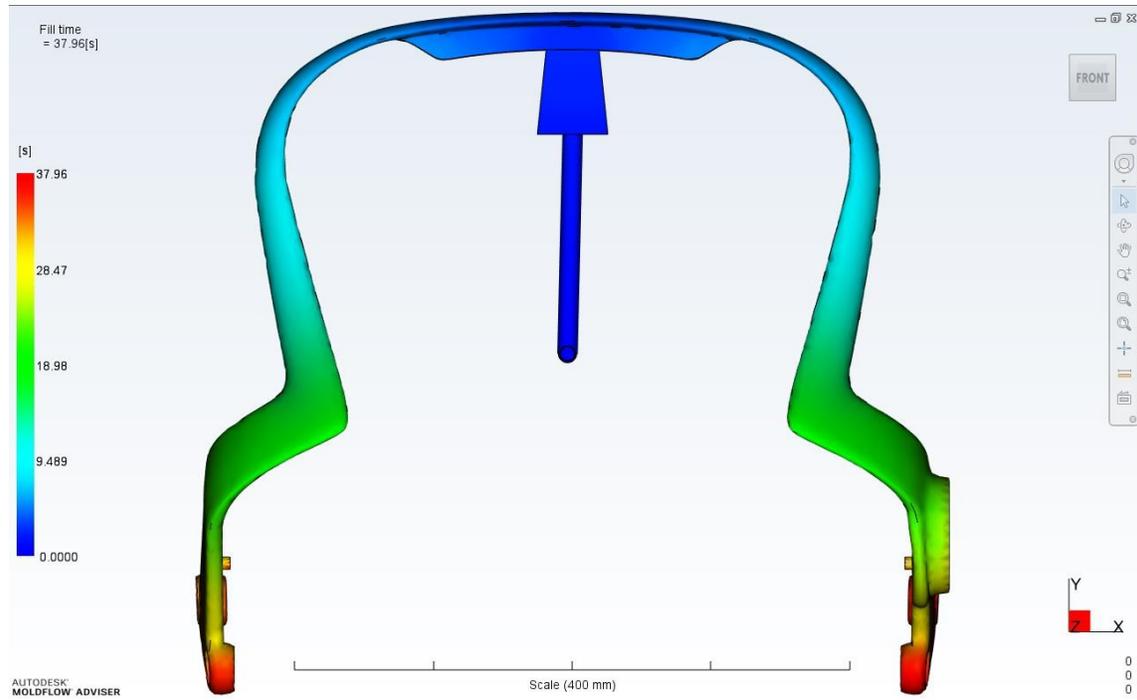
Figure 6. Sample #41 Tested in Moldflow

Figure 6 shows the results of the fill time obtained from another leap ribbon's trial (sample #41). This trial was run at medium mold temperature, medium melt temperature, medium viscosity and medium injection speed. As shown in this figure, the results display how the fill time goes from 0.00 to 37.96 seconds. A very notable difference of almost twenty seconds between sample 1 and sample 41 can be perceived. However, there is not enough information to discard one sample over the other one from this data, or decide which sample would be a better option to substitute the resin that is currently used in the injection mold process, because other samples showed similar behavior for this reason other testing methods will be used in order to decide which combination (sample) is the optimum solution.
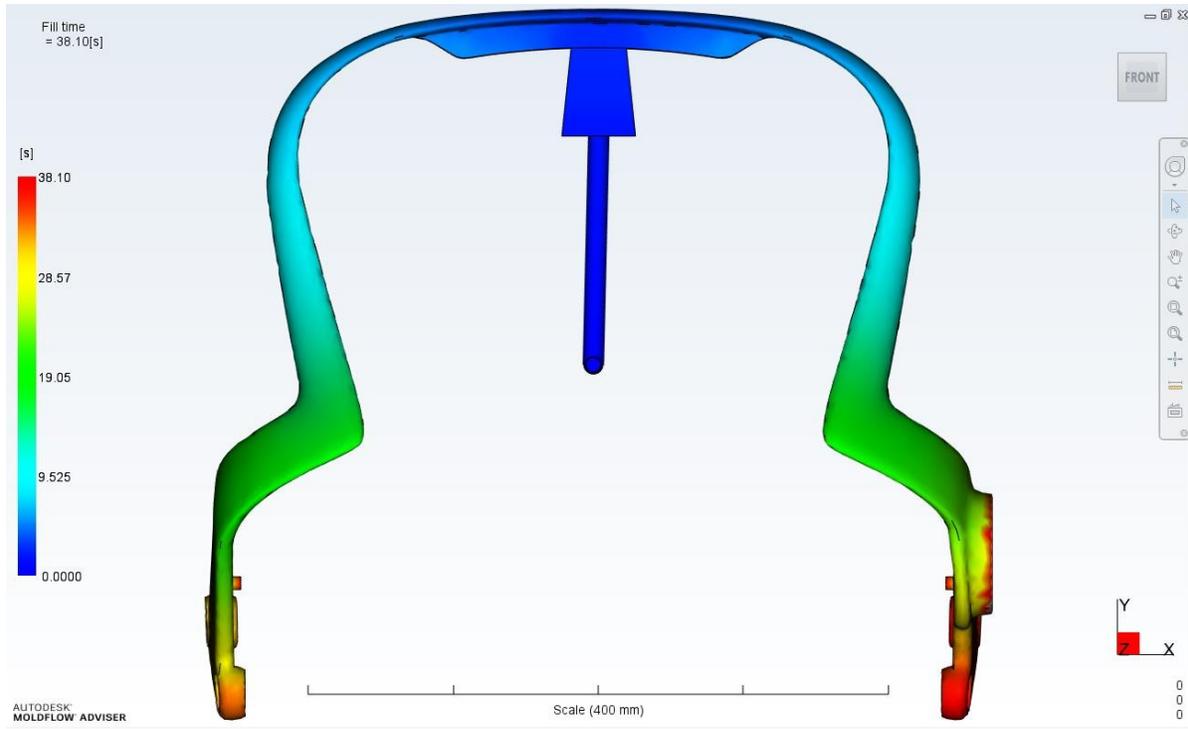
Figure 7. Sample #81 Tested in Moldflow

Figure 7 illustrates the results obtained of the fill time from a third leap ribbon's trial (sample #81). This trial was run at high mold temperature, high melt temperature, high viscosity and high injection speed. As shown in the figure, the results display how the fill time goes from 0.00 to 38.10 seconds. The difference between sample #41 and sample #81 is almost null, but the same twenty seconds between sample 1 and sample 81 remain. There is not a clear relationship between one sample to another to make a conclusion, but there are 78 other samples to evaluate in order to find the correct substitute for the resin to avoid the defects that are showing in the LCR plastic part.

Results

Eighty-one samples were run in the moldflow analysis software based on the response of the three levels and four factors of the full factorial design of experiment. Table 4 summarizes the eighty-one different combinations that were tested in the moldflow simulation software. What full factorial design of experiment (DOE) does is measure the response of every possible combination of an "*n*" number of factors and an "*n*" number of levels. These responses are then analyzed to provide information about every main effect and every interaction effect. A full factorial DOE is practical when fewer than five factors are being investigated. Testing all combinations of factor levels becomes too expensive and time-consuming with five or more factors [13]. For this experiment, it is worth performing the complete full factorial because it is important to analyze all the different options that can be considered during the injection molding process that is being analyzed.

Table 2. Samples Tested in Moldflow

Values	70, 80, 90 (°F)	265, 275, 285 (°F)	171, 209, 471 (MFI)	10, 15, 20 (sec)		
Sample	Mold Temp	Melt Temp	Viscosity	Injection speed	Time (sec)	Pressure (MPa)
1	Low	Low	Low	low	12.32	35.43
2	Low	low	Low	medium	18.5	34.27
3	Low	Low	low	high	24.73	33.77
4	Low	Low	medium	low	12.07	41.74
5	Low	Low	medium	medium	18.14	39.73
6	Low	low	medium	high	24.19	39.28
7	Low	Low	high	low	12.7	79.6
8	Low	low	high	medium	19.09	78.5
9	Low	Low	high	high	25.56	80.51
10	low	medium	low	low	12.32	31.27
11	Low	medium	Low	medium	18.5	29.83

12	Low	medium	Low	high	24.73	29.2
13	Low	medium	medium	Low	12.08	37.05
14	low	medium	medium	medium	18.15	35.37
15	low	medium	medium	high	24.22	35.3
16	Low	medium	high	low	12.67	72.72
17	low	medium	high	medium	19.08	72.92
18	low	medium	high	high	25.53	73.19
19	low	high	low	low	12.33	27.75
20	Low	high	Low	medium	18.5	25.93
21	Low	high	Low	high	24.73	25.21
22	Low	high	medium	low	12.1	32.73
23	low	high	medium	medium	18.17	30.89
24	low	high	medium	high	24.23	30.63
25	Low	high	high	Low	12.66	66.09
26	low	high	high	medium	19.06	66.69
27	low	high	high	high	25.49	66.66
28	medium	low	low	low	12.3	34.58
29	medium	Low	Low	medium	18.48	33.45
30	medium	low	Low	high	24.69	32.54
31	medium	Low	medium	Low	12.07	40.68
32	medium	low	medium	medium	18.11	38.6
33	medium	low	medium	high	24.19	37.74
34	medium	Low	high	low	12.69	79.02
35	medium	low	high	medium	19.05	77.64
36	medium	low	high	high	25.52	79.19
37	medium	medium	Low	Low	12.31	30.39
38	medium	medium	low	medium	18.48	28.91
39	medium	medium	low	high	24.72	28.09
40	medium	medium	medium	low	12.08	36.1
41	medium	medium	medium	medium	18.16	34.25
42	medium	medium	medium	high	24.2	33.71
43	medium	medium	high	low	12.66	72.43
44	medium	medium	high	medium	19.05	71.61
45	medium	medium	high	high	25.46	72.14
46	medium	high	Low	low	12.32	27.17
47	medium	high	low	medium	18.49	25.09
48	medium	high	low	high	24.7	24.23
49	medium	high	medium	low	12.08	31.91
50	medium	high	medium	medium	18.16	29.82

51	medium	high	medium	high	24.22	29.23
52	medium	high	high	low	12.65	65.79
53	medium	high	high	medium	19.03	65.67
54	medium	high	high	high	25.43	65.33
55	high	low	low	low	12.29	34.16
56	high	low	Low	medium	18.44	32.27
57	high	Low	Low	high	24.66	31.4
58	high	Low	medium	low	12.06	39.68
59	high	low	medium	medium	18.11	37.3
60	high	low	medium	high	24.16	36.22
61	high	Low	high	Low	12.68	78.11
62	high	low	high	medium	19.01	76.58
63	high	low	high	high	25.46	77.71
64	high	medium	Low	low	12.3	29.83
65	high	medium	low	medium	18.46	28.04
66	high	medium	low	high	24.66	27.03
67	high	medium	medium	low	12.06	35.34
68	high	medium	medium	medium	18.11	33.05
69	high	medium	medium	high	24.18	32.14
70	high	medium	high	low	12.64	71.8
71	high	medium	high	medium	19.02	70.64
72	high	medium	high	high	25.41	70.62
73	high	high	Low	Low	12.31	26.44
74	high	high	low	medium	18.44	24.27
75	high	high	low	high	24.66	23.27
76	high	high	medium	low	12.08	31.09
77	high	high	medium	medium	18.12	28.73
78	high	high	medium	high	24.21	27.83
79	high	high	high	low	12.64	65.35
80	high	high	high	medium	19	64.58
81	high	high	high	high	25.38	63.99

Mold temperature was set up as low (70ºF), medium (80ºF), and high (90ºF) divided into four

sets of 27 samples each. After that, each 27 samples were divided into sets of nine of low

(265ºF), medium (275ºF), and high (285ºF) melt temperature. Then, those nine samples were

divided into sets of three different viscosities, low (MFI 171), medium (MFI 209), and high (MFI

471). MFI stands for Melt Flow Index which is a measure of the ease of the flow of the melt of a thermoplastic polymer. Those three different viscosities had three more different variables of injection speed with a low (10 sec), medium (15 sec), and high (20 sec). All of those 81 different combinations were tested in moldflow and some of the results are shown in Figure 5, Figure 6, and Figure 7. The rest of the results of the experiment can be found in Appendix B of this thesis.

After running the 81 trials of the three different materials and the four different variables, the results obtained for melt flow time and pressure are shown hereafter. Figure 8 depicts the line graph of the melt flow time as a function of melt temperature at various mold temperature, low viscosity, and low injection speed. The melt flow time at medium and high mold temperatures showed a steady and significant rise at different melt temperatures, while the melt flow time at low mold temperature experienced a decrease at different melt temperatures. From low to medium melt temperature, the medium and high mold temperature increased at a similar rate, and from medium to high melt temperature, the high mold temperature the melt flow time increased but at medium mold temperature it remained steady. On the other hand, with a different behavior, the melt flow time from low to medium melt temperature of the mold temperature decreased and from medium to high melt temperature the melt flow time remained steady. Figure 9 shows the line graph of the melt flow time as a function of melt temperature at various mold temperature, medium viscosity and medium injection speed. The melt flow time at low, medium, and high mold temperatures showed a steady decrease at different melt temperatures. All mold temperatures decreased from low to medium melt temperature, the high mold temperature showing the higher change in time. At high melt temperature, the low and medium mold temperature had a steady decrease in melt flow time but at high mold temperature, the decrease in melt flow time exhibited the greatest change of all three mold temperatures.
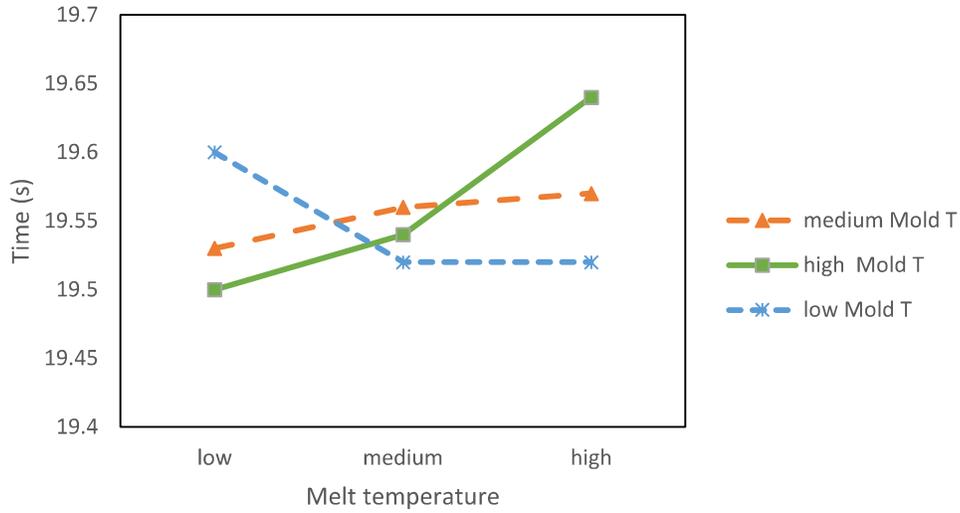
Figure 8. Melt Flow Time as a Function of Melt Temperature at Various Mold Temperature, Low Viscosity, and Low Injection Speed
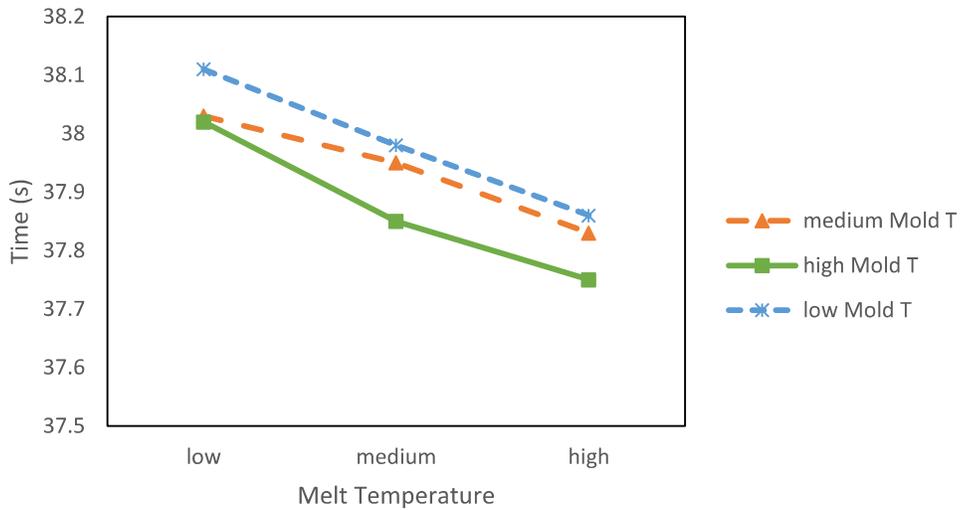
Figure 9. Melt Flow Time as a Function of Melt Temperature at Various Mold Temperature, Medium Viscosity, and Medium Injection Speed

Figure 10 displays the line graph of the melt flow time as a function of melt temperature at various mold temperature, high viscosity and high injection speed. The melt flow time at medium and high mold temperature showed a steady and almost insignificant rise at different melt temperatures, while the melt flow time at low mold temperature experienced a minimal

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decrease to then rise back to its same melt flow time. At low and medium melt temperature of the medium and high mold temperature had no change in melt flow time, but at high melt temperature, both of their melt flow time increased by a very small difference. On the other hand, the melt flow time from low to medium melt temperature decreased to then rise back to its same melt flow time at high melt temperature
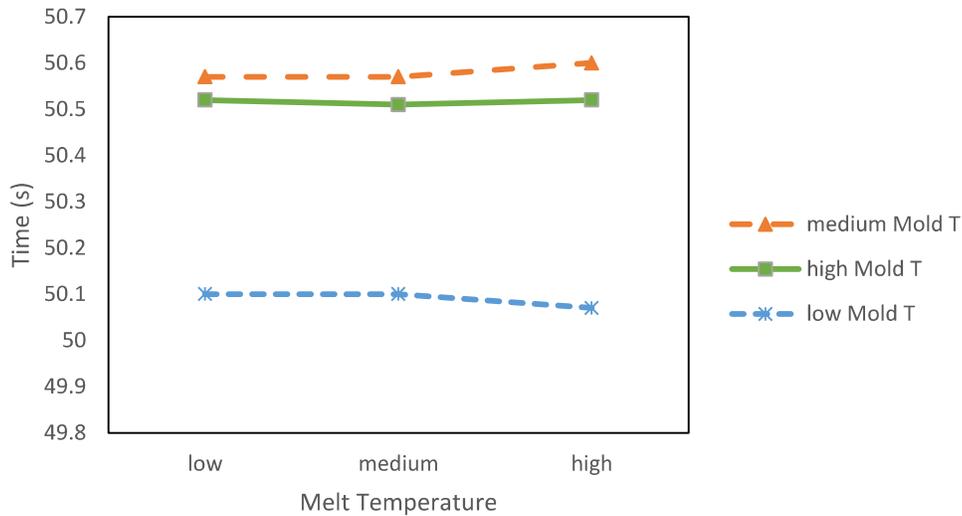
Figure 10. Melt Flow Time as a Function of Melt Temperature at Various Mold Temperature, High Viscosity, and High Injection Speed

Figure 11 shows the line graph of the pressure in cavity as function of melt temperature at various mold temperature, low viscosity and low injection speed. The pressure in the cavity at low, medium, and high mold temperature showed a steady but significant decrease at different melt temperatures. The pressure in the cavity at low mold temperature shows the higher pressures at all different melt temperatures, followed by the medium mold temperature and at high mold temperature the pressure had the lowest pressures in the cavity. The pressure in the cavity in all mold temperatures decreased from low to high melt temperature from the 50 MPa to the 40 MPa.

Figure 12 illustrates the line graph of pressure in cavity as function of melt temperature at various mold temperature, medium viscosity and medium injection speed. The pressure in the cavity at low, medium, and high mold temperature showed a steady but significant decrease at different melt temperatures. The pressure in the cavity at low mold temperature shows the higher pressures at all different melt temperatures followed by the medium mold temperature and at high mold temperature the pressure had the lowest pressures in the cavity. The pressure in the cavity in all mold temperatures decreased from low to high melt temperature from the 80 MPa to the 60 MPa.

On figure 13 the graph illustrates the pressure in cavity as function of melt temperature at various mold temperature, high viscosity and high injection speed. The pressure in the cavity at low, medium, and high mold temperature showed a steady but significant decrease at different melt temperatures. The pressure in the cavity at low mold temperature shows the higher pressures at all different melt temperatures, followed by the medium mold temperature and at high mold temperature the pressure had the lowest pressures in the cavity. The pressure in the cavity in all mold temperatures decreased from low to high melt temperature from the 50 MPa to the 40 MPa
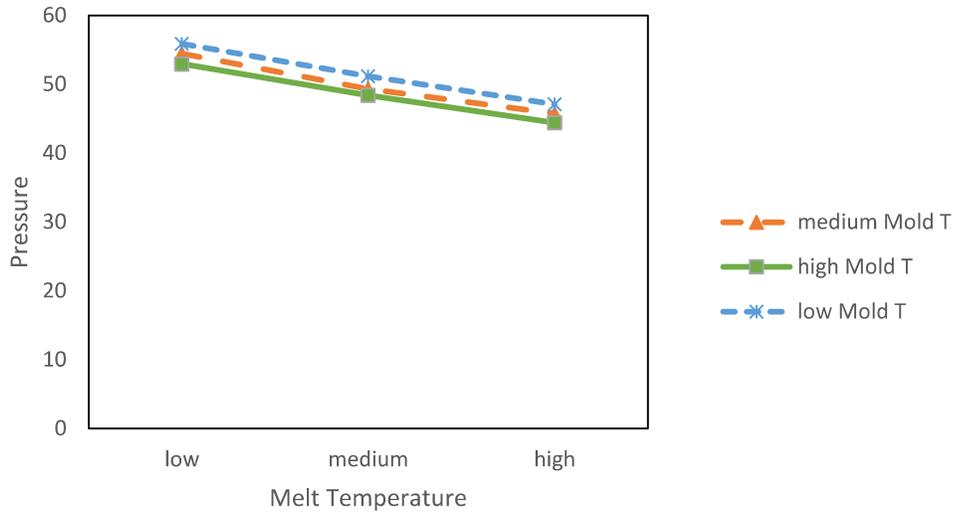
Figure 11. Pressure in Cavity as Function of Melt Temperature at Various Mold Temperature, Low Viscosity, and Low Injection Speed.
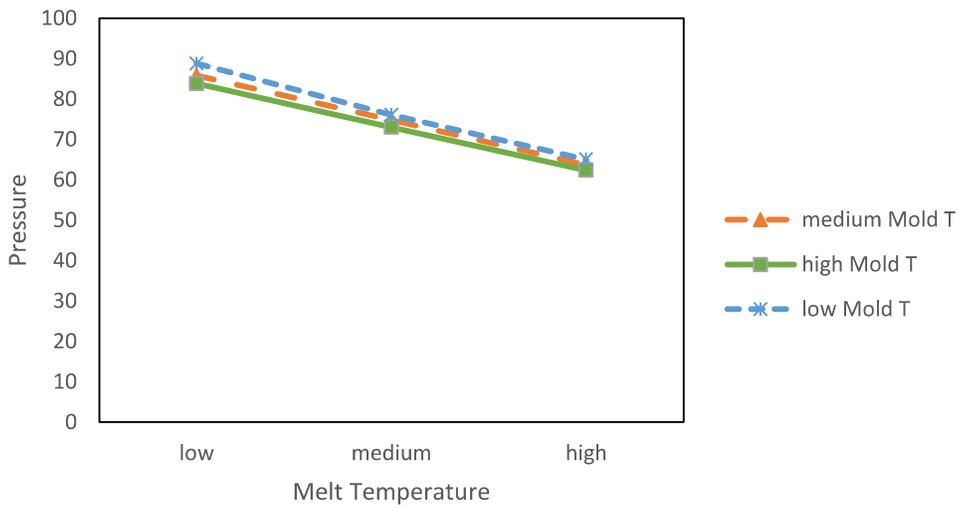
Figure 12. Pressure in Cavity as Function of Melt Temperature at Various Mold temperature, Medium Viscosity, and Medium Injection Speed.
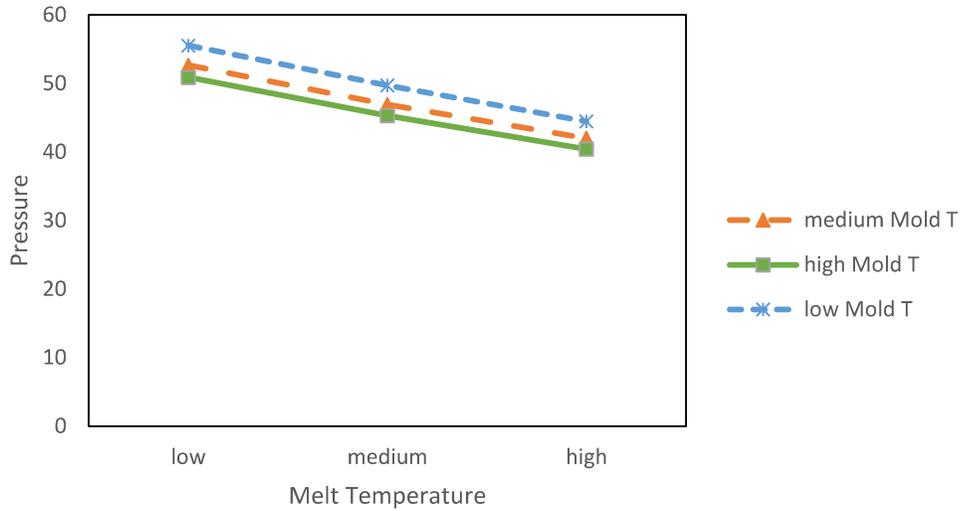
Figure 13. Pressure in Cavity as Function of Melt Temperature at Various Mold Temperature, High Viscosity, and High Injection Speed.

Figure 14 shows the line graph of the melt flow time as a function of viscosity at various mold temperature, at low melt temperature and low injection speed. The melt flow time at low medium and high mold temperature showed a steady but significant decrease at different viscosities. The melt flow time from low to medium melt temperature of the mold temperature decreased and remained steady from medium to high melt temperature in all different viscosities. The low mold temperature having the higher times, followed by the medium mold temperature and the high mold temperature with the lowest melt flow times.

Figure 15 displays the line graph of the melt flow time as a function of viscosity at various mold temperature, at medium melt temperature and medium injection speed. The melt flow time at low and medium mold temperature showed a steady but significant decrease at different viscosities. At high mold temperature, the melt flow also decreases, but then increases at high viscosity. The melt flow time from low to medium melt temperature of the mold temperature decreased and remained steady from medium to high melt temperature in all

different viscosities. At high mold temperature, the melt flow time also decreased from low to medium viscosity, and increased back at high viscosity.

Figure 16 illustrates the line graph of the melt flow time as a function of viscosity at various mold temperature, at high melt temperature and high injection speed. The melt flow time at low and medium mold temperature showed a steady but significant decrease at different viscosities and then increased back. At low mold temperature, the melt flow also decreases, but never increased back. The melt flow time from low to medium melt temperature of the mold temperature decreased and remained steady from medium to high melt temperature in all different viscosities. At high and medium mold temperature, the melt flow time increased from medium to high viscosity, but the low mold temperature continues to decrease at this same viscosity.
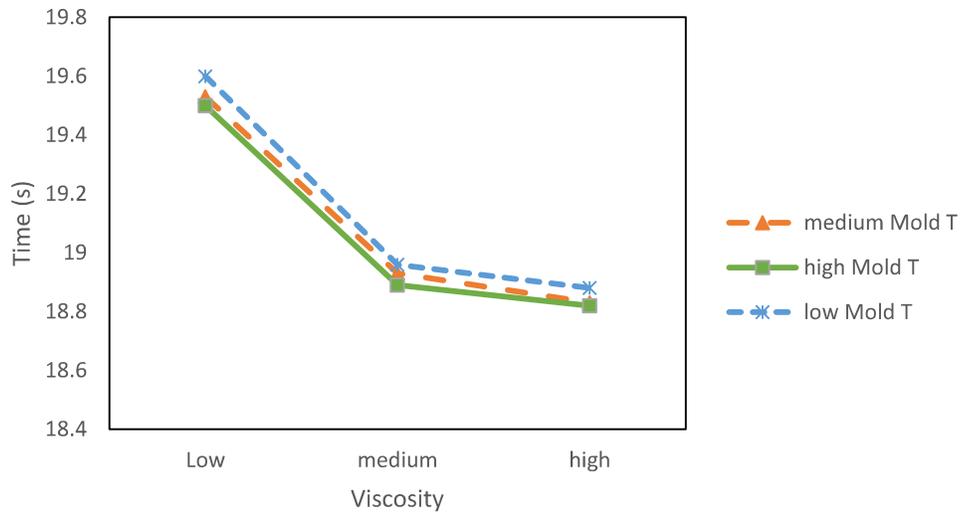
Figure 14. Melt Flow Time as a Function of Viscosity at Various Mold Temperature, Low Melt Temperature, and Low Injection Speed.
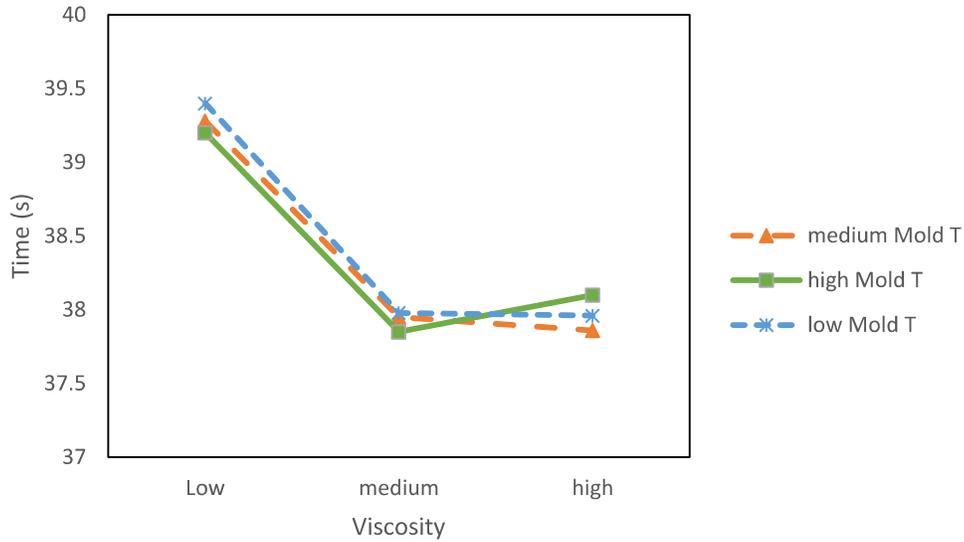
Figure 15. Melt Flow time as a Function of Viscosity at Various Mold Temperature, Medium Melt Temperature, and Medium Injection Speed
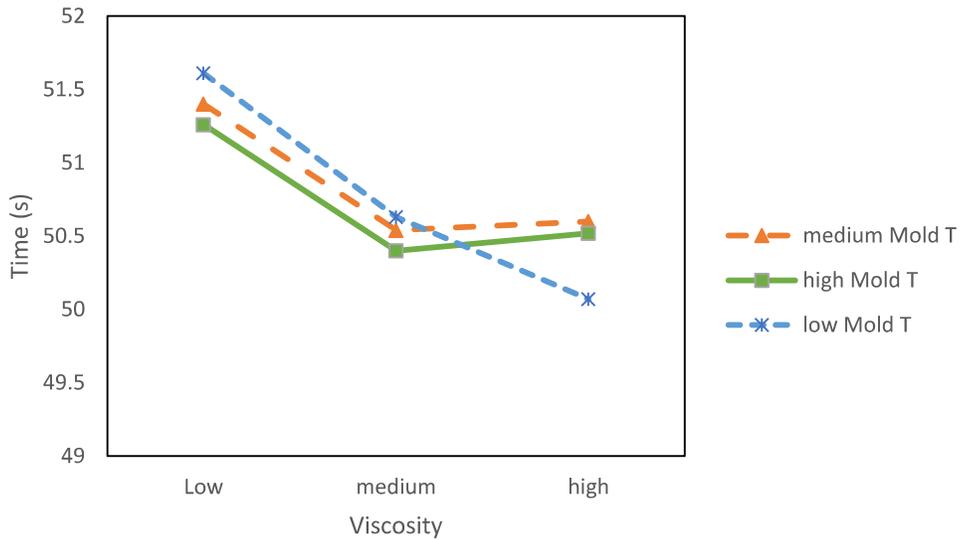
Figure 16. Melt Flow Time as a Function of Viscosity at Various Mold Temperature, High Melt Temperature, and High Injection Speed

Figure 17 illustrates the line graph for the pressure in cavity as function of viscosity at various mold temp, at low melt temperature and low injection speed. The pressure in the cavity

at low, medium, and high mold temperature showed an increase from low to medium viscosity, to then decrease to its initial pressure at high viscosity. The pressure in the cavity in all mold temperatures increase from low to medium viscosity from the 50 Mpa to the high 70MPa to then decrease back to the 50 MPa at high viscosity.

Figure 18 shows line graph for the pressure in cavity as function of viscosity at various mold temperature, at medium melt temperature and medium injection speed. The pressure in the cavity at low, medium, and high mold temperature showed an increase from low to medium viscosity, to then decrease to its initial pressure at high viscosity. The pressure in the cavity in all mold temperatures increase from low to medium viscosity from the 50 MPa to the high 70 MPa to then decrease back to the 50 MPa at high viscosity.

Figure 19 represents the line graph of the pressure in cavity as function of viscosity at various mold temperature, at high melt temperature and high injection speed. The pressure in the cavity at low, medium, and high mold temperature showed an increase from low to medium viscosity, to then decrease to its initial pressure at high viscosity. The pressure in the cavity in all mold temperatures increase from low to medium viscosity from the 50 MPa to the high 70 MPa to then decrease back to the 40 MPa at high viscosity.
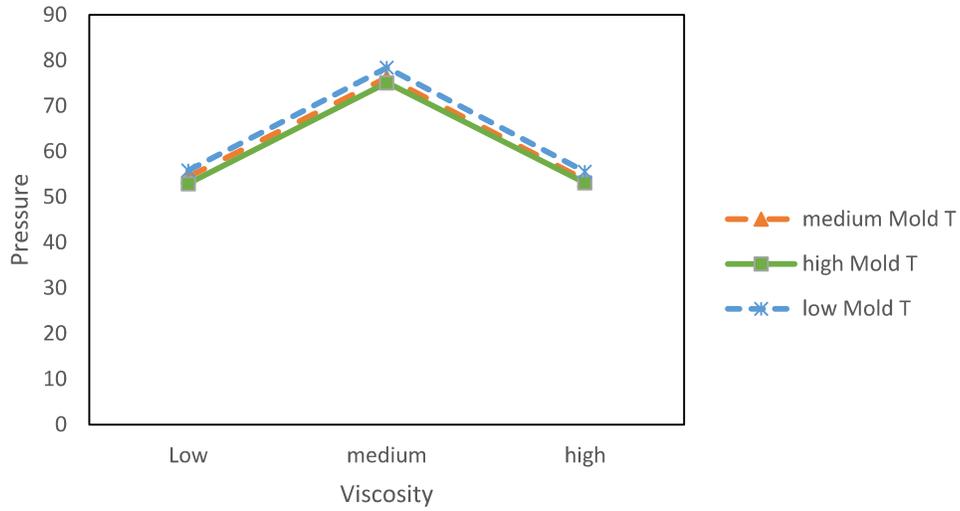
Figure 17. Pressure in Cavity as a Function of Viscosity at Various Mold Temperature, Low Melt Temperature and Low Injection Speed
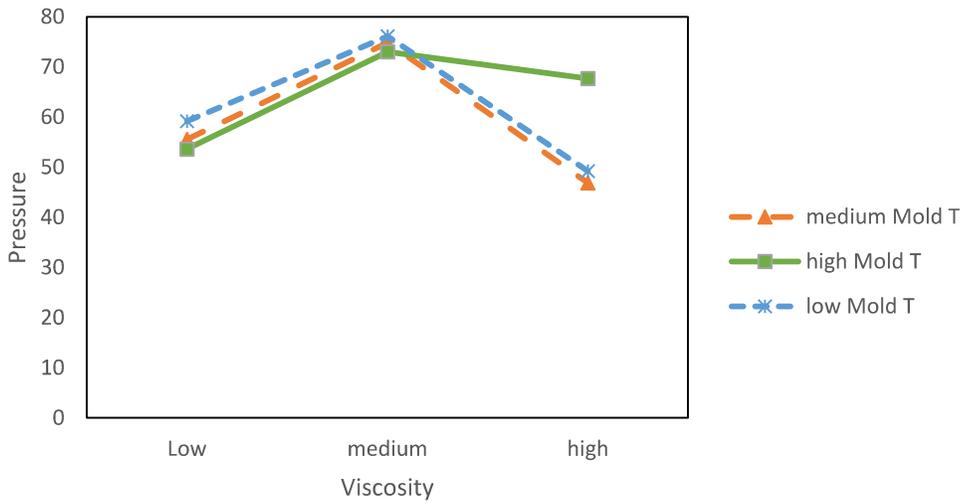
Figure 18. Pressure in Cavity as a Function of Viscosity at Various Mold Temperature, Medium Melt Temperature and Medium Injection Speed
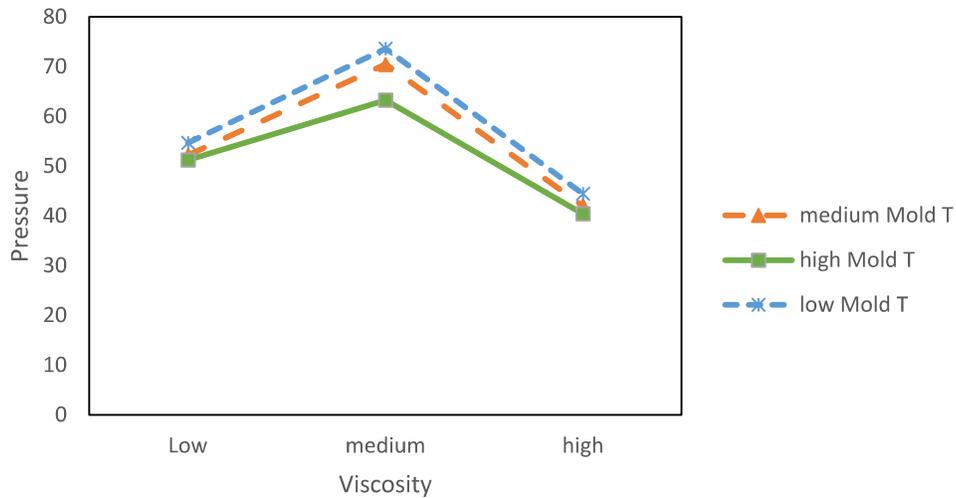
Figure 19. Pressure in Cavity as a Function of Viscosity at Various Mold Temperature, High
Melt Temperature and High Injection Speed

Figures 20, 21, and 22 show the line graphs of the melt flow time as a function of
injection speed at various mold temperature, at low, medium and high melt temperature and at
low, medium and high viscosity. The melt flow time at low medium and high mold temperature
showed a steady rise at all different injection speed. Melt flow time was almost identical for all
mold temperature at the different injection speed.
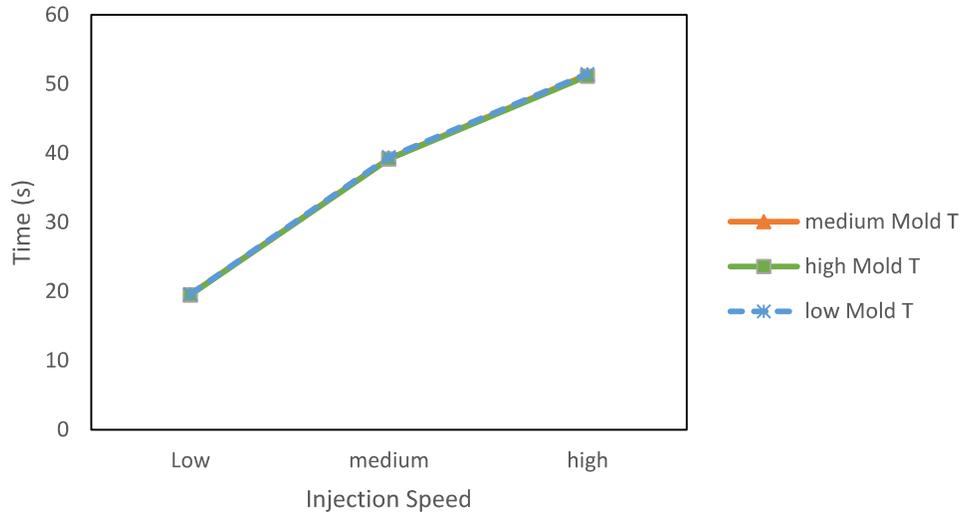
Figure 20 Melt Flow Time as a Function of Injection Speed at Various Mold temperature, Low Melt Temperature and Low Viscosity
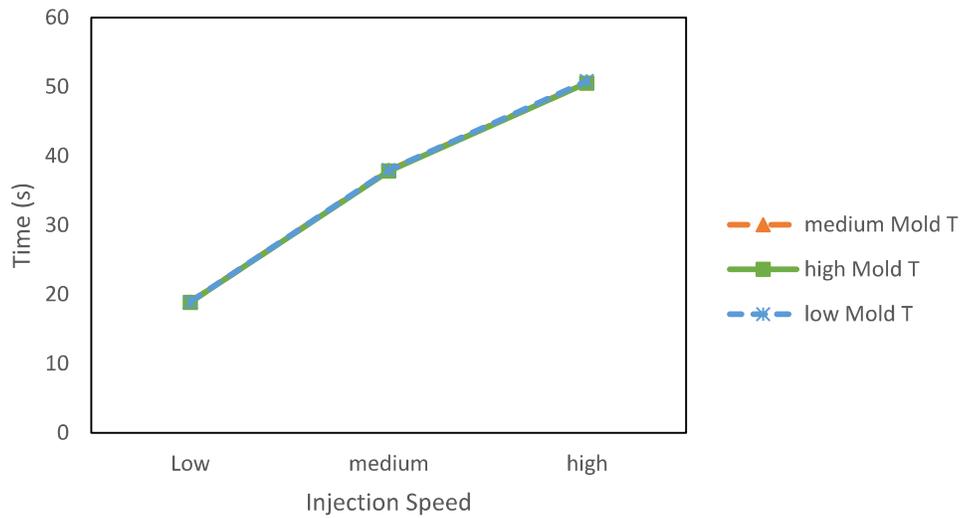
Figure 21 Melt Flow Time as a Function of Injection Speed at Various Mold temperature, Medium Melt Temperature and Medium Viscosity
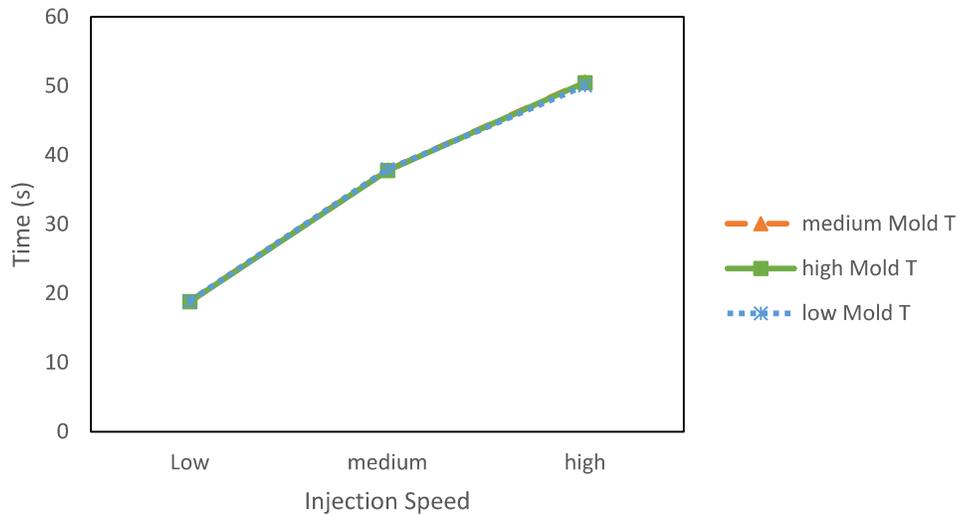
Figure 22. Melt Flow Time as a Function of Injection Speed at Various Mold Temperature, High Melt Temperature and High Viscosity

The line graph of Figure 23 illustrates the pressure in the cavity as function of Injection speed at various mold temperature, at low melt temperature and low viscosity. The pressure in the cavity at low, medium, and high mold temperature showed a steady increase at different injection speeds. The pressure in the cavity at low mold temperature shows the higher pressures at all different melt temperatures, followed by the medium mold temperature and at high mold temperature the pressure had the lowest pressures in the cavity. The pressure in the cavity in all mold temperatures increased from low to high injection speed from the 50 sec to the 60 sec.

Figure 24 shows the pressure in cavity as function of Injection speed at various mold temperature, at medium melt temperature and medium viscosity. The pressure in the cavity at low, medium, and high mold temperature showed a steady increase at different injection speeds. The pressure in the cavity at low mold temperature shows the higher pressures at all different melt temperatures even when it was the lowest at start, followed by the medium mold temperature and at high mold temperature the pressure had the lowest pressures in the cavity,

these two started at almost the same pressure at the start. The pressure in the cavity in all mold temperatures increased from low to high injection speed from the 60 sec to the 80 sec.

Figure 25 displays the line graph of the pressure in the cavity as function of injection speed at various mold temperature, at high melt temperature and high viscosity. The pressure in the cavity at low, medium, and high mold temperature showed a steady decrease at different injection speeds and then an increase at high injection speed. The pressure in the cavity at low mold temperature shows the higher pressures at all different melt temperatures, followed by the medium mold temperature and at high mold temperature the pressure had the lowest pressures in the cavity and keep decreasing at all different injection speeds. The pressure in the cavity in all mold temperatures stayed from low to high injection speed in the range of 40 sec.
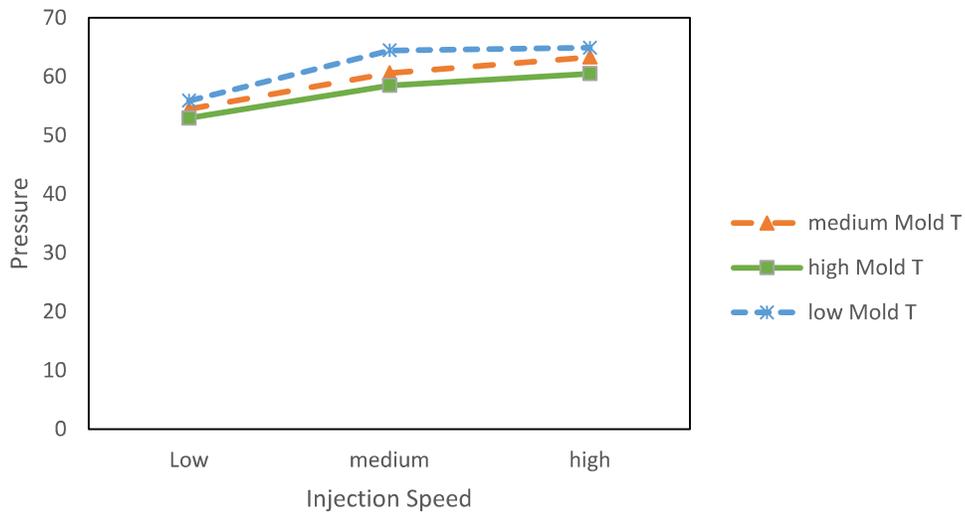
Figure 23. Pressure in Cavity as a Function of Injection Speed at Various Mold Temperature, Low Melt Temperature and Low Viscosity
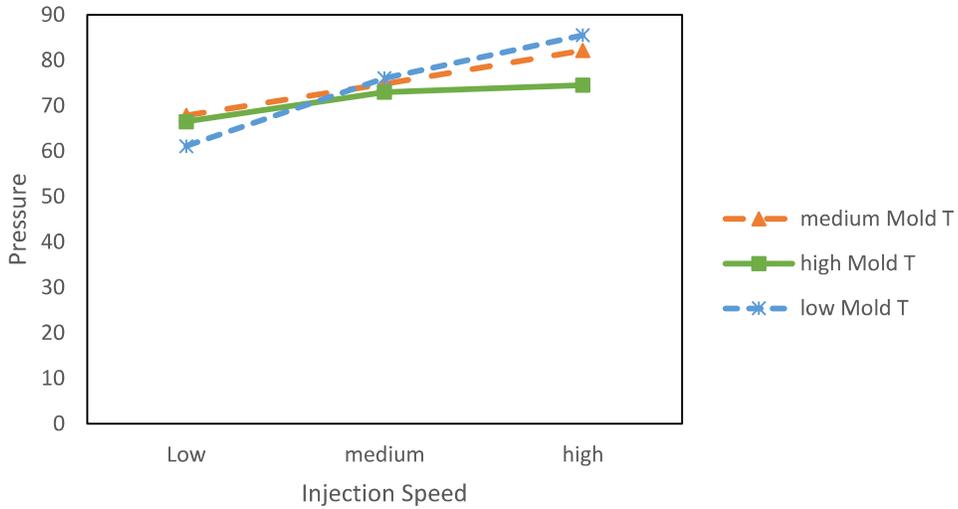
Figure 24. Pressure in Cavity as a Function of Injection Speed at Various Mold Temperature, Medium Melt Temperature and Medium Viscosity
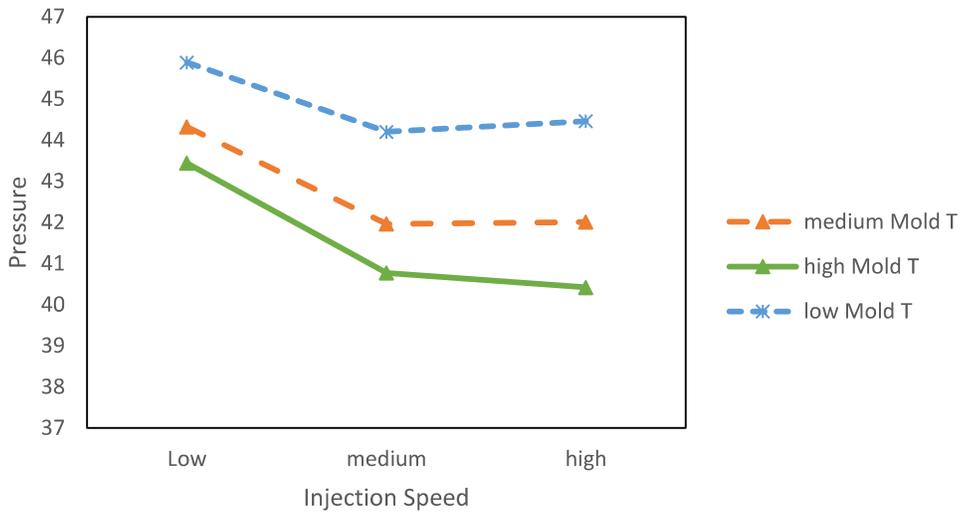
Figure 25. Pressure in Cavity as a Function of Injection Speed at Various Mold Temperature, High Melt Temperature and High Viscosity

DOE Analysis Results

Taguchi experimental method is a sort of statistical and experimental design method, developed by Genichi Taguchi to improve the quality of manufactured goods, and more recently

also applied to engineering, biotechnology, marketing and other areas where statistics is used. The Taguchi experimental method can arrange experiments by given an orthogonal table in advance and comes to a better conclusion through less runs of experiments. By minority of representative experimental data, the statistics are executed and the best experimental conditions are found out. Orthogonal experiments select the parameters affecting experimental target as factors. Each factor has several levels. According to experiences, mold temperature, melt temperature, viscosity, and injection speed are chosen as main factors affecting the time and pressure which contribute to the flash appearing on the plastic parts. To prove this assumption, Minitab 17 software was used for statistical analysis and experimental design generation. The experimental plan was set for the four parameters with three levels each by using Taguchi (3^4) orthogonal array. Mold temperature was set to 70ºF for level 1, 80ºF for level 2, and at 90ºF for level 3. Melt temperature was set to 265ºF for level 1, 275ºF for level 2, and at 285ºF for level 3. Then three different viscosities were set at MFI 171 for level 1, MFI 209 for level 2, and at MFI 471 for level 3. Lastly, the injection speed was set at 10 sec for level 1, 15 sec for level 2 and 20 sec for level 3.

The response data below will be plotted in several ways in order to see if any trends or abnormalities appear that would not be accounted for by the standard linear response model. The results obtained from this analysis were evaluated in terms of nominal is best by using the S/N ratio equation shown below.

Table 3. Taguchi Analysis: Time, Pressure Versus Mold Temp, Melt Temp, Viscosity, Injection Speed.

```
Taguchi Orthogonal Array Design

L9(3^4)

Factors:  4
Runs:     9


Columns of L9(3^4) Array

1 2 3 4


Response Table for Signal to Noise Ratios
Nominal is best (10×Log10(Ybar^2/s^2))

                                        injection
Level  mold temp  melt temp  viscosity     speed
1          4.707      4.959     13.480      2.488
2          7.877     10.220      7.047      7.206
3          9.757      7.162      1.813     12.647
Delta      5.050      5.261     11.667     10.158
Rank           4          3          1          2


Response Table for Means

                                        injection
Level  mold temp  melt temp  viscosity     speed
1         32.24      34.21      23.84      29.33
2         31.77      31.72      26.44      32.12
3         31.74      29.82      45.47      34.29
Delta      0.50       4.40      21.64       4.96
Rank           4          3          1          2
```

The main effects plot for this Taguchi method displays the means for each group within a categorical variable. Figure 26 shows the main effects for each of the variables and the reference line at the overall mean. From the figure, it can be presumed that there is a main effect present because the variables are not horizontal to the overall mean line. It can also be deduced that injection speed is the variable with the steeper slope which means that it has the greater magnitude of the main effect for time.
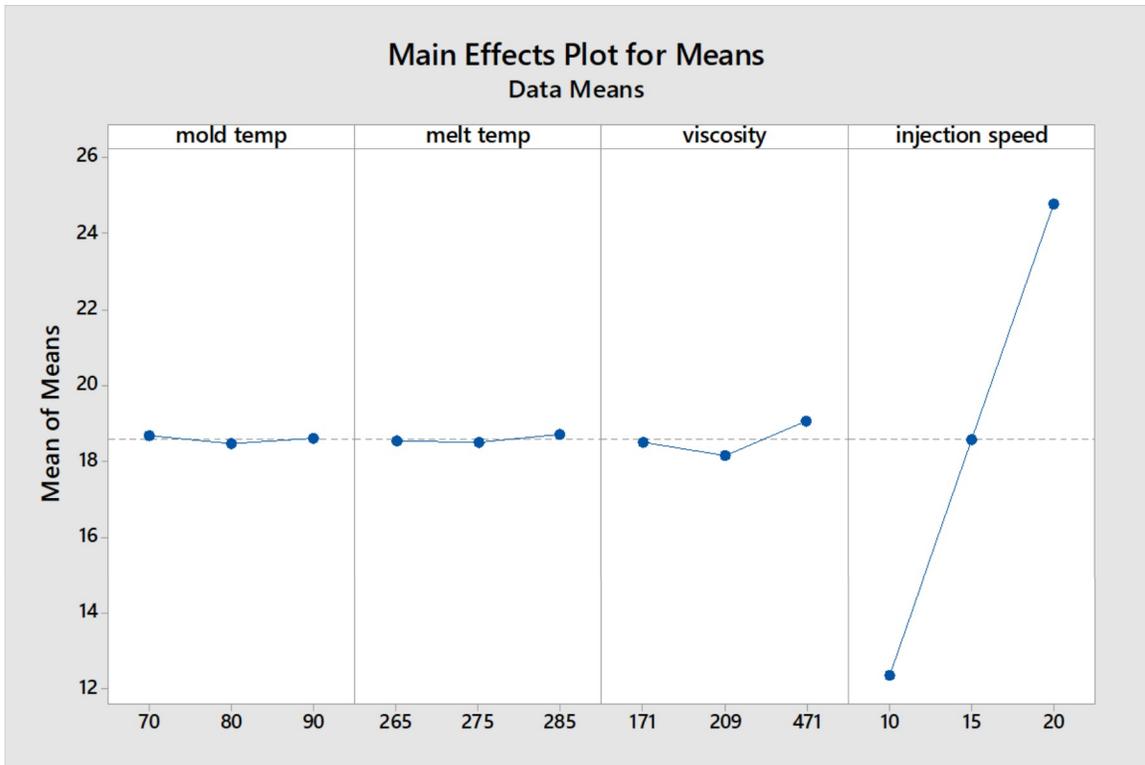
Figure 26. Taguchi Main Effects Plot for Means-Time

Main effects plots for SN ratios show the variation of individual responses with four different parameters separately. Figure 27, shows a plot which represents the value of each process parameter on x- axis and response value on y-axis. Optimal settings for time are the minimum values (the smaller the better) which given by the S/N ratio. However, these values can't be considered to be the optimal settings, due to the lack of these significant factors affecting time. From this graph only injection speed and viscosity can be considered to be significant factors to time.
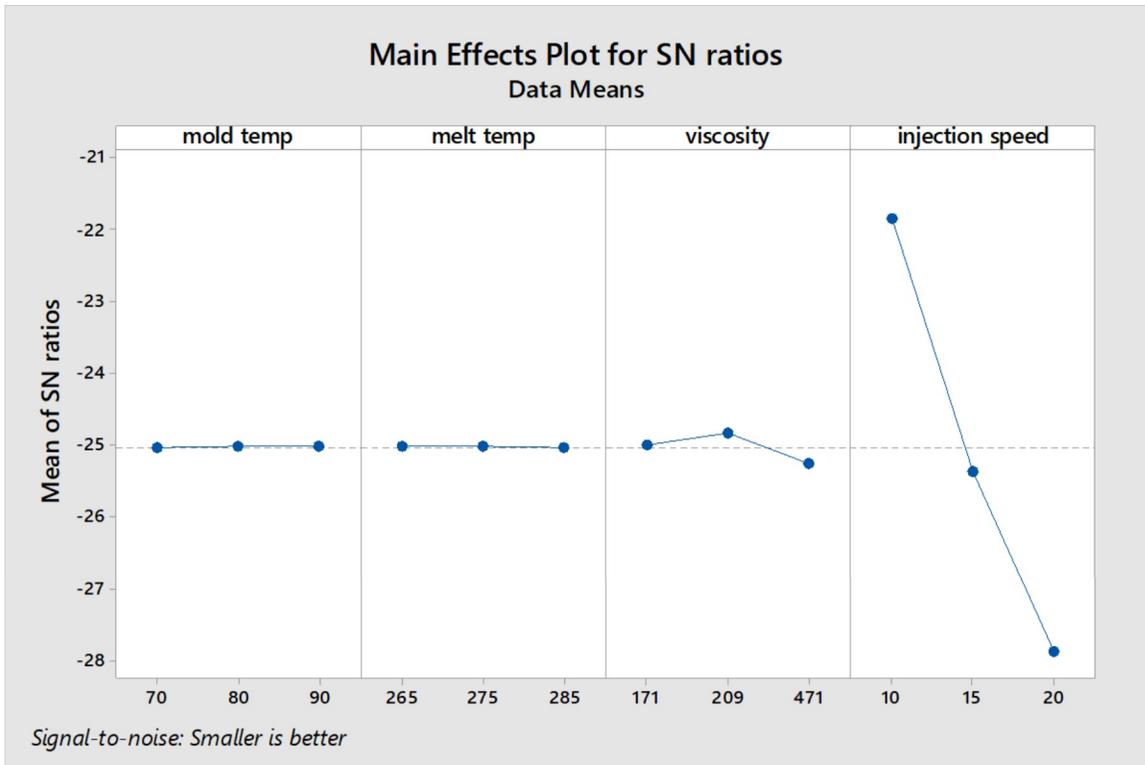
Figure 27. Taguchi Main Effects Plot for SN Ratios-Time

Figure 28 shows the main effects for each of the variables and the reference line at the overall mean. From the figure, it can be presumed that there is a main effect present in most of the variables presented. It can also be deduced that the viscosity is the variable with the steeper slope which means that it has the greater magnitude of the main effect in pressure, nevertheless further steps need to be performed to evaluate the statistical significance of the effects and it cannot be interpreted without considering the interaction effects of the rest of the variables.
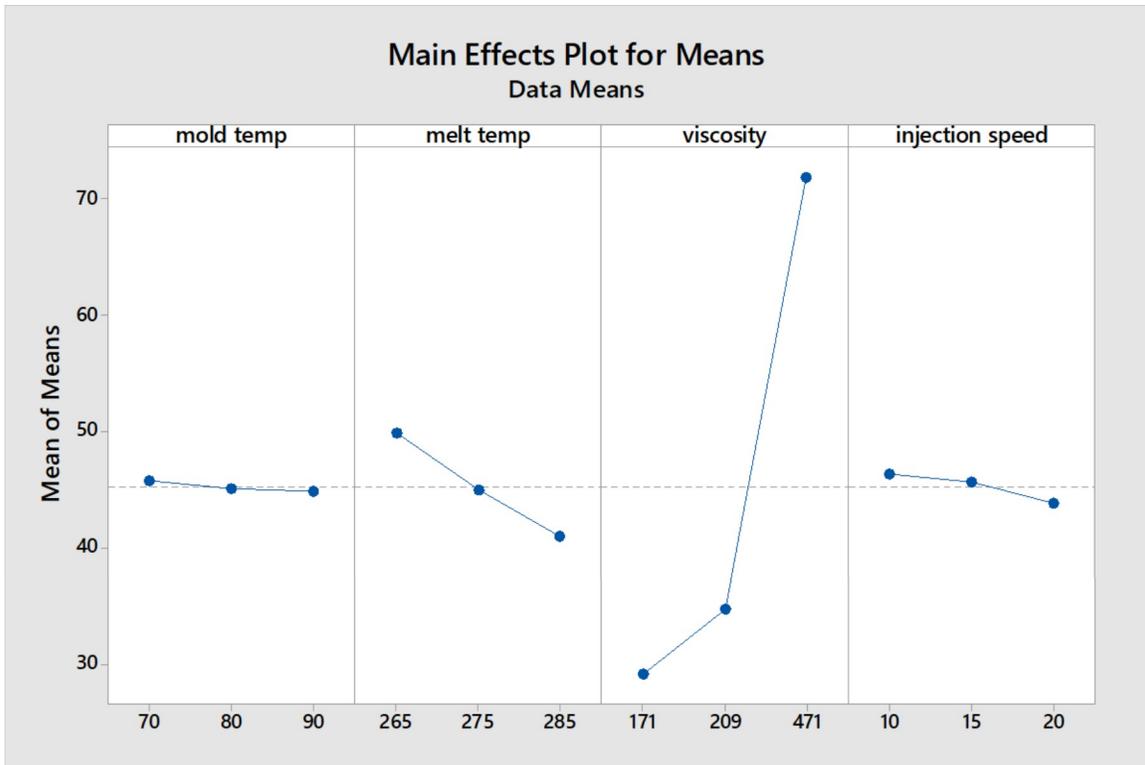
Figure 28. Taguchi Main Effects Plot for Means-Pressure

Figure 29 shows the main effects plots for SN ratios and the variation of individual responses with four different parameters separately. Viscosity seem to be the variable with the most significant effect on pressure, however the other variables also seem to have some influence on pressure. Optimal settings for time and pressure are the minimum values (smaller is best) which given by the S/N ratio these points were as follows: for mold temperature is 90°F, for melt temperature is 285°F, for viscosity is MFI 171 and for injection speed is 20 sec. Although these values could be considered the optimal settings, to fully optimize the process, these significant factors can also be passed to the next stage for further analysis.
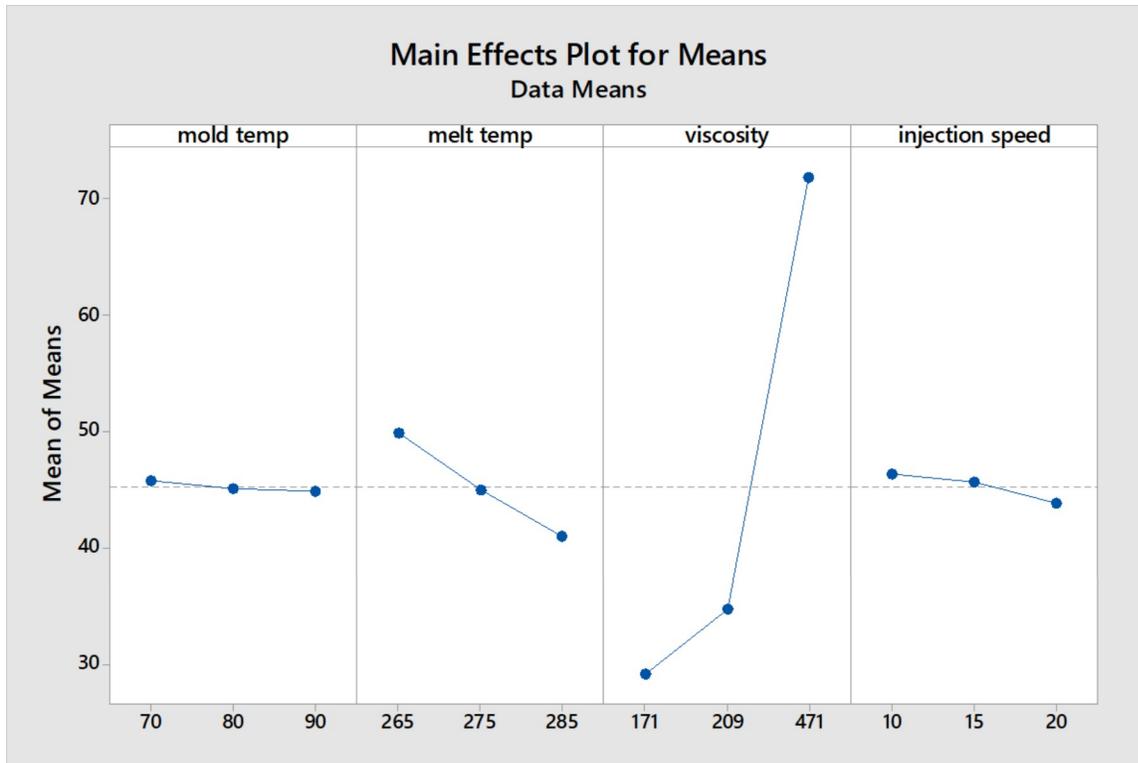
Figure 29. Taguchi Main Effects Plot for SN Ratios-Pressure

After the completion of the Taguchi analysis, the next step was to perform and compare it
to the full factorial design of the DOE. The main objective for running the full factorial design
analysis was solely to perform an experimental run at every combination of the factor levels.
These experiments showed all combinations of the factors that were investigated in each run of
the experiment. Full factorial design is the only way to completely study all the interactions
between all factors in addition to identifying significant factors in them in order to find the most
optimal way to solve the current problem. Table 4 show each experimental setting that was used
for the full-factorial DOE and results for time and pressure were reported in the following results
shown below. The P-values shown with lower values from 0.5 are the significant values for that
model. P-values of 0.5 was given as a default value on the Minitab software.

Figures 30 and 31 show the main effect plots of the different factors on the time and pressure, respectively. It can be noticed that mold temperature and melt temperature had almost no effect on time, but it does in pressure by a small amount. Viscosity has does affect both, time and pressure and injection speed had the biggest effect on time, but the least effect on pressure.
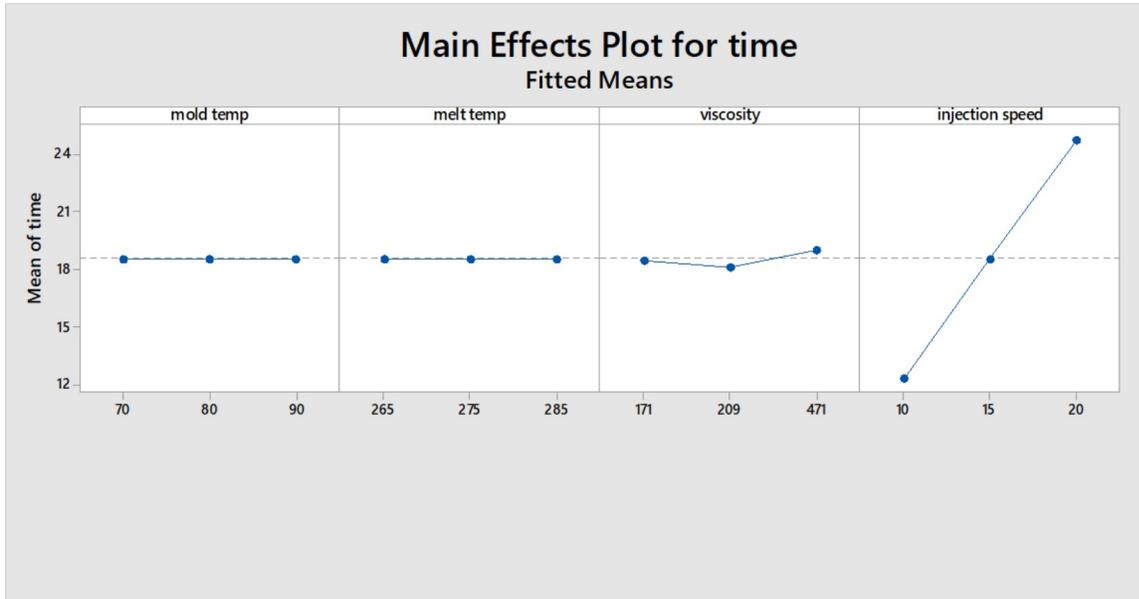
Figure 30. Main Effects Plot for Time
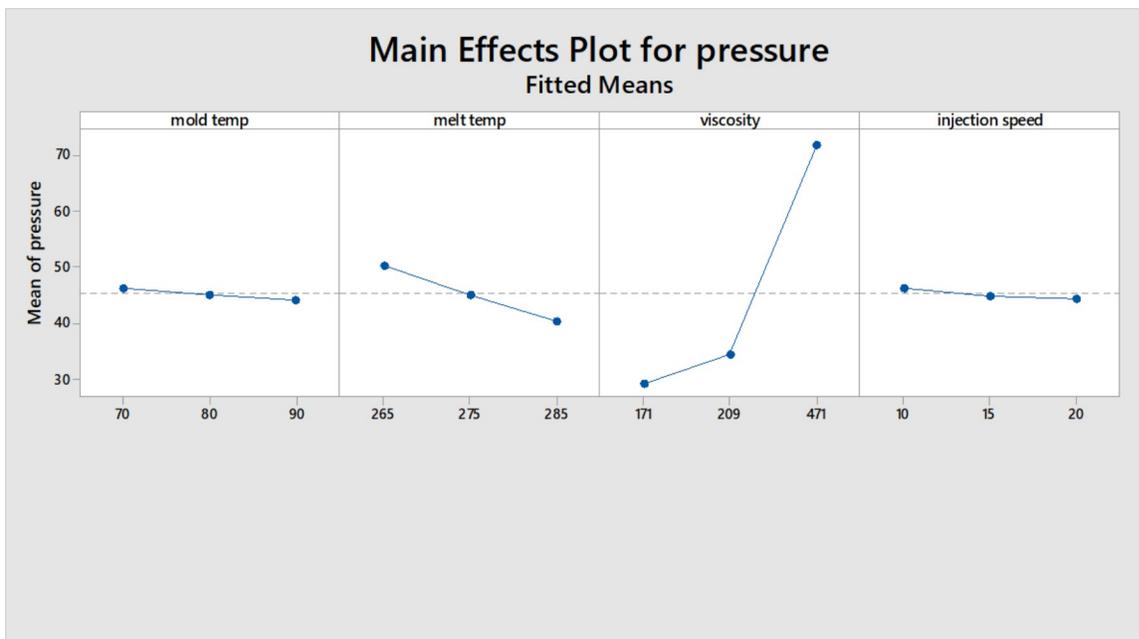
Figure 31. Main Effects Plot for Pressure

Table 4. ANOVA Analysis of Variance (Time)

```
Factors:        4      Replicates:     1
Base runs:     81      Total runs:     81
Base blocks:    1      Total blocks:    1

Number of levels: 3, 3, 3, 3


Factor Information

Factor           Levels  Values
mold temp            3   70, 80, 90
melt temp            3   265, 275, 285
viscosity            3   171, 209, 471
injection speed      3   10, 15, 20


Analysis of Variance

Source                      DF   Adj SS    Adj MS       F-Value  P-Value
Model                       32  2101.61     65.68    430745.14    0.000
  Linear                     8  2100.52    262.57   1722087.60    0.000
    mold temp                2     0.03      0.02       103.44    0.000
    melt temp                2     0.00      0.00         0.40    0.675
    viscosity                2    11.68      5.84     38315.23    0.000
    injection speed          2  2088.81   1044.40   6849931.34    0.000
  2-Way Interactions        24     1.09      0.05       297.65    0.000
    mold temp*melt temp      4     0.00      0.00         0.14    0.966
    mold temp*viscosity      4     0.00      0.00         5.47    0.001
    mold temp*injection speed 4    0.01      0.00         9.30    0.000
    melt temp*viscosity      4     0.01      0.00        23.22    0.000
    melt temp*injection speed 4    0.00      0.00         1.87    0.132
    viscosity*injection speed 4    1.06      0.27      1745.91    0.000
Error                       48     0.01      0.00
Total                       80  2101.62


Model Summary

        S     R-sq  R-sq(adj)  R-sq(pred)
0.0123478  100.00%    100.00%     100.00%


Coefficients

Term                      Coef  SE Coef    T-Value  P-Value   VIF
Constant               18.5642   0.0014  13530.93    0.000
mold temp
  70                    0.02284  0.00194     11.77    0.000  1.33
  80                    0.00247  0.00194      1.27    0.209  1.33
melt temp
  265                   0.00136  0.00194      0.70    0.487  1.33
  275                   0.00025  0.00194      0.13    0.899  1.33
viscosity
  171                  -0.06901  0.00194    -35.57    0.000  1.33
  209                  -0.42679  0.00194   -219.96    0.000  1.33
injection speed
  10                   -6.21346  0.00194  -3202.36    0.000  1.33
  15                   -0.01198  0.00194     -6.17    0.000  1.33
mold temp*melt temp
  70 265                0.00049  0.00274      0.18    0.858  1.78
  70 275               -0.00062  0.00274     -0.22    0.823  1.78
```

```
 80 265                           -0.00136   0.00274      -0.49     0.623   1.78
 80 275                            0.00198   0.00274       0.72     0.475   1.78
mold temp*viscosity
 70 171                           -0.00025   0.00274      -0.09     0.929   1.78
 70 209                           -0.01025   0.00274      -3.73     0.000   1.78
 80 171                            0.00123   0.00274       0.45     0.655   1.78
 80 209                            0.00123   0.00274       0.45     0.655   1.78
mold temp*injection speed
 70 10                            -0.01247   0.00274      -4.54     0.000   1.78
 70 15                             0.00160   0.00274       0.58     0.561   1.78
 80 10                            -0.00210   0.00274      -0.76     0.448   1.78
 80 15                             0.00198   0.00274       0.72     0.475   1.78
melt temp*viscosity
 265 171                          -0.00654   0.00274      -2.38     0.021   1.78
 265 209                          -0.01654   0.00274      -6.03     0.000   1.78
 275 171                           0.00235   0.00274       0.85     0.397   1.78
 275 209                           0.00012   0.00274       0.04     0.964   1.78
melt temp*injection speed
 265 10                            0.00123   0.00274       0.45     0.655   1.78
 265 15                           -0.00580   0.00274      -2.11     0.040   1.78
 275 10                           -0.00432   0.00274      -1.57     0.122   1.78
 275 15                            0.00420   0.00274       1.53     0.133   1.78
viscosity*injection speed
 171 10                            0.02938   0.00274      10.71     0.000   1.78
 171 15                           -0.00654   0.00274      -2.38     0.021   1.78
 209 10                            0.15160   0.00274      55.25     0.000   1.78
 209 15                            0.01123   0.00274       4.09     0.000   1.78


Regression Equation 1

time = 18.5642 + 0.02284 mold temp_70 + 0.00247 mold temp_80 - 0.02531 mold temp_90
       + 0.00136 melt temp_265 + 0.00025 melt temp_275 - 0.00160 melt temp_285
       - 0.06901 viscosity_171 - 0.42679 viscosity_209 + 0.49580 viscosity_471
            - 6.21346 injection speed_10 - 0.01198 injection speed_15
       + 6.22543 injection speed_20
       + 0.00049 mold temp*melt temp_70 265 - 0.00062 mold temp*melt temp_70 275
       + 0.00012 mold temp*melt temp_70 285 - 0.00136 mold temp*melt temp_80 265
       + 0.00198 mold temp*melt temp_80 275 - 0.00062 mold temp*melt temp_80 285
       + 0.00086 mold temp*melt temp_90 265 - 0.00136 mold temp*melt temp_90 275
       + 0.00049 mold temp*melt temp_90 285 - 0.00025 mold temp*viscosity_70 171
       - 0.01025 mold temp*viscosity_70 209 + 0.01049 mold temp*viscosity_70 471
       + 0.00123 mold temp*viscosity_80 171 + 0.00123 mold temp*viscosity_80 209
       - 0.00247 mold temp*viscosity_80 471 - 0.00099 mold temp*viscosity_90 171
       + 0.00901 mold temp*viscosity_90 209 - 0.00802 mold temp*viscosity_90 471
            - 0.01247 mold temp*injection speed_70 10
       + 0.00160 mold temp*injection speed_70 15
       + 0.01086 mold temp*injection speed_70 20
       - 0.00210 mold temp*injection speed_80 10
       + 0.00198 mold temp*injection speed_80 15
       + 0.00012 mold temp*injection speed_80 20
       + 0.01457 mold temp*injection speed_90 10
       - 0.00358 mold temp*injection speed_90 15
       - 0.01099 mold temp*injection speed_90 20 - 0.00654 melt temp*viscosity_265 171
       - 0.01654 melt temp*viscosity_265 209 + 0.02309 melt temp*viscosity_265 471
       + 0.00235 melt temp*viscosity_275 171 + 0.00012 melt temp*viscosity_275 209
       - 0.00247 melt temp*viscosity_275 471 + 0.00420 melt temp*viscosity_285 171
       + 0.01642 melt temp*viscosity_285 209 - 0.02062 melt temp*viscosity_285 471
            + 0.00123 melt temp*injection speed_265 10
       - 0.00580 melt temp*injection speed_265 15
       + 0.00457 melt temp*injection speed_265 20
       - 0.00432 melt temp*injection speed_275 10
```

```
        + 0.00420 melt temp*injection speed_275 15
        + 0.00012 melt temp*injection speed_275 20
        + 0.00309 melt temp*injection speed_285 10
        + 0.00160 melt temp*injection speed_285 15
        - 0.00469 melt temp*injection speed_285 20
        + 0.02938 viscosity*injection speed_171 10
        - 0.00654 viscosity*injection speed_171 15
        - 0.02284 viscosity*injection speed_171 20
        + 0.15160 viscosity*injection speed_209 10
        + 0.01123 viscosity*injection speed_209 15
        - 0.16284 viscosity*injection speed_209 20
        - 0.18099 viscosity*injection speed_471 10
        - 0.00469 viscosity*injection speed_471 15
        + 0.18568 viscosity*injection speed_471 20



Fits and Diagnostics for Unusual Observations

Obs     time      Fit    Resid  Std Resid
  6  24.1900  24.2133  -0.0233     -2.45  R
 36  25.5200  25.4989   0.0211      2.22  R
 78  24.2100  24.1833   0.0267      2.81  R
 81  25.3800  25.4004  -0.0204     -2.14  R

R  Large residual
```

Table 5. ANOVA Analysis of Variance (Pressure)

```
Table
Factor Information

Factor           Levels  Values
mold temp          3     70, 80, 90
melt temp          3     265, 275, 285
viscosity          3     171, 209, 471
injection speed    3     10, 15, 20



Analysis of Variance

Source                    DF   Adj SS   Adj MS     F-Value  P-Value
Model                     32  30696.4    959.3   13566.85    0.000
  Linear                   8  30608.5   3826.1   54112.03    0.000
    mold temp              2     55.6     27.8     393.15    0.000
    melt temp              2   1323.7    661.8    9360.29    0.000
    viscosity              2  29180.4  14590.2  206349.47    0.000
    injection speed        2     48.8     24.4     345.21    0.000
  2-Way Interactions      24     87.9      3.7      51.79    0.000
    mold temp*melt temp    4      0.2      0.0       0.57    0.685
    mold temp*viscosity    4      0.9      0.2       3.15    0.022
    mold temp*injection speed  4   3.4      0.8      11.86    0.000
    melt temp*viscosity    4     64.8     16.2     229.20    0.000
    melt temp*injection speed  4   0.9      0.2       3.06    0.025
    viscosity*injection speed  4  17.8      4.4      62.90    0.000
Error                     48      3.4      0.1
Total                     80  30699.8
```

46

```
Model Summary

       S    R-sq  R-sq(adj)  R-sq(pred)
0.265907  99.99%     99.98%      99.97%


Coefficients

Term                        Coef  SE Coef  T-Value  P-Value   VIF
Constant                 45.3709   0.0295  1535.64    0.000
mold temp
  70                       1.0091   0.0418    24.15    0.000  1.33
  80                       0.0110   0.0418     0.26    0.794  1.33
melt temp
  265                      4.9884   0.0418   119.39    0.000  1.33
  275                     -0.0757   0.0418    -1.81    0.076  1.33
viscosity
  171                    -15.9701   0.0418  -382.21    0.000  1.33
  209                    -10.6990   0.0418  -256.06    0.000  1.33
injection speed
  10                       1.0828   0.0418    25.92    0.000  1.33
  15                      -0.3846   0.0418    -9.20    0.000  1.33
mold temp*melt temp
  70 265                   0.0572   0.0591     0.97    0.338  1.78
  70 275                   0.0123   0.0591     0.21    0.835  1.78
  80 265                   0.0120   0.0591     0.20    0.840  1.78
  80 275                  -0.0140   0.0591    -0.24    0.814  1.78
mold temp*viscosity
  70 171                  -0.1143   0.0591    -1.93    0.059  1.78
  70 209                   0.1768   0.0591     2.99    0.004  1.78
  80 171                  -0.0284   0.0591    -0.48    0.633  1.78
  80 209                  -0.0117   0.0591    -0.20    0.844  1.78
mold temp*injection speed
  70 10                   -0.3095   0.0591    -5.24    0.000  1.78
  70 15                    0.0190   0.0591     0.32    0.749  1.78
  80 10                   -0.0125   0.0591    -0.21    0.834  1.78
  80 15                    0.0072   0.0591     0.12    0.904  1.78
melt temp*viscosity
  265 171                 -0.8480   0.0591   -14.35    0.000  1.78
  265 209                 -0.6636   0.0591   -11.23    0.000  1.78
  275 171                 -0.1484   0.0591    -2.51    0.015  1.78
  275 209                  0.1049   0.0591     1.78    0.082  1.78
melt temp*injection speed
  265 10                   0.0023   0.0591     0.04    0.968  1.78
  265 15                  -0.1591   0.0591    -2.69    0.010  1.78
  275 10                  -0.0525   0.0591    -0.89    0.379  1.78
  275 15                   0.0472   0.0591     0.80    0.429  1.78
viscosity*injection speed
  171 10                   0.2964   0.0591     5.02    0.000  1.78
  171 15                   0.1016   0.0591     1.72    0.092  1.78
  209 10                   0.5031   0.0591     8.51    0.000  1.78
  209 15                  -0.0940   0.0591    -1.59    0.118  1.78


Regression Equation 2

pressure = 45.3709 + 1.0091 mold temp_70 + 0.0110 mold temp_80 - 1.0201 mold temp_90
         + 4.9884 melt temp_265 - 0.0757 melt temp_275 - 4.9127 melt temp_285
         - 15.9701 viscosity_171 - 10.6990 viscosity_209 + 26.6691 viscosity_471
         + 1.0828 injection speed_10 - 0.3846 injection speed_15
         - 0.6983 injection speed_20 + 0.0572 mold temp*melt temp_70 265
         + 0.0123 mold temp*melt temp_70 275 - 0.0695 mold temp*melt temp_70 285
         + 0.0120 mold temp*melt temp_80 265 - 0.0140 mold temp*melt temp_80 275
```

```
         + 0.0020 mold temp*melt temp_80 285 - 0.0691 mold temp*melt temp_90 265
         + 0.0016 mold temp*melt temp_90 275 + 0.0675 mold temp*melt temp_90 285
         - 0.1143 mold temp*viscosity_70 171 + 0.1768 mold temp*viscosity_70 209
         - 0.0625 mold temp*viscosity_70 471 - 0.0284 mold temp*viscosity_80 171
         - 0.0117 mold temp*viscosity_80 209 + 0.0401 mold temp*viscosity_80 471
         + 0.1427 mold temp*viscosity_90 171 - 0.1651 mold temp*viscosity_90 209
                    + 0.0223 mold temp*viscosity_90 471
           - 0.3095 mold temp*injection speed_70 10
         + 0.0190 mold temp*injection speed_70 15
         + 0.2905 mold temp*injection speed_70 20
         - 0.0125 mold temp*injection speed_80 10
         + 0.0072 mold temp*injection speed_80 15
         + 0.0053 mold temp*injection speed_80 20
         + 0.3220 mold temp*injection speed_90 10
         - 0.0262 mold temp*injection speed_90 15
         - 0.2958 mold temp*injection speed_90 20
         - 0.8480 melt temp*viscosity_265 171 - 0.6636 melt temp*viscosity_265 209
         + 1.5116 melt temp*viscosity_265 471 - 0.1484 melt temp*viscosity_275 171
                    + 0.1049 melt temp*viscosity_275 209
         + 0.0435 melt temp*viscosity_275 471  + 0.9964 melt temp*viscosity_285 171
         + 0.5586 melt temp*viscosity_285 209  - 1.5551 melt temp*viscosity_285 471
         + 0.0023 melt temp*injection speed_265 10
         - 0.1591 melt temp*injection speed_265 15
         + 0.1568 melt temp*injection speed_265
         20 - 0.0525 melt temp*injection speed_275 10
           + 0.0472 melt temp*injection speed_275 15
           + 0.0053 melt temp*injection speed_275
         20 + 0.0501 melt temp*injection speed_285 10
                   + 0.1120 melt temp*injection speed_285 15
           - 0.1621 melt temp*injection speed_285
         20 + 0.2964 viscosity*injection speed_171 10
                   + 0.1016 viscosity*injection speed_171 15
           - 0.3980 viscosity*injection speed_171
         20 + 0.5031 viscosity*injection speed_209 10
                   - 0.0940 viscosity*injection speed_209 15
           - 0.4091 viscosity*injection speed_209
         20 - 0.7995 viscosity*injection speed_471 10
                   - 0.0077 viscosity*injection speed_471 15
           + 0.8072 viscosity*injection speed_471 20


Fits and Diagnostics for Unusual Observations

Obs   pressure      Fit    Resid  Std Resid
  8     78.500   79.011  -0.511      -2.50  R
  9     80.510   80.100   0.410       2.00  R
 26     66.690   66.188   0.502       2.45  R
 35     77.640   78.059  -0.419      -2.05  R

R  Large residual
```

The interaction effects on Figures 32 and 33 show different effect on all their interactions.

Similar to Table 4, Table 5 show the ANOVA analysis for the full-factorial for time and pressure

respectively. The P-values for this table was calculated with the same default settings of the

Minitab software. The information on the tables is reflected on the interaction graphs and it can be claimed that four interaction factors are significant for the time which are mold temp*viscosity, mold temp*injection speed, melt temp*viscosity and viscosity*injection speed. On the other hand, pressure has five interaction effects that are significant for pressure and these are, mold temp*viscosity, mold temp*injection speed, melt temp*viscosity, melt temp*injection speed and viscosity*injection speed. From both interactions (time and pressure) it can be presumed that pressure has the most interaction between its variables and that most of them are related to viscosity. Nonetheless there is still one more step before concluding which parameters are the optimal to minimize flash in the molded part.
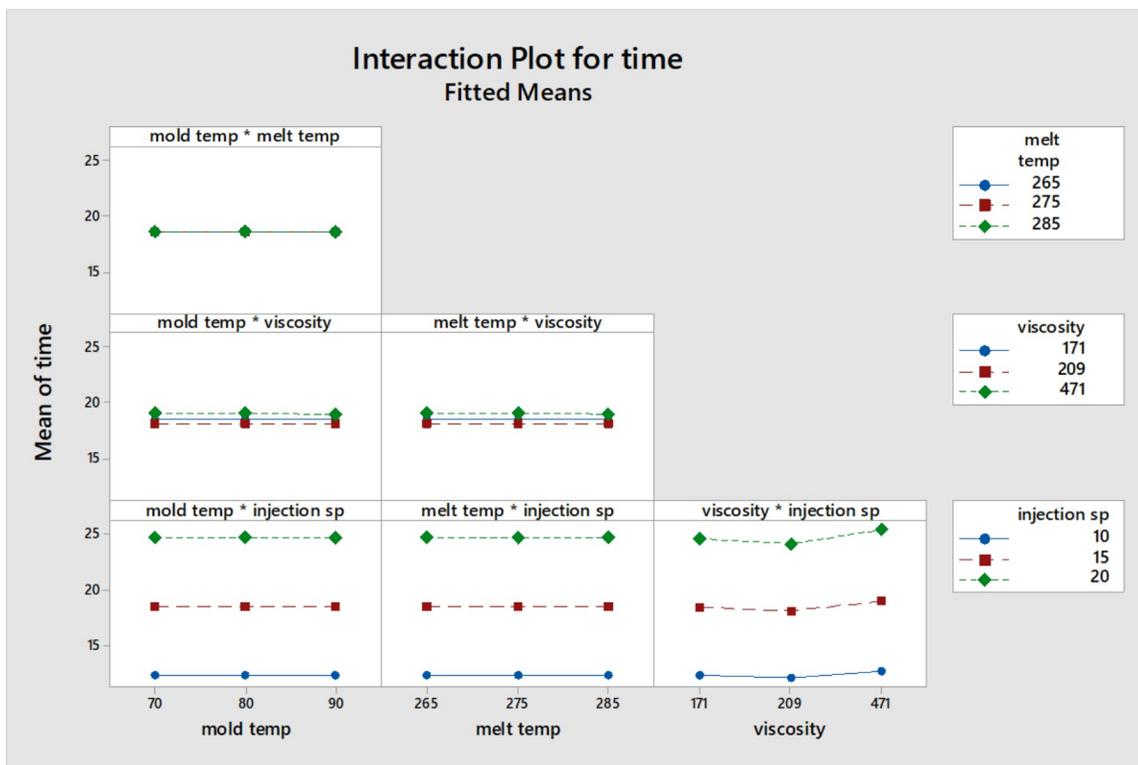
Figure 32. Interaction Effects on Time
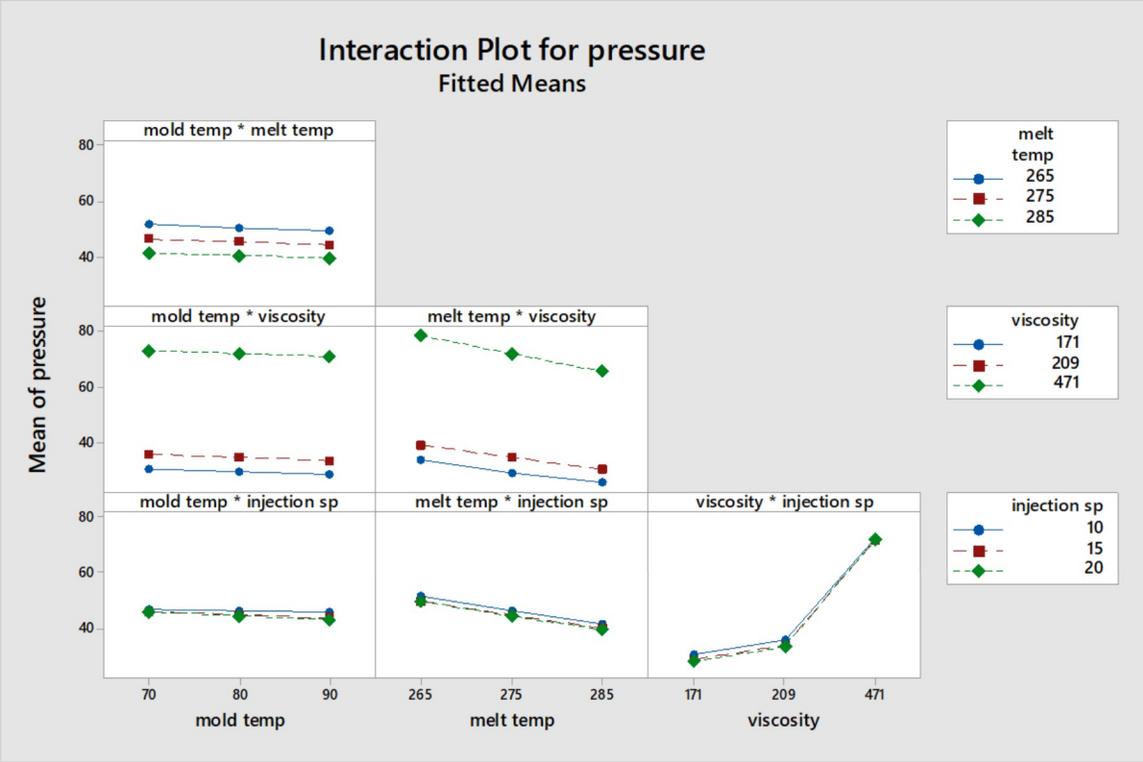
Figure 33. Interaction Effects on Pressure

Table 6 shows the best subset results for time and pressure. Column 3 represents the adjusted R^2 value for the chosen model, and on column 4 Mallow's Cp is shown. Mallows's Cp was used for model selection, and the goal is to find the best model involving a subset of these predictors. For that purpose, the lower the Cp factor, the better the model is. For further validation, we selected two models with the lowest Cp [1]. These are given in the equations shown above for time and pressure respectively. Both models (pressure and time) are acceptable models based on their significantly high 95.0% and 99.4% level of confidence.

Table 6. Best Subsets Regression: Pressure Versus Mold Temp, Melt Temp, Injection Speed

```
Response is pressure

                                                        i
                                                        n
                                                        j
                                                        e
                                                        c
                                                        t
                                              m m v     i
                                              o e i     o
                                              l l s     n
                                              d t c
                                                    o   s
                                              t t s     p
                                              e e i     e
                 R-Sq   R-Sq                  m m t     e
Vars  R-Sq  (adj)  (pred)  Mallows Cp      S  p p y     d
   1  95.1   95.0    94.8      1104.4  4.3858      X
   1   4.3    3.1     0.0     22760.5  19.283  X
   2  99.4   99.3    99.3        77.5  1.5859    X X
   2  95.2   95.1    94.8      1063.1  4.3324  X   X
   3  99.5   99.5    99.5        36.3  1.3512  X X X
   3  99.5   99.5    99.4        46.2  1.4112    X X X
   4  99.7   99.7    99.6         5.0  1.1342  X X X X
```

Regression Analysis: Pressure Versus Mold Temp, Melt Temp, Viscosity, Injection Speed

```
Analysis of Variance

Source               DF    Adj SS    Adj MS    F-Value   P-Value
Regression            4   30602.0    7650.5    5947.57     0.000
  mold temp           1      55.6      55.6      43.22     0.000
  melt temp           1    1323.4    1323.4    1028.85     0.000
  viscosity           1   29180.2   29180.2   22684.94     0.000
  injection speed     1      42.8      42.8      33.29     0.000
Error                76      97.8       1.3
Total                80   30699.8


Model Summary

      S    R-sq  R-sq(adj)   R-sq(pred)
1.13416  99.68%     99.66%       99.63%


Coefficients

Term               Coef   SE Coef   T-Value   P-Value    VIF
Constant         151.93      4.45     34.11     0.000
mold temp       -0.1015    0.0154     -6.57     0.000   1.00
melt temp       -0.4951    0.0154    -32.08     0.000   1.00
viscosity      0.142313  0.000945    150.62     0.000   1.00
injection speed -0.1781    0.0309     -5.77     0.000   1.00
```

```
Regression Equation

pressure = 151.93 - 0.1015 mold temp - 0.4951 melt temp + 0.142313 viscosity
           - 0.1781 injection speed


Fits and Diagnostics for Unusual Observations

Obs  pressure    Fit   Resid  Std Resid
  9    80.510  77.105   3.405       3.15  R
 25    66.090  68.985  -2.895      -2.68  R
 36    79.190  76.091   3.099       2.84  R
 63    77.710  75.076   2.634       2.44  R

R  Large residual
```

Table 7. Best Subsets Regression: Time Versus Mold Temp, Melt Temp, Injection Speed

```
Response is time
```

							i
							n
							j
							e
							c
							t
					m m v	i
					o e i	o
					l l s	n
					d t c	
						o	s
					t t s	p
					e e i	e
	R-Sq	R-Sq			m m t	e
Vars	R-Sq	(adj)	(pred)	Mallows Cp	S	p p y	d
1	99.4	99.4	99.4	172.8	0.40280		X
1	0.4	0.0	0.0	40701.0	5.1469	X	
2	99.8	99.8	99.8	1.6	0.22451	X	X
2	99.4	99.4	99.3	174.2	0.40488	X	X
3	99.8	99.8	99.8	3.0	0.22507	X X	X
3	99.8	99.8	99.8	3.6	0.22596	X X	X
4	99.8	99.8	99.8	5.0	0.22654	X X X	X

Regression Analysis: Pressure Versus Mold Temp, Melt Temp, Viscosity, Injection Speed

```
Analysis of Variance

Source            DF   Adj SS   Adj MS    F-Value   P-Value
Regression         4  30602.0   7650.5    5947.57     0.000
  mold temp        1     55.6     55.6      43.22     0.000
  melt temp        1   1323.4   1323.4    1028.85     0.000
  viscosity        1  29180.2  29180.2   22684.94     0.000
  injection speed  1     42.8     42.8      33.29     0.000
Error             76     97.8      1.3
Total             80  30699.8
```

```
Model Summary

      S    R-sq  R-sq(adj)  R-sq(pred)
1.13416  99.68%     99.66%      99.63%


Coefficients

Term                 Coef   SE Coef   T-Value  P-Value   VIF
Constant           151.93      4.45     34.11    0.000
mold temp         -0.1015    0.0154     -6.57    0.000  1.00
melt temp         -0.4951    0.0154    -32.08    0.000  1.00
viscosity        0.142313  0.000945    150.62    0.000  1.00
injection speed   -0.1781    0.0309     -5.77    0.000  1.00


Regression Equation

pressure = 151.93 - 0.1015 mold temp - 0.4951 melt temp + 0.142313 viscosity
           - 0.1781 injection speed


Fits and Diagnostics for Unusual Observations

Obs   pressure      Fit    Resid  Std Resid
  9     80.510   77.105    3.405       3.15  R
 25     66.090   68.985   -2.895      -2.68  R
 36     79.190   76.091    3.099       2.84  R
 63     77.710   75.076    2.634       2.44  R

R  Large residual
```

Figure 34 shows the results from the before and after samples of the best fit model. The image on

the left side shows the plastic part that is currently being molded for production. These parts

need to be trimmed and sanded before they can be used in production. The image of the right

side shows the sample molded with the results obtained from the best fit model. As it can be seen

from the picture those areas are now free of flash. These parts can be used in production without

undergoing through any other rework process.

Figure 34. Before and after samples of Leap ribbon plastic part

Figure 35 exhibits the measurement taken to compare the flash of the current sample and the

sample obtained from the best fit results. The left side shows the optical comparator image of the

current production plastic part. The right side of the image shows the optical comparator image

of the experiment sample obtained from the best fit results. As it can be observed on the left side

of the image, the flash defect is very pronounce compared to the image of the right side of the

figure. Optical comparator measuerents showed that the flash in red area of the image reaches as

high as 0.037" compared to the surface of the experiment sample.
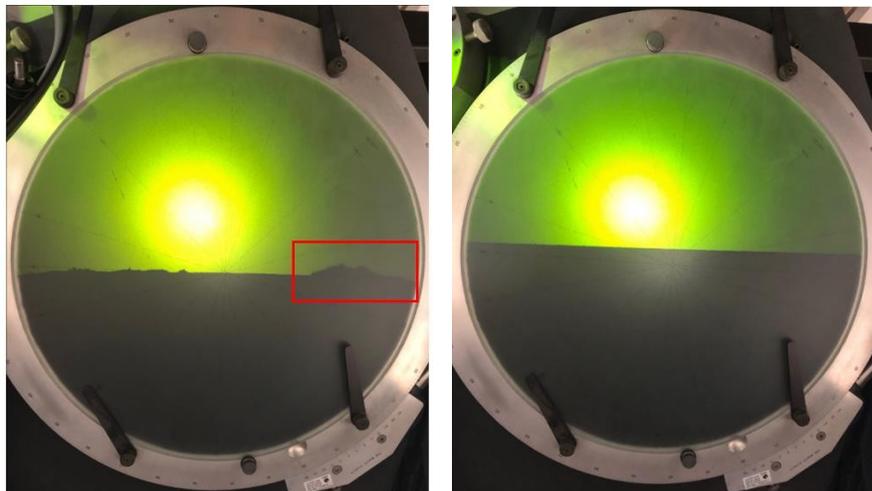
Figure 35. Optical comparator of before and after samples

CHAPTER IV

SUMMARY AND CONCLUSION

Summary

This report has explored a multistage experiment seeking for a solution that will solve the flash problem that can be encountered in plastic molded parts. There were some major contributions obtained from the theoretical work done by the Moldflow software and some other important findings that were found by numerical analysis such as Taguchi method and full factorial DOE analysis. The first step was to run all the possible combinations in the Moldflow analysis software. This past of the experiment was very important, because it provided all the result needed for time and pressure, which were the two responses that were analyzed by the Taguchi method and the full factorial analysis. The Taguchi method help to reduce the significant factors and presented which parameters were the most important ones to consider when selecting the best suitable solution from this analysis. The full factorial was performed after the Taguchi method. Full factorial was the most complete analysis of all as it accounted for all the different combination that were there. All the solutions obtained from the different methods were found by using time and pressure, which were used to evaluated which of both had the biggest influence on the formation of flash.

Conclusion

Flash is a defect that can be found in molded part. This type of defect is not able to be predicted just by using the Moldflow simulation alone. However, by using the design of experiment (DOE) to analyze the four process parameters (mold temperature, melt temperature, viscosity and injection speed), and the two responses: (time and pressure) at the flash point, it was possible to obtained more information to detect and prevent flash formation. These methods (DOE) were able to demonstrate that the viscosity and pressure were two variables with the greatest impact on flash. Although, and because viscosity was used as an input variable and in order to avoid influence of viscosity changes, time was considered. The lower the better was used and optimum conditions for time and pressure were found by using both, Taguchi and full factorial design of experiment. From the results obtained from full factorial pressure optimum, sample 66 from the Moldflow simulation (Akulon K224-HG6U BK223) was tested and it was proven that this polymer reduces flash formation significantly, compared to the other specimens such as the one currently in use (OMNI Plastics-Omnilon PA6 GR43 EF LV NA). With is in mind, it can be concluded that in order to produce high quality parts and reduce flash, it is very important to identify and use pressure at the flash point as a control in Moldflow simulations. In the specific case of the flash issue of the Leap ribbon, it can be presumed that by the success of eliminating this defect, a considerable cost reduction could be achieved once the new resin is used in production. Nevertheless, there is still more analysis and durability tests (ANSI/BIFMA) that are still pending to be performed in order to decide if this specific the material would work in for the Leap chair ribbon.

REFERENCES

1. Barghash M., Alkaabneh F., Shrinkage and Warpage Detailed Analysis and Optimization for the Injection Molding Using Multistage Experimental Design, Quality Engineering, Pages 76-85; July 2014.

2. Atre, S.V., Park, S.J., Zauner, R., German, Randall M., Process simulation of powder injection moulding: identification of significant parameters during mould filling phase, Powder Metallurgy, 76-85; 2007

3. Li, H., Guo, Z. & Li, D. "Reducing the effects of weldlines on appearance of plastic products by Taguchi experimental method" International Journal of Advanced Manufacturing Technology, Volume 32, Issue 9–10, pp 927–931.

4. Jung-Tang Huang, Shao-Chang, Cheng. Study of injection molding pressure sensor with low cost and small probe. Sensors and Actuators A: Physical, ISSN: 0924-4247, Vol: 101, Issue: 3, Page: 269-274.

5. Eladl, Abdelkhalik, Mostafa, Rania, Islam, Aminul, Loaldi, Dario, Soltan, Hassan, Hansen, Hans N., Tosello, Guido. "Effect of Process Parameters on Flow Length and Flash Formation in Injection Moulding of High Aspect Ratio Polymeric Micro Features" Micromachines, January 2018, Pages: 1-19.

6. Handbook of Statistical Methods. [ONLINE] Available at: https://www.itl.nist.gov/div898/handbook/pri/section4/pri471.htm. [Accessed 27 May 2018].

7. Bull, S.J., Zhou, Qiusha. "A simulation test for wear in injection moulding machines" Wear, Volume 249, Issues 5–6, June 2001, Pages 372-378. NIST/SEMATECH. 2003. E

8. Rogelj, S., & Krajnc, M. (2008). Pressure and temperature behavior of thermoplastic polymer melts during high-pressure expansion injection molding. Polymer Engineering and Science, 48(9), 1815-1823.

9. Chen, C.S., Determination of the Injection Molding Process Parameters in Multicavity Injection Molds, Journal of Reinforced Plastics and Composites, September 2009.

10. Crescent Industries. 2018. News and Blog. [ONLINE] Available at: https://info.crescentind.com/blog/bid/72378/What-are-Causes-of-Flash-in-Plastic-Injection-Molding. [Accessed 10 May 2018].

11. iSixSigma. 2018. Full factorial DOE. [ONLINE] Available at: https://www.isixsigma.com/dictionary/full-factorial-doe/. [Accessed 18 May 2018].

12. Hopmann, C., Abel, D., Heinisch, J. et al. Prod. Eng. Res. Devel. (2017) 11: 97. https://doi-org.ezhost.utrgv.edu/10.1007/s11740-017-0719-6.

13. Le Goff, R., Delaunay, D., Boyard, N., Jarny, Y., Jurkowski, T., Deterre, R., On-line temperature measurements for polymer thermal conductivity estimation under injection molding conditions, International Journal of Heat and Mass Transfer, February 2009.

14. Kasmer, David. Injection Mold Design Engineering. Munich; Carl Hanser Verlang, 2007. Print

15. Bernards' Injection Molding Tips, Techniques and Technology for Shop Floor Technicians and Supervisors. 2018. MOLD FLOW ANALYSIS. [ONLINE] Available at: http://bernardray0.tripod.com/index.htm. [Accessed 21 May 2018].

16. Collins, C. "Monitoring cavity pressure perfects injection molding", Assembly Automation, Vol.19, Issue:3, pp.197-202.

17. "The influence of flow and thermal properties on injection pressure and cooling time prediction", Applied Mathematical Modeling, Vol.40, Issue:15-16, pp.7001-7011.

18. Uzair Ahmed Dar; Ying Jie Xu; Sheikh Muhammad Zakir; Muhammad-Umar Saeed. The effect of injection molding process parameters on mechanical and fracture behavior of polycarbonate polymer. Journal of Applied Polymer Science, September 2016.

19. Kumar, Amit, Ghoshdastidar, P.S., Muju, M.K., "Computer simulation of transport processes during injection mold-filling and optimization of the molding conditions" Journal of Materials Processing Technology, Volume 120, Issues 1–3, 15 January 2002, Pages 438-449.

20. Volpe, Valentina. "Determination of the effect of pressure on viscosity at high shear rates by using an injection molding machine" Journal of applied polymer science, Volume: 135, Issue: 24, Page: 45277.

21. Donggang Yao, Byung Kim, Jaehong Choi & Robert Brown (2008) Optimizing Injection Molding Toward Multiple Quality and Cost Issues, Polymer-Plastics Technology and Engineering, 38:5, 955-966.

22. K. Shen, H. W. Chien, and Yi Lin. "Optimization of the Micro-Injection Molding Process using Grey Relational Analysis and MoldFlow Analysis" Journal of Reinforced Plastics and Composites, Vol 23, Issue 17, pp. 1799 – 1814.

23. Fan, Zhaoyan, A pressure-temperature dual sensing methodology for injection molding monitoring, University of Massachusetts Amherst, ProQuest Dissertations Publishing, 2009.

24. Tuncol, Goker; Danisman, Murat; Kaynar, Alper; Sozer, E. Murat. Constraints on monitoring resin flow in the resin transfer molding (RTM) process by using thermocouple sensors. Composites Part A: Applied Science and Manufacturing Volume 38, Issue 5, Pages 1271-1444 (May 2007).

25. Tutar, M.; Karakus, A. Computational Study of the Effect of Governing Parameters on a Polymer Injection Molding Process for Single-Cavity and Multicavity Mold Systems. Journal of Manufacturing Science and Engineering., February 2010.

26. Wang, Jian, Online pressure-volume-temperature measurements of PP using a testing mold to simulate the injection molding process, Journal of applied polymer science, October 2010.

APPENDIX A

APPENDIX A

Thermoplastics material

Tabs: Filler / Fiber | Environmental Impact | Quality Indicators
Description | Recommended Processing | Rheological Properties | Thermal Properties | pvT Properties | Mechanical Properties | Shrinkage Properties

Field	Value
Family name	POLYAMIDES (NYLONS, PPA, ...)
Trade name	Akulon K224-HG6U BK223 (J-3/30/HS BK223)
Manufacturer	DSM EP (Americas)
Link	
Family abbreviation	PA6
Material structure	Crystalline
Data source	Moldflow (Formerly C-Mold) : pvT-Measured : mech-Measured
Date last modified	11-OCT-05
Date tested	07-APR-98
Data status	Non-Confidential
Material ID	6526
Grade code	CM6526
Supplier code	DSMEPA
Fibers/fillers	33% Glass Fiber Filled

Name: Akulon K224-HG6U BK223 (J-3/30/HS BK223) : DSM EP (Americas)

OK   Help

Thermoplastics material

Tabs: Filler / Fiber | Environmental Impact | Quality Indicators
Description | Recommended Processing | Rheological Properties | Thermal Properties | pvT Properties | Mechanical Properties | Shrinkage Properties

Field	Value	Units
Melt density	1.2179	g/cm^3
Solid density	1.4201	g/cm^3

2-domain modified Tait pvT model coefficients

Coefficient	Value	Units
b5	493.15	K
b6	4.35e-08	K/Pa
b1m	0.0008	m^3/kg
b2m	3.83e-07	m^3/kg-K
b3m	2.04e+08	Pa
b4m	0.005149	1/K
b1s	0.0007588	m^3/kg
b2s	2.8e-07	m^3/kg-K
b3s	2.76e+08	Pa
b4s	0.004121	1/K
b7	4.12e-05	m^3/kg
b8	0.08239	1/K
b9	5.3e-09	1/Pa

Plot pvT data...

View test information...

Name: Akulon K224-HG6U BK223 (J-3/30/HS BK223) : DSM EP (Americas)

OK   Help

Analysis Wizard

Sequence | Gate Location | Material | **Process Settings** | Molding Window | Advanced | Accuracy

Material properties

Mold temperature [50.00:90.00] C `70.00` ▲▼ [Default]

Melt temperature [250.00:290.00] C `270.00` ▲▼ [Default]

Maximum injection pressure limit

Maximum machine injection pressure [10.00:500.00] MPa `180.00` ▲▼

☑ Automatic velocity/pressure switch-over

Velocity/pressure switch-over by volume % `99`

Machine injection time

☐ Automatic injection time

Time (sec) : `15.00`

Machine clamp open time

Time (sec) : `5.00`

[‹Back] [Next›] [**Finish**] [Analyze] [Cancel] [Help]

Thermoplastics material

	Filler / Fiber	Environmental Impact	Quality Indicators

Description | Recommended Processing | Rheological Properties | Thermal Properties | pvT Properties | Mechanical Properties | Shrinkage Properties

Family name	POLYAMIDES (NYLONS, PPA, ...)
Trade name	Unitika Nylon6 FR-RUNG50LWJ
Manufacturer	Unitika
Link	
Family abbreviation	PA6
Material structure	Crystalline
Data source	Manufacturer (Unitika) : pvT-Supplemental : mech-Measured
Date last modified	13-SEP-11
Date tested	28-OCT-09
Data status	Non-Confidential
Material ID	13849
Grade code	CM13849
Supplier code	UNITIKA
Fibers/fillers	50% Glass Fiber Filled

Name Unitika Nylon6 FR-RUNG50LWJ : Unitika

[OK] [Help]

Thermoplastics material

Filler / Fiber		Environmental Impact		Quality Indicators	
Description	Recommended Processing	Rheological Properties	Thermal Properties	pvT Properties	Mechanical Properties	Shrinkage Properties

Viscosity

Default viscosity model   Cross-WLF   [View viscosity model coefficients...]

[Plot Viscosity]

Juncture loss method coefficients

| c1 | | $Pa^{(1-c2)}$ |
| c2 | | |

| Transition temperature | 180 | C |
| Moldflow Viscosity Index | VI(270)0209 | |

Melt mass-flow rate (MFR)

Temperature		C
Load		Kg
Measured MFR		g/10min

☐ Extension viscosity

Name [Unitika Nylon6 FR-RUNG50LWJ : Unitika]

[OK] [Help]

Thermoplastics material

Filler / Fiber		Environmental Impact		Quality Indicators	
Description	Recommended Processing	Rheological Properties	Thermal Properties	pvT Properties	Mechanical Properties	Shrinkage Properties

| Melt density | 1.3979 | g/cm^3 |
| Solid density | 1.4925 | g/cm^3 |

2-domain modified Tait pvT model coefficients

b5	486.65	K
b6	4e-08	K/Pa
b1m	0.0007031	m^3/kg
b2m	2.171e-07	$m^3/kg\cdot K$
b3m	5.31885e+08	Pa
b4m	0.005338	1/K
b1s	0.000693	m^3/kg
b2s	1.22e-07	$m^3/kg\cdot K$
b3s	4.34038e+08	Pa
b4s	0.003139	1/K
b7	1.008e-05	m^3/kg
b8	0.08992	1/K
b9	1.958e-09	1/Pa

[Plot pvT data...]

[View test information...]

Name [Unitika Nylon6 FR-RUNG50LWJ : Unitika]

[OK] [Help]

Analysis Wizard   ✕

| Sequence | Gate Location | Material | Process Settings | Molding Window | Advanced | Accuracy |

◉ Commonly used materials:

Novamid-1040H2: DSM Japan Engineering Plastics	▲
Unitika Nylon6 FR-RUNG50LWJ: Unitika	
Akulon K224-HG6U BK223 (J-3/30/HS BK223): DSM EP (Americas)	
Grilon A28GM: Cranfield University	
LUMID HI5052A: LG Chemical	▼

Remove

◯ Specific material: Customize Material List...   Reset Material List

Manufacturer

DSM Japan Engineering Plastics   ▼   Import...

Trade name

Novamid-1040H2   ▼   Search...

Selected material

Details...   Report...   Resin   ♻   Energy usage   🔆
                                   identification   7   indicator:
                                   code:

☑ Add material to commonly used list after selecting

<Back   Next>   Finish   Analyze   Cancel   Help

Analysis Wizard   ✕

| Sequence | Gate Location | Material | Process Settings | Molding Window | Advanced | Accuracy |

Material properties

Mold temperature [70.00:110.00] C   90.00   ▲▼   Default

Melt temperature [235.00:300.00] C   265.00   ▲▼   Default

Maximum injection pressure limit

Maximum machine injection pressure [10.00:500.00] MPa   180.00   ▲▼

☑ Automatic velocity/pressure switch-over

Velocity/pressure switch-over by volume %   99

Machine injection time   Machine clamp open time

☐ Automatic injection time

Time (sec) :   15.00   Time (sec) :   5.00

<Back   Next>   Finish   Analyze   Cancel   Help

Thermoplastics material

| Filler / Fiber | | Environmental Impact | | Quality Indicators | |
| Description | Recommended Processing | Rheological Properties | Thermal Properties | pvT Properties | Mechanical Properties | Shrinkage Properties |

Family name	POLYAMIDES (NYLONS, PPA...)
Trade name	Novamid-1040H2
Manufacturer	DSM Japan Engineering Plastics
Link	
Family abbreviation	PA6
Material structure	Crystalline
Data source	Manufacturer (DSM Japan Engineering Plastics) : pvT-Measured : mech-Supplemental
Date last modified	15-SEP-11
Date tested	
Data status	Non-Confidential
Material ID	2987
Grade code	CM2987
Supplier code	MITSUBI
Fibers/fillers	Unfilled

Name Novamid-1040H2 : DSM Japan Engineering Plastics

OK   Help

Thermoplastics material

| Filler / Fiber | | Environmental Impact | | Quality Indicators | |
| Description | Recommended Processing | Rheological Properties | Thermal Properties | pvT Properties | Mechanical Properties | Shrinkage Properties |

Viscosity

| Default viscosity model | Cross-WLF | View viscosity model coefficients... |
| | | Plot Viscosity |

Juncture loss method coefficients

| c1 | | Pa^(1-c2) |
| c2 | | |

| Transition temperature | 185 | C |
| Moldflow Viscosity Index | VI(270)0471 | |

Melt mass-flow rate (MFR)

Temperature		C
Load		Kg
Measured MFR		g/10min

☐ Extension viscosity

Name Novamid-1040H2 : DSM Japan Engineering Plastics

OK   Help

Thermoplastics material   ✕

Filler / Fiber		Environmental Impact		Quality Indicators	
Description	Recommended Processing	Rheological Properties	Thermal Properties	pvT Properties	Mechanical Properties	Shrinkage Properties

Melt density	0.95683	g/cm^3
Solid density	1.1413	g/cm^3

2-domain modified Tait pvT model coefficients

b5	503.15	K
b6	3.35e-08	K/Pa
b1m	0.001024	m^3/kg
b2m	6.12e-07	m^3/kg·K
b3m	1.36e+08	Pa
b4m	0.002673	1/K
b1s	0.0009502	m^3/kg
b2s	3.61e-07	m^3/kg·K
b3s	1.6e+08	Pa
b4s	0.005344	1/K
b7	7.35e-05	m^3/kg
b8	0.03555	1/K
b9	2.08e-09	1/Pa

Plot pvT data...

View test information...

Name   Novamid-1040H2 : DSM Japan Engineering Plastics

OK   Help
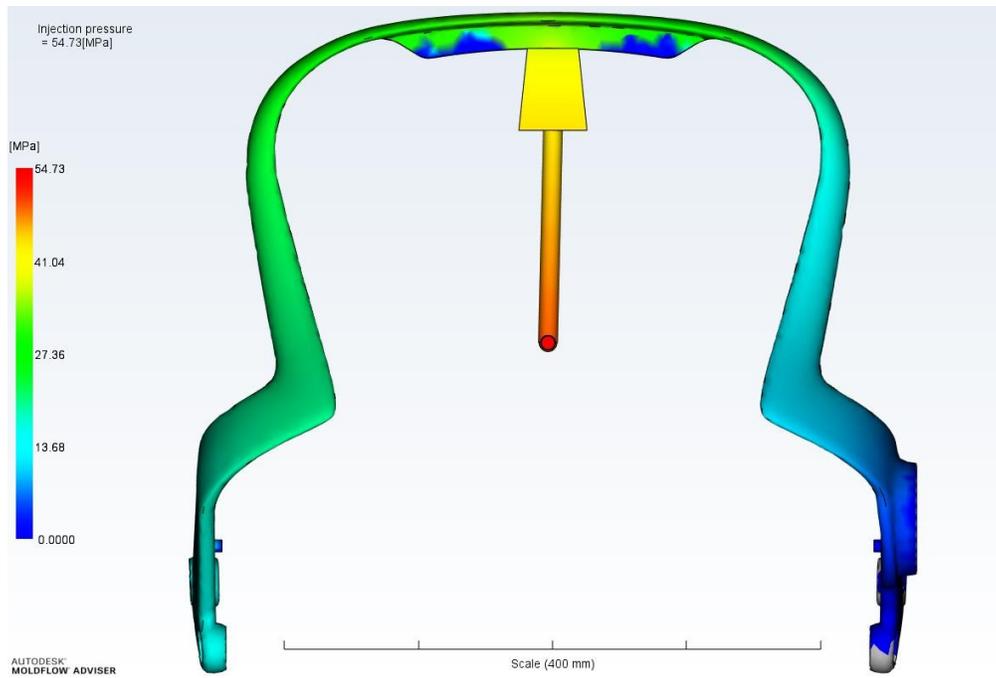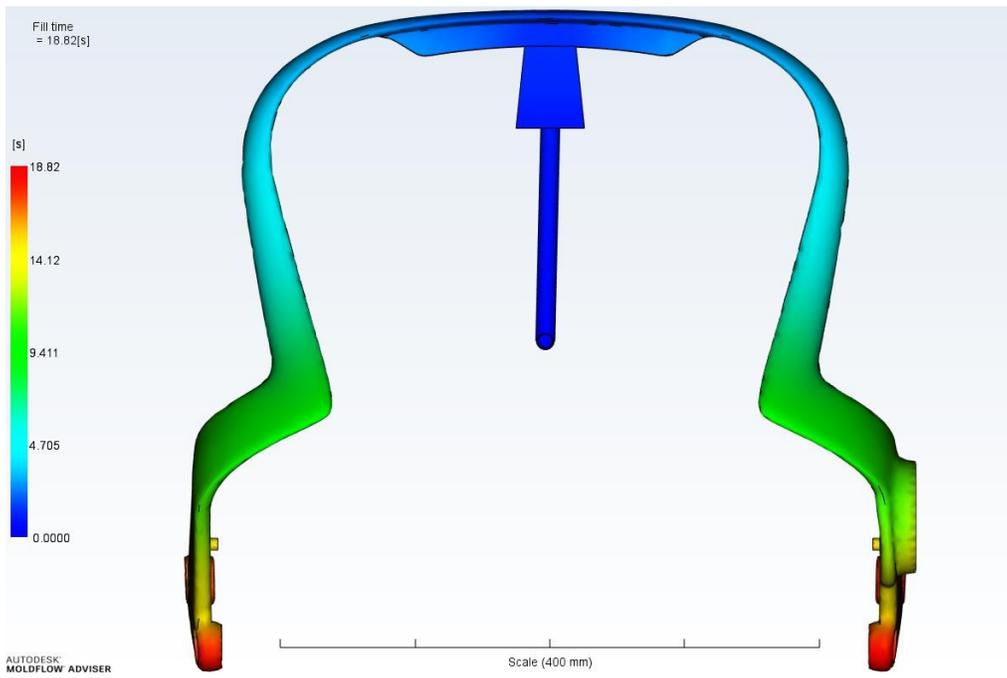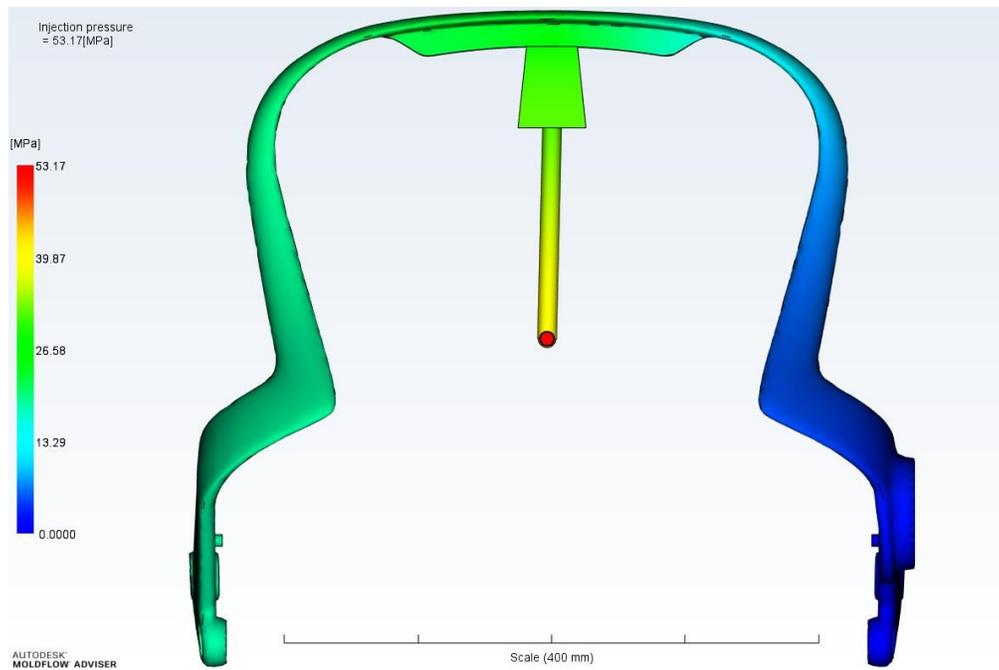
APPENDIX B

APPENDIX B

Sample #1 Fill time
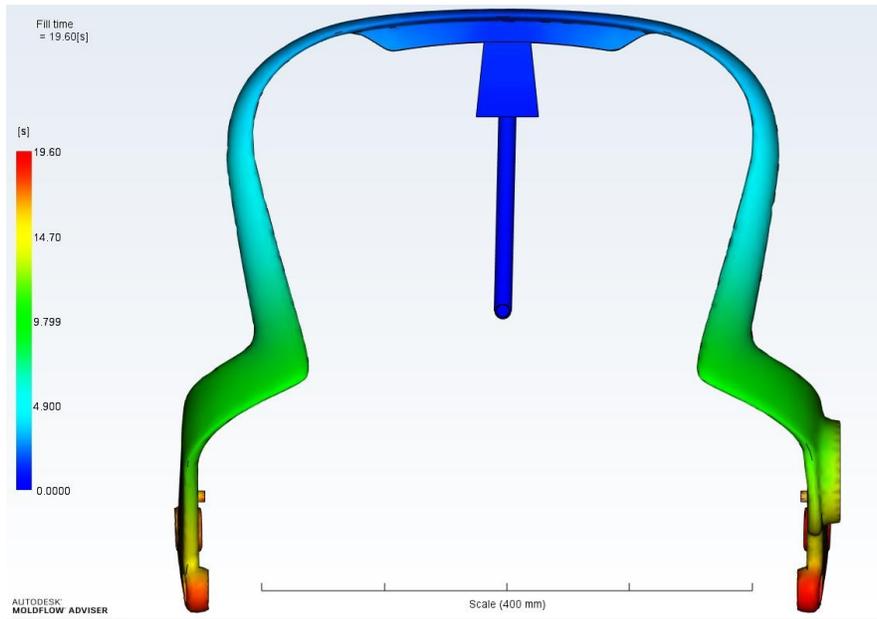
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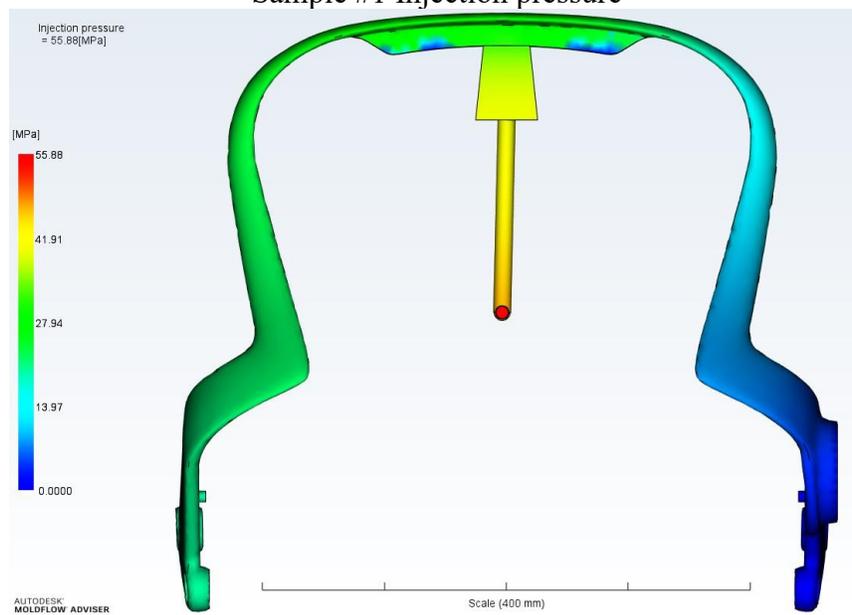
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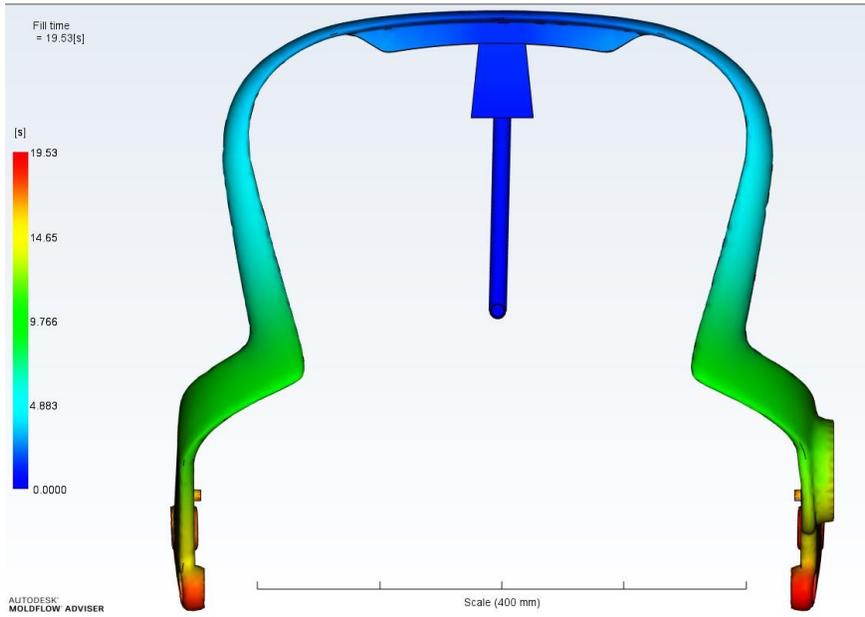
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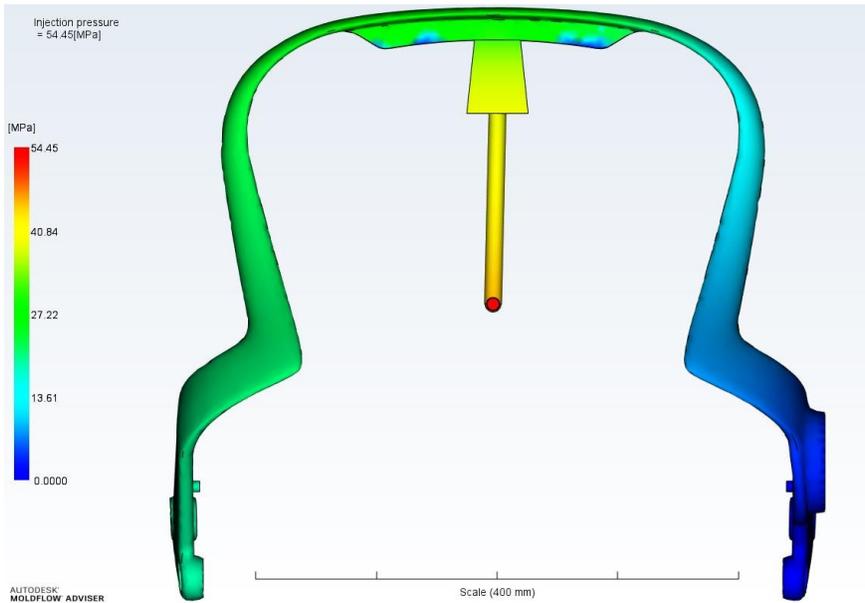
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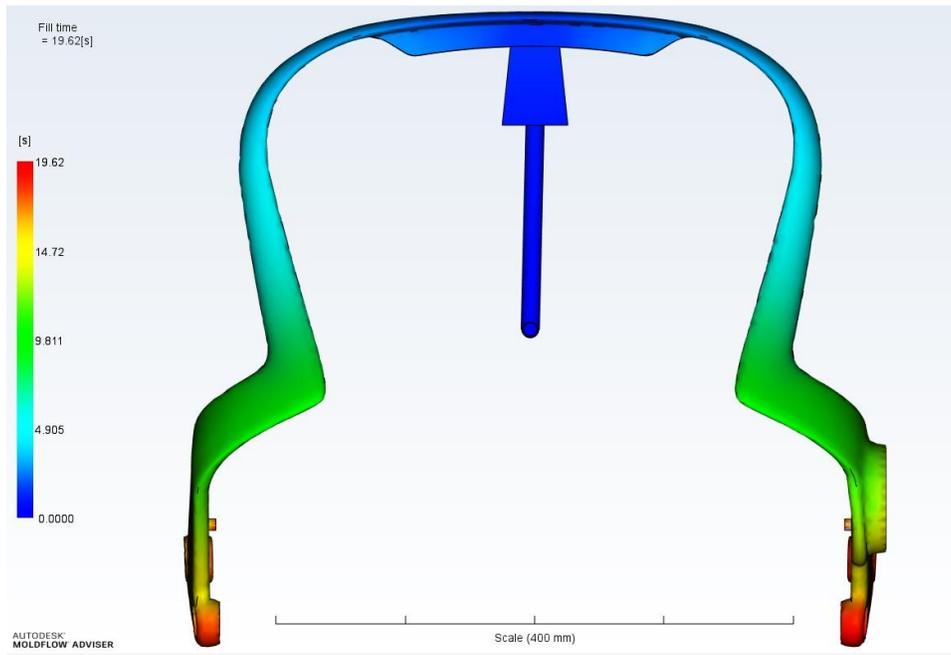
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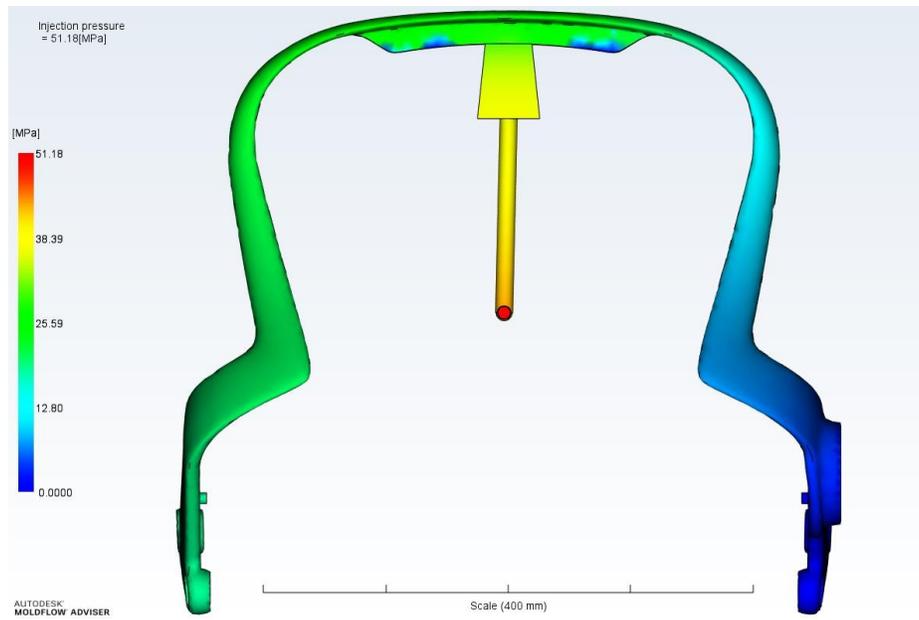
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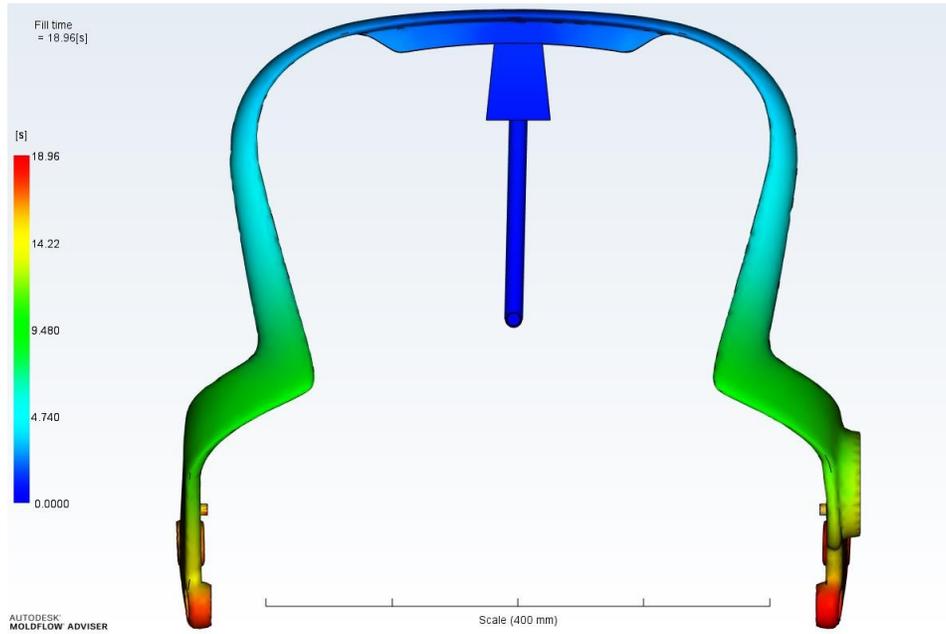
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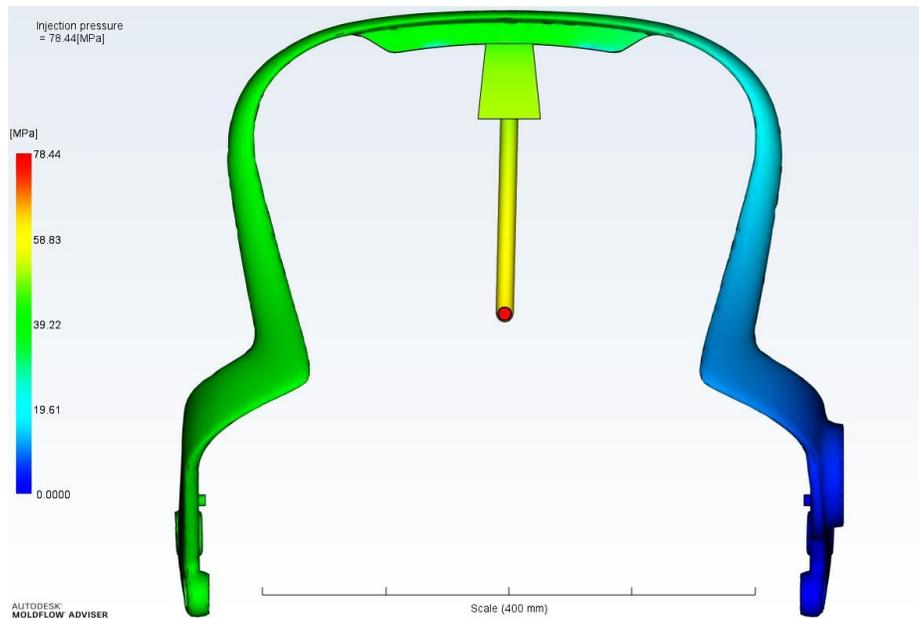
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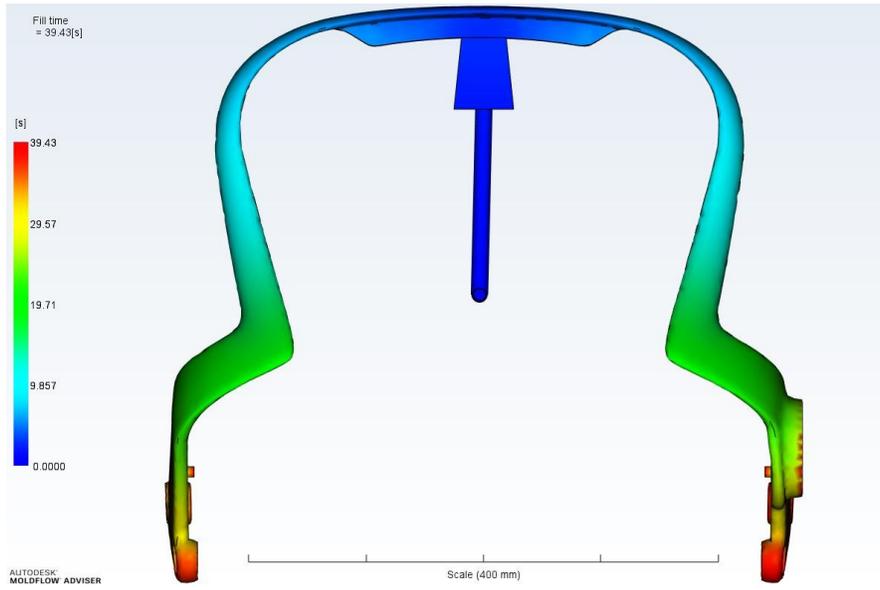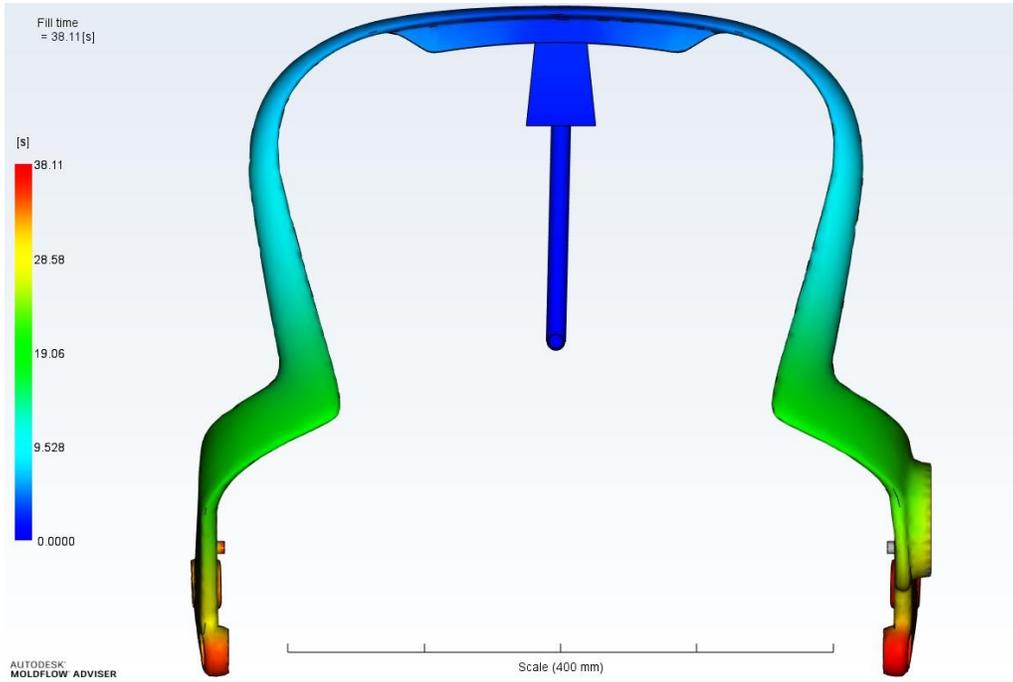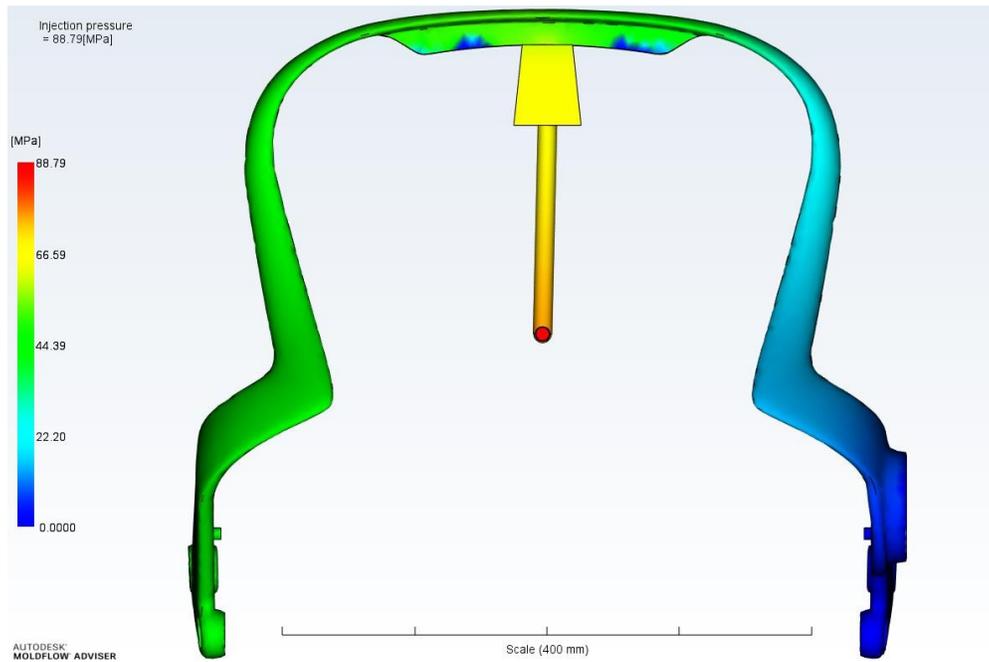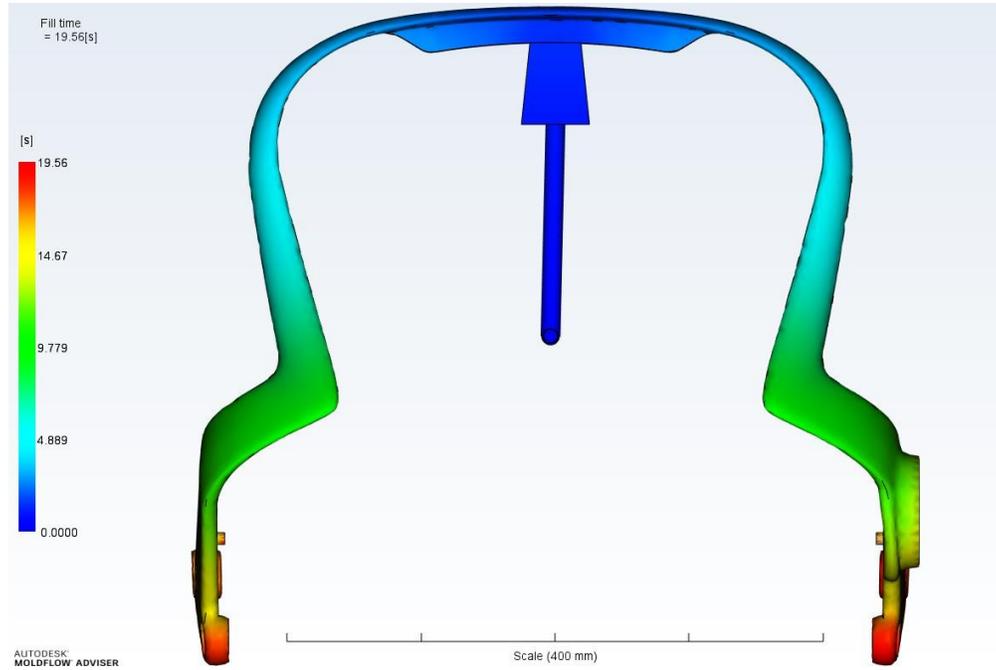

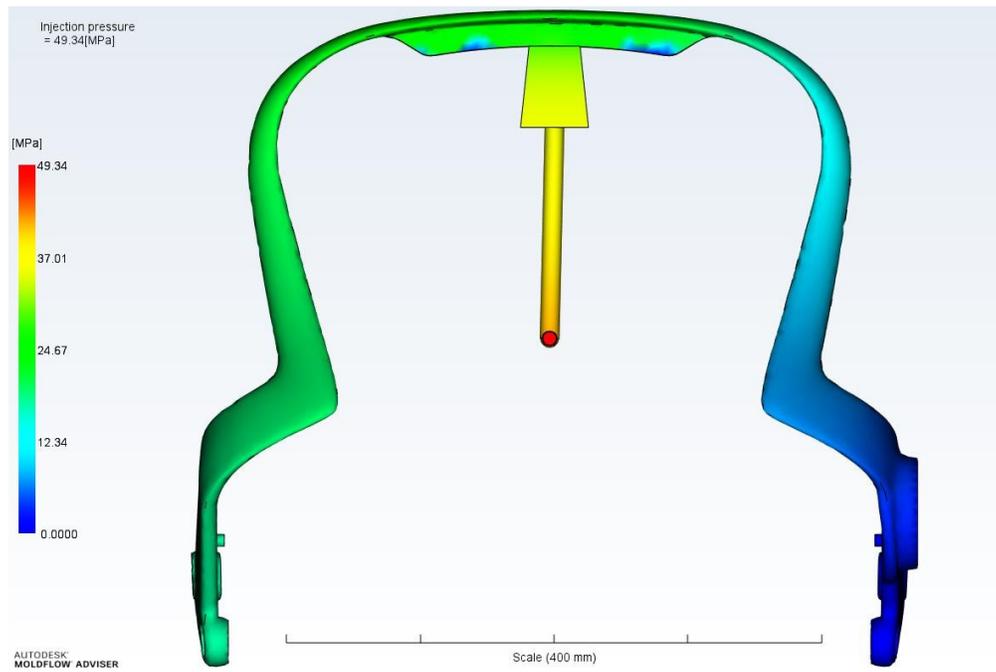Sample #5 Injection pressure
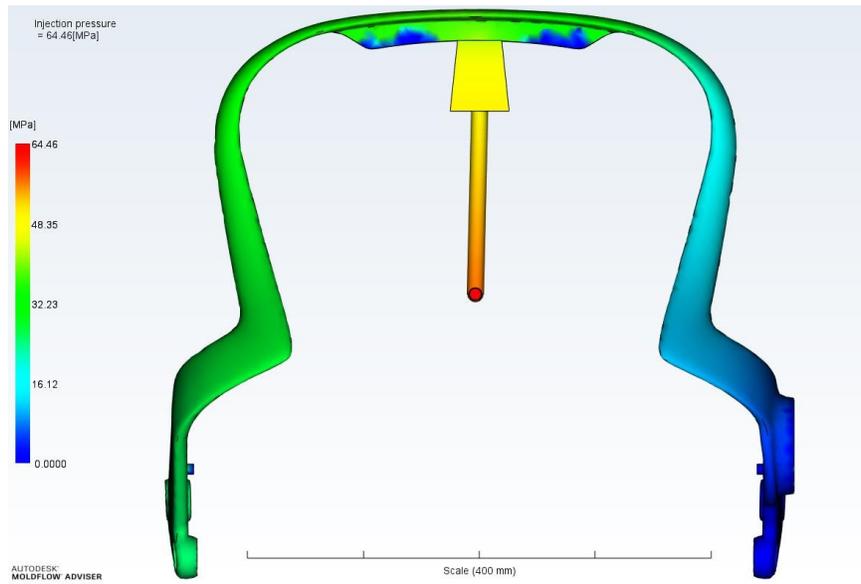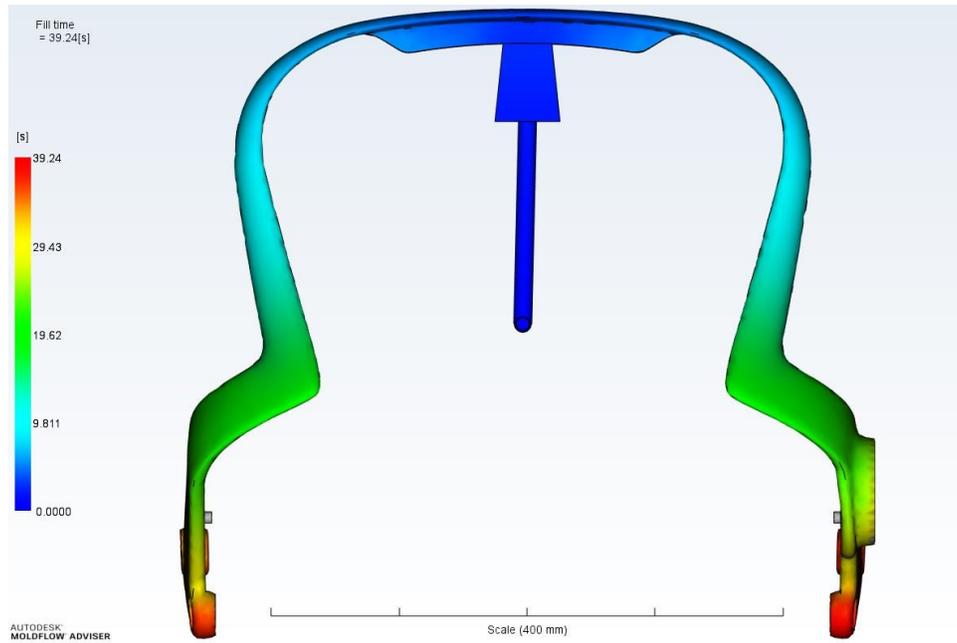
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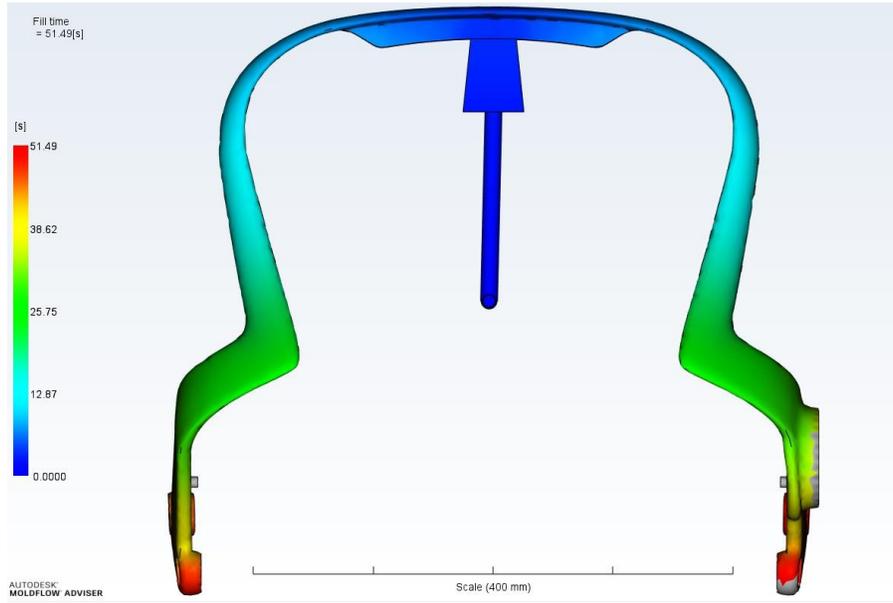
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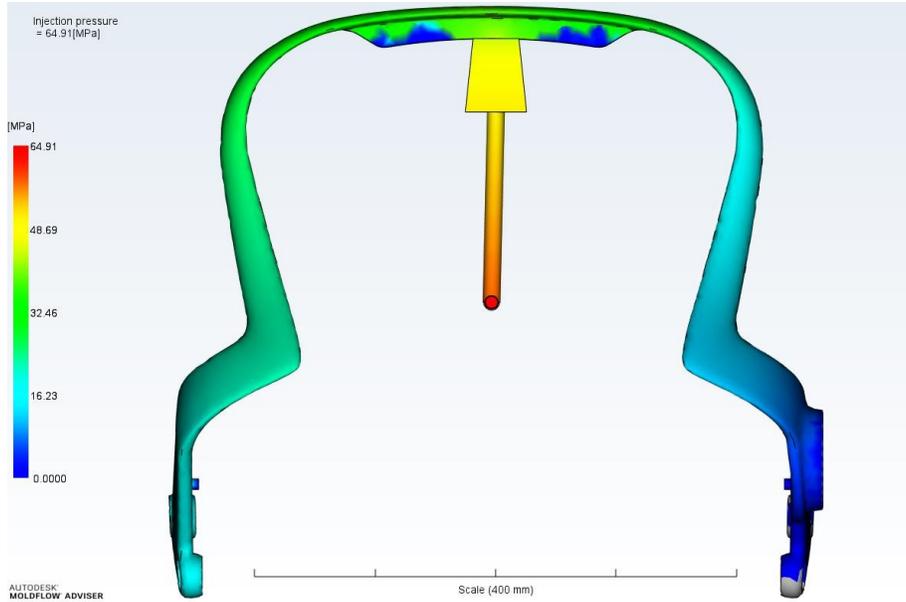
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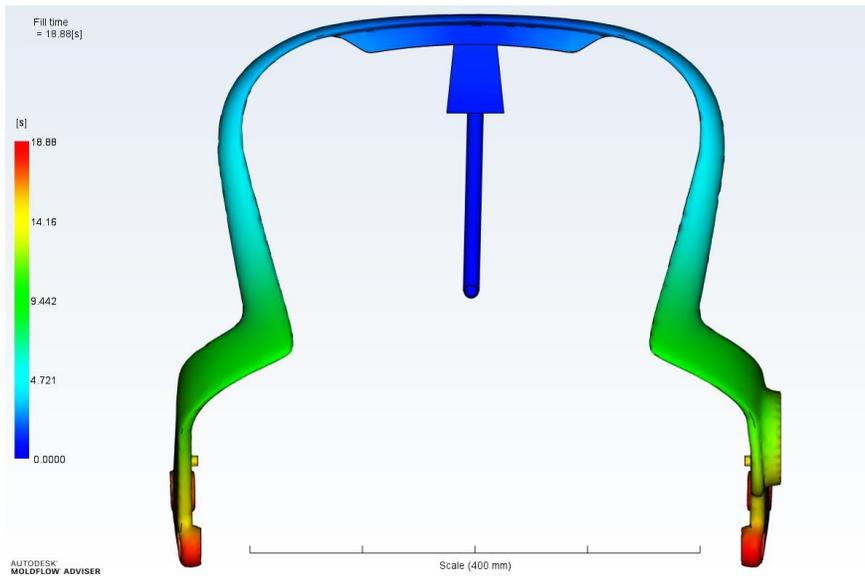
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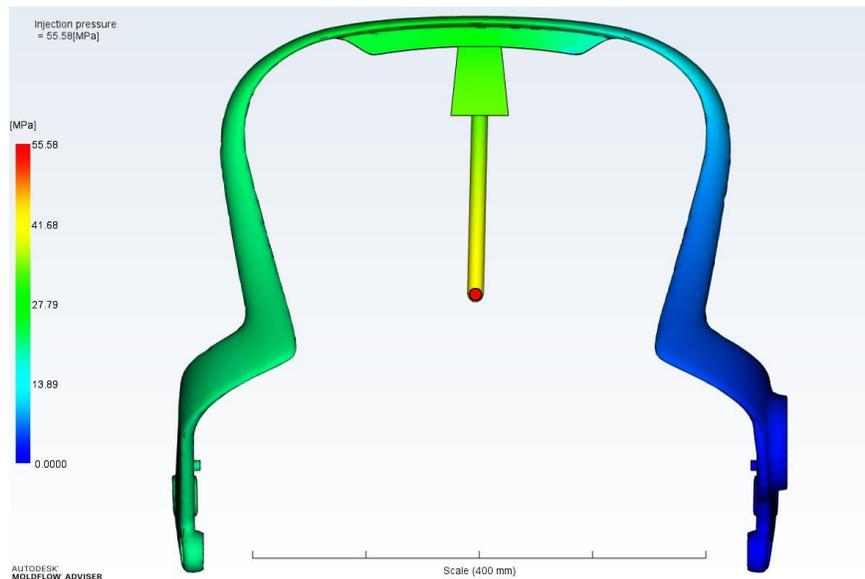
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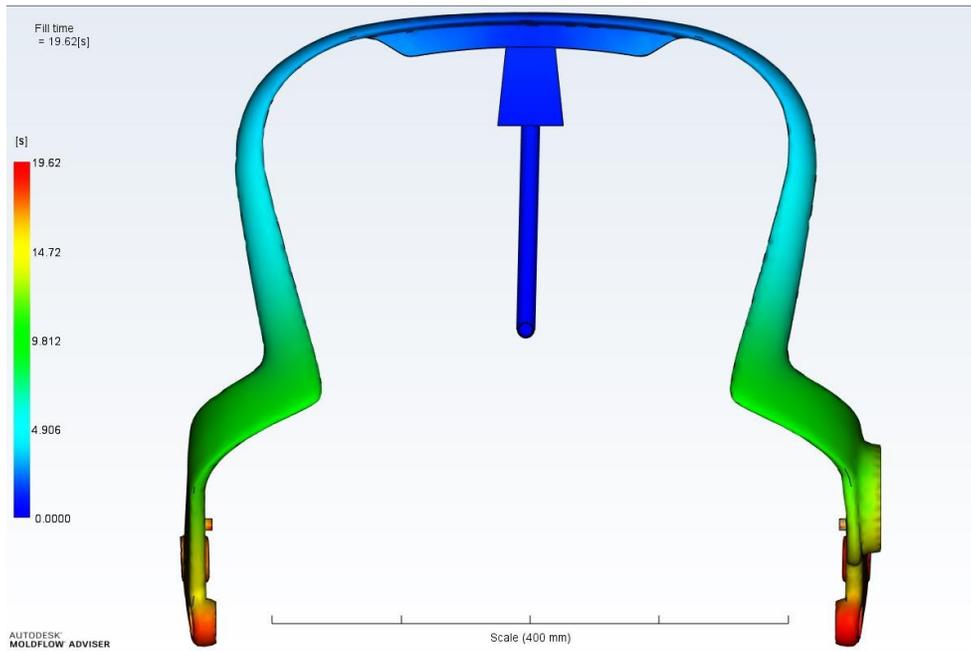
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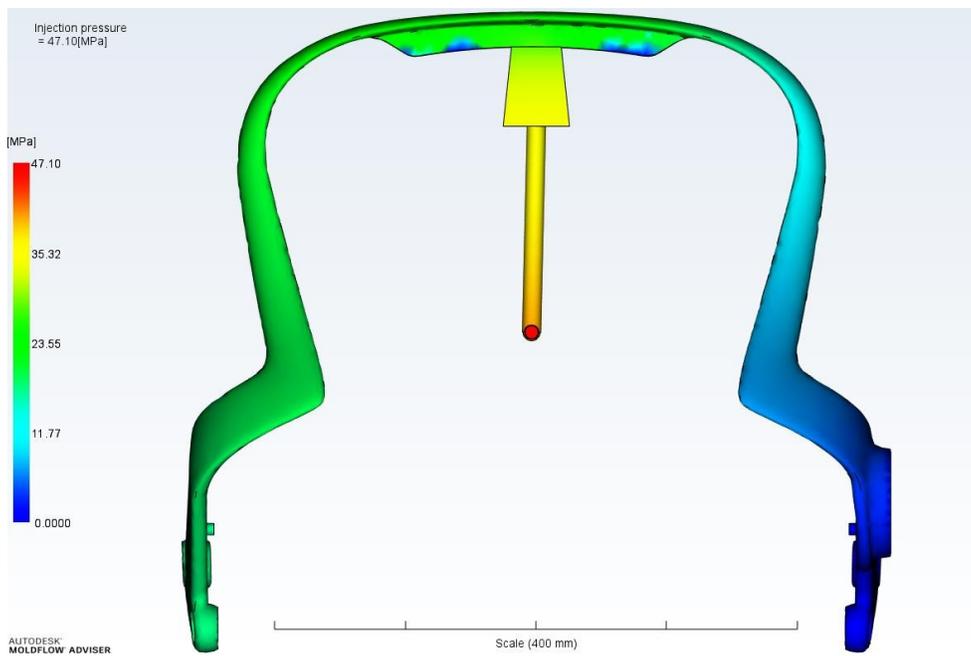
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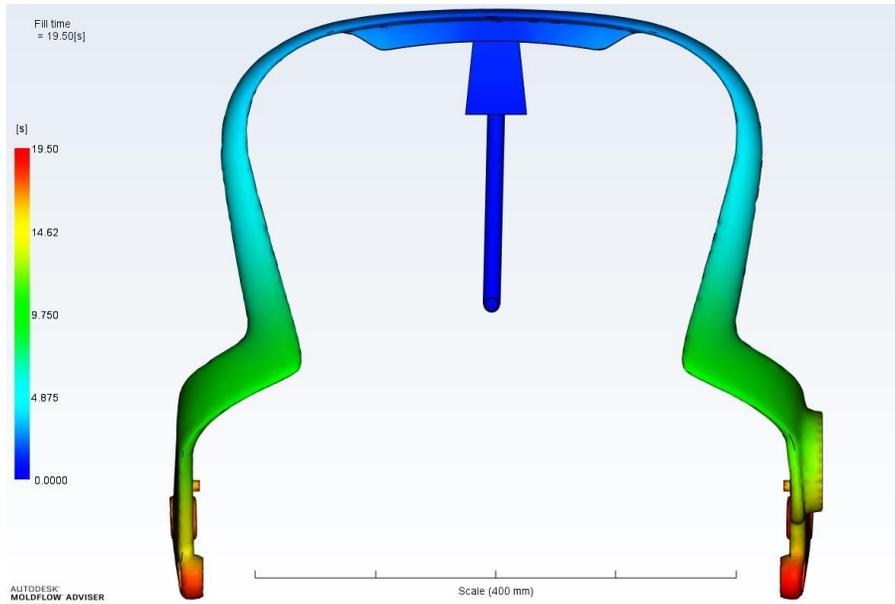
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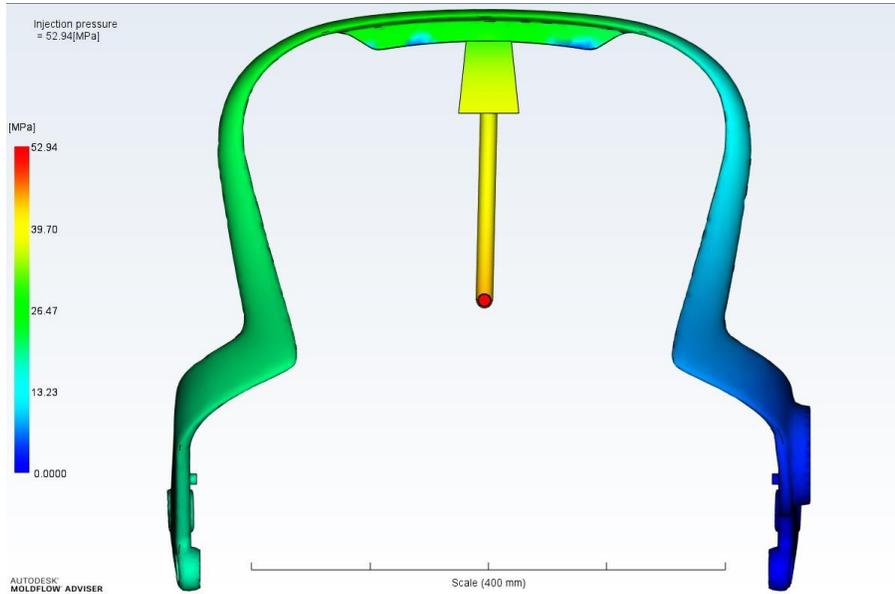
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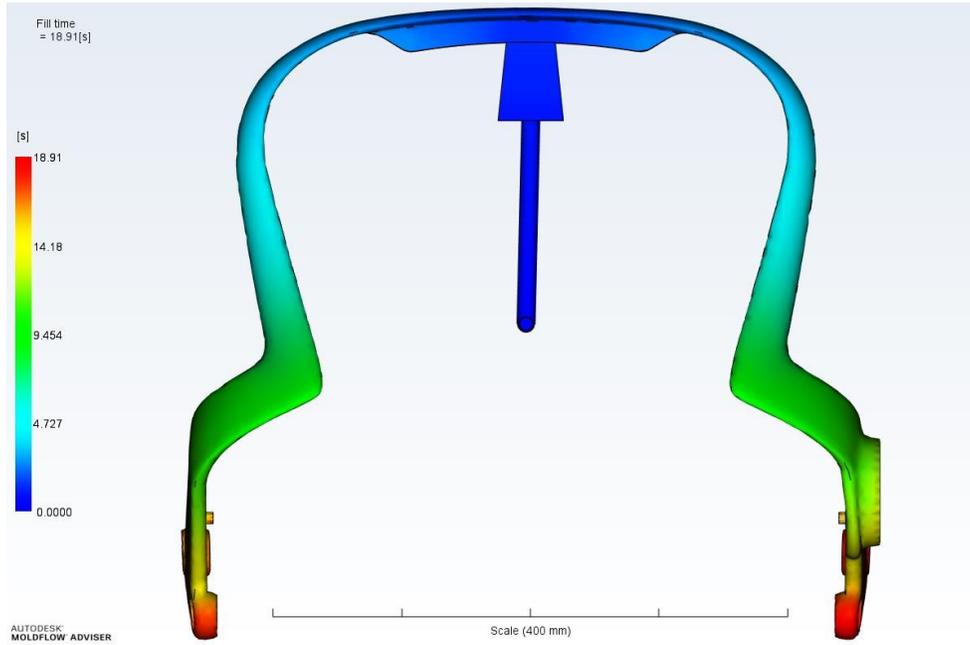
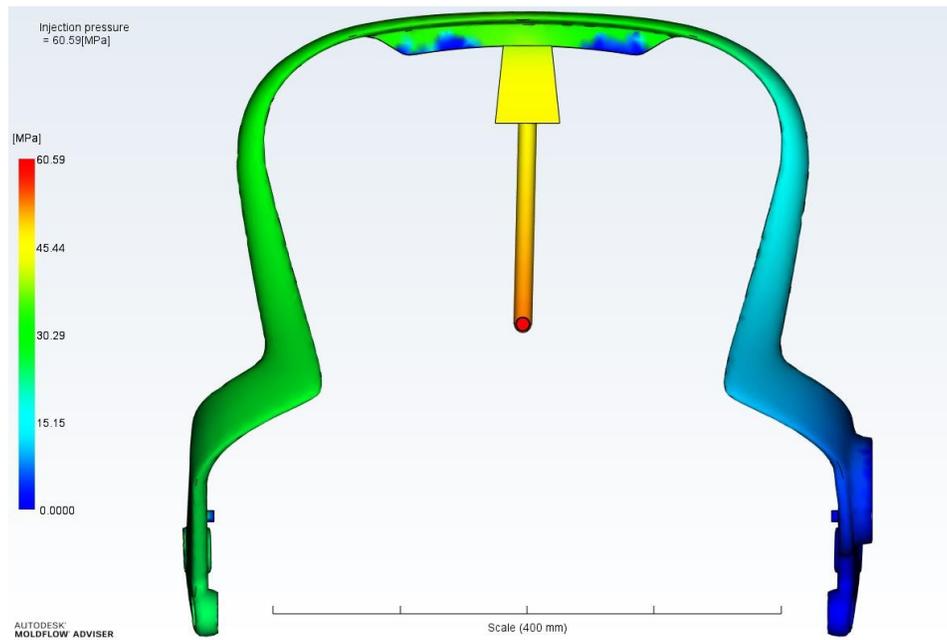Sample #10 Injection pressure
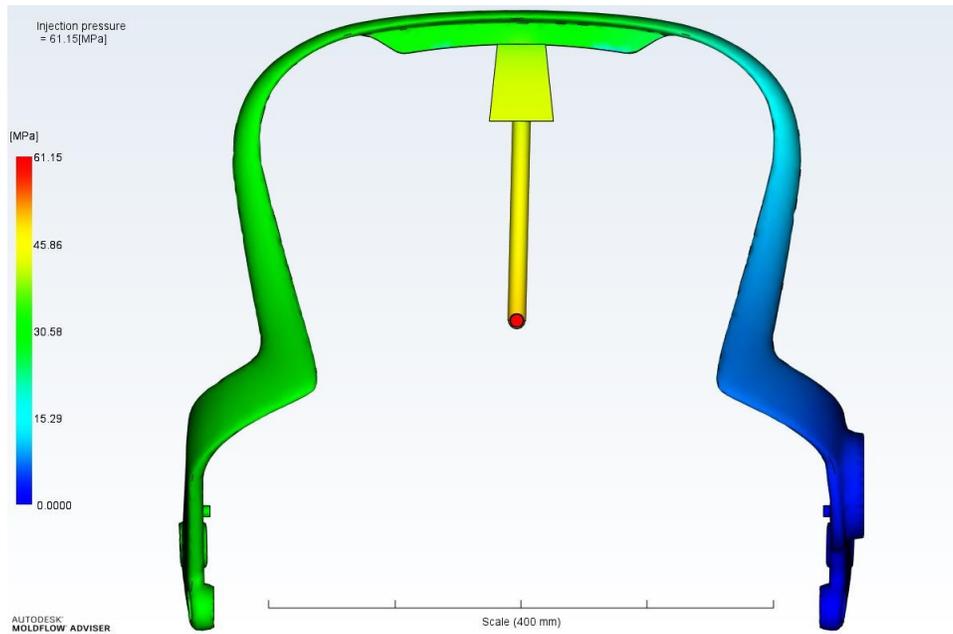
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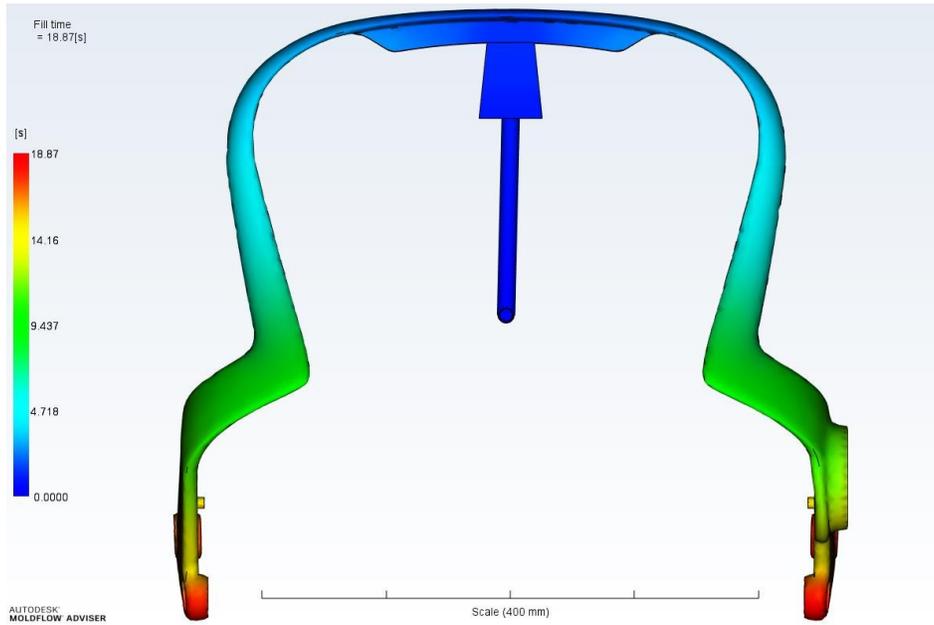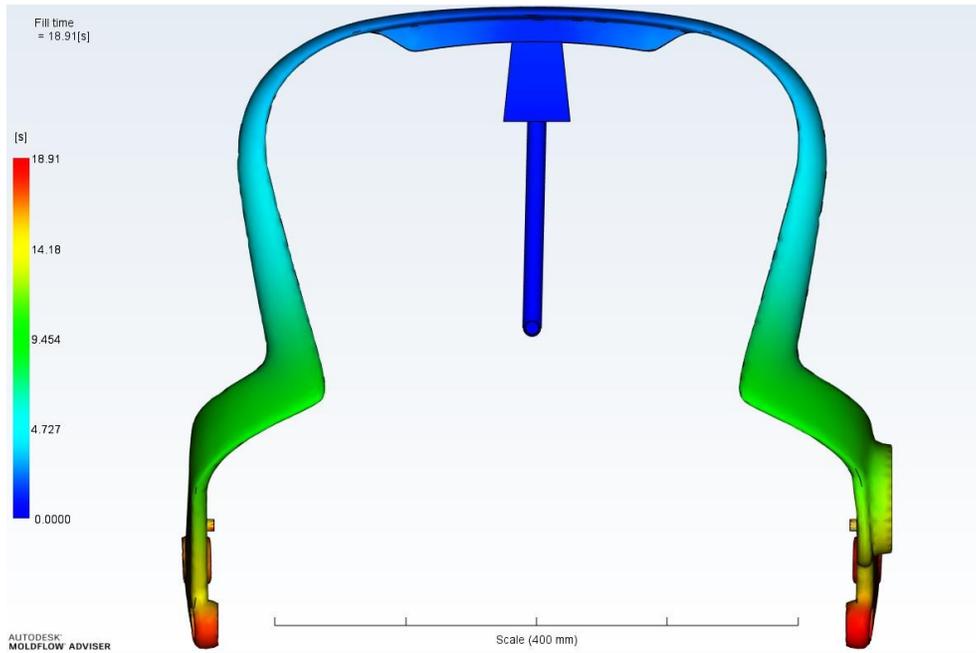

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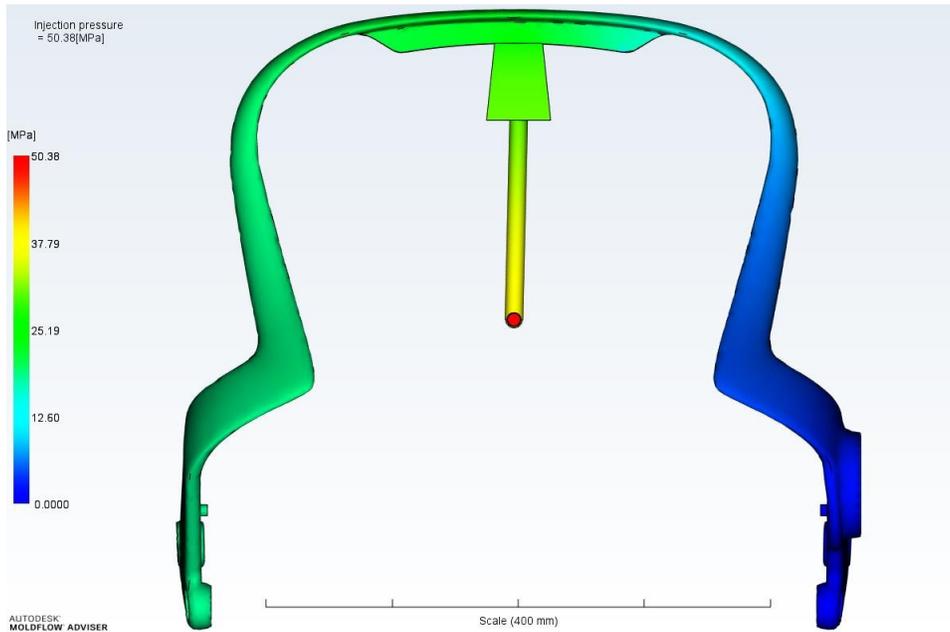
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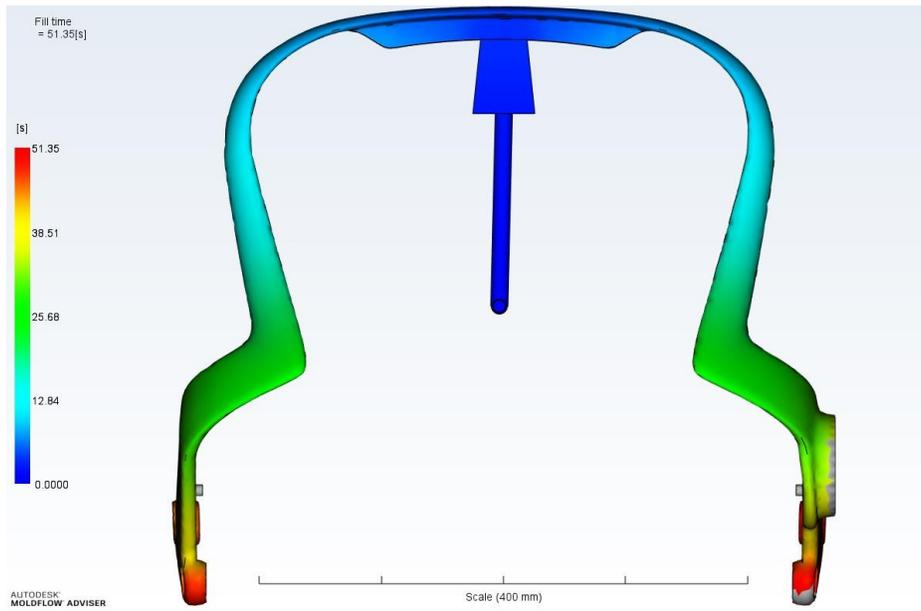
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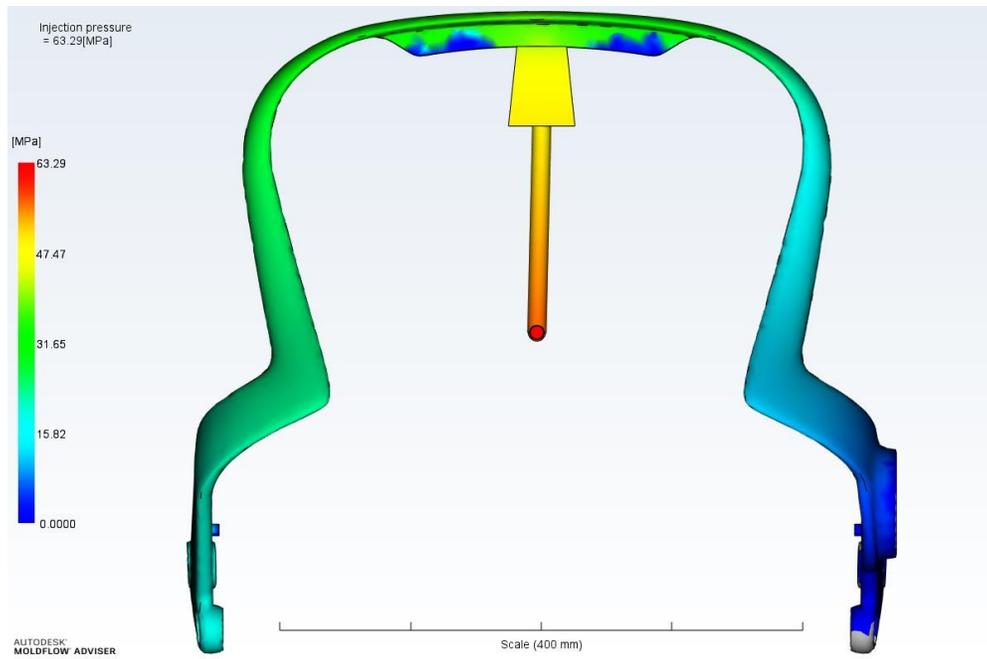
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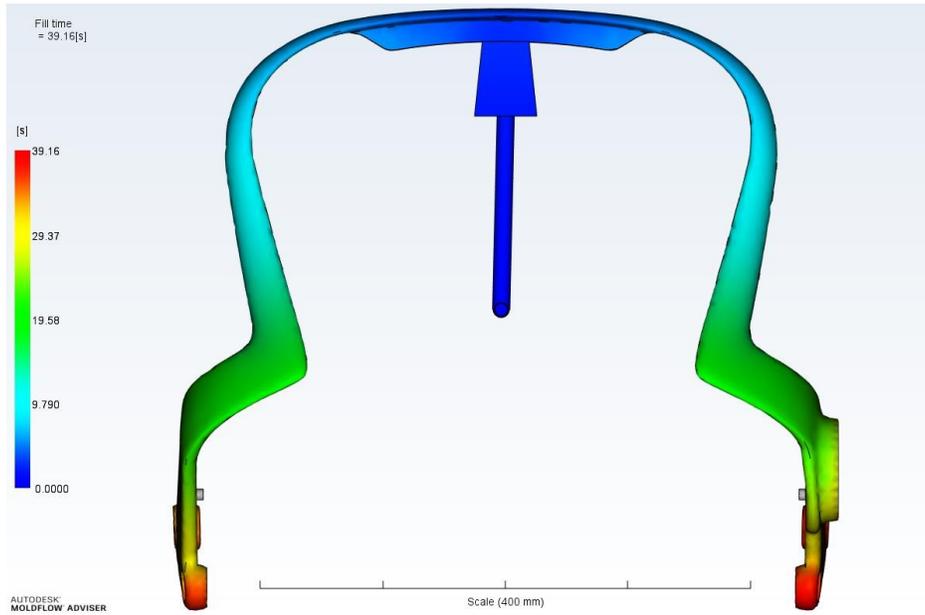
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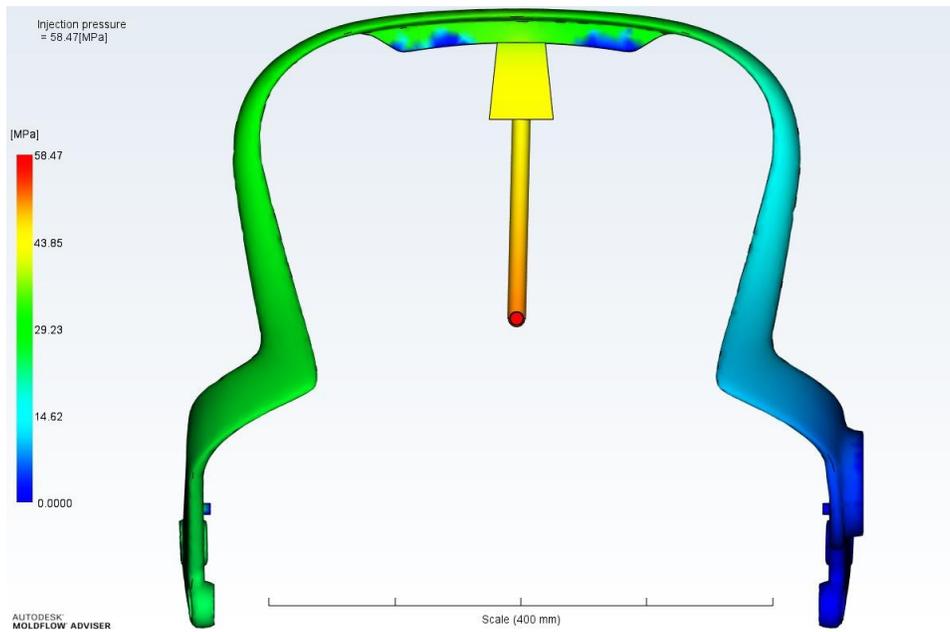
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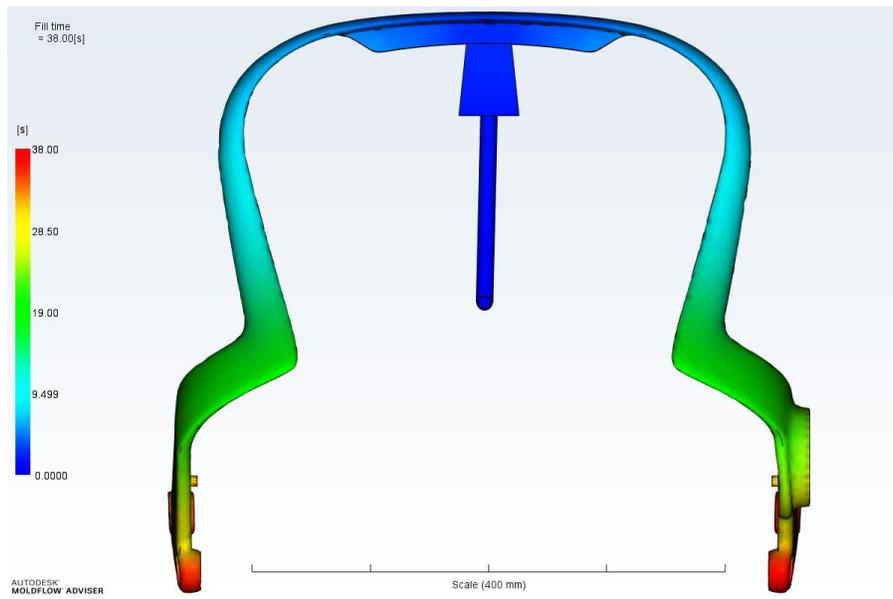
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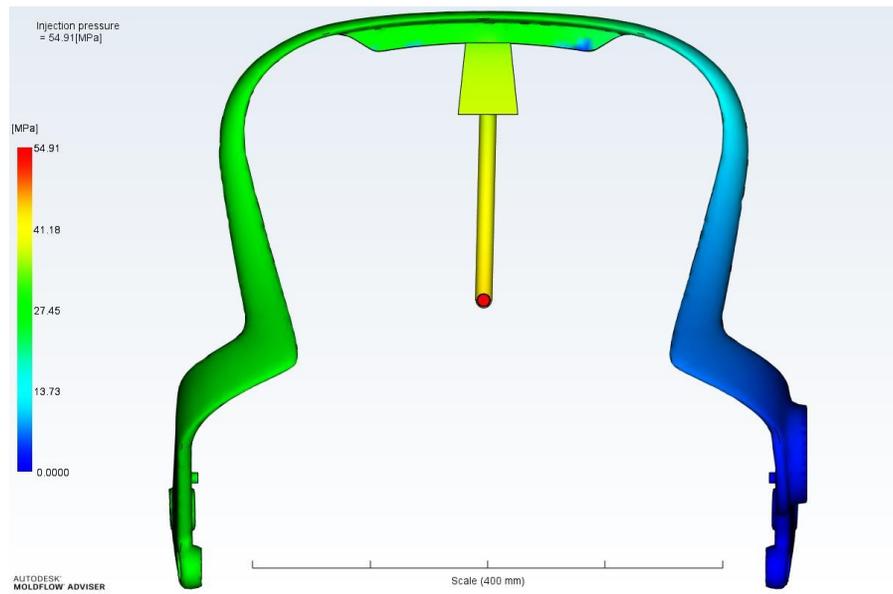
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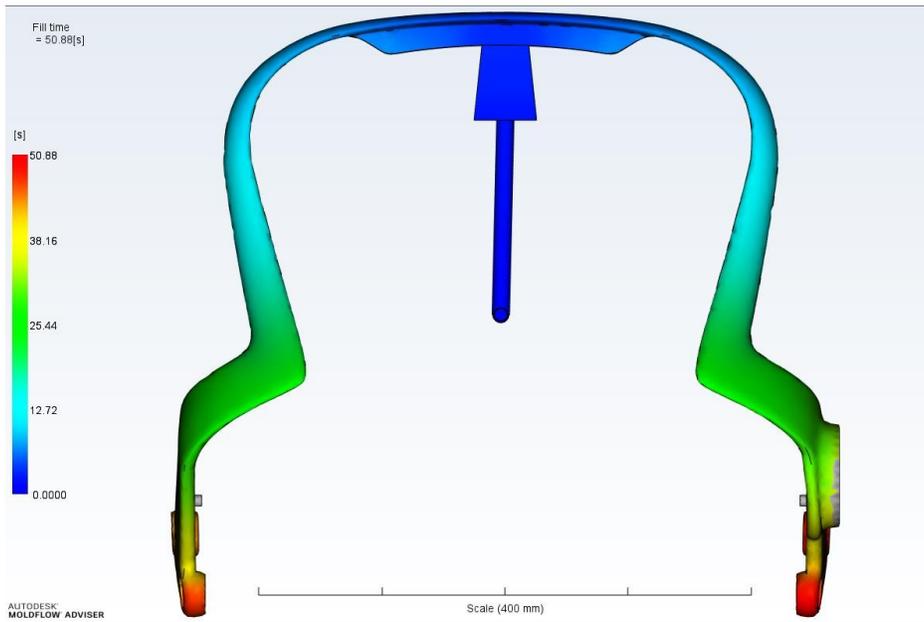
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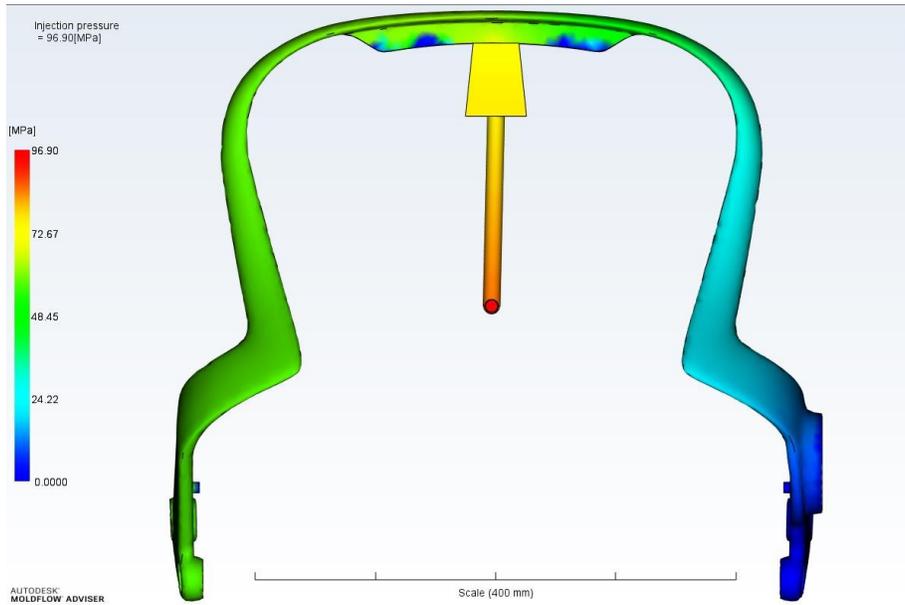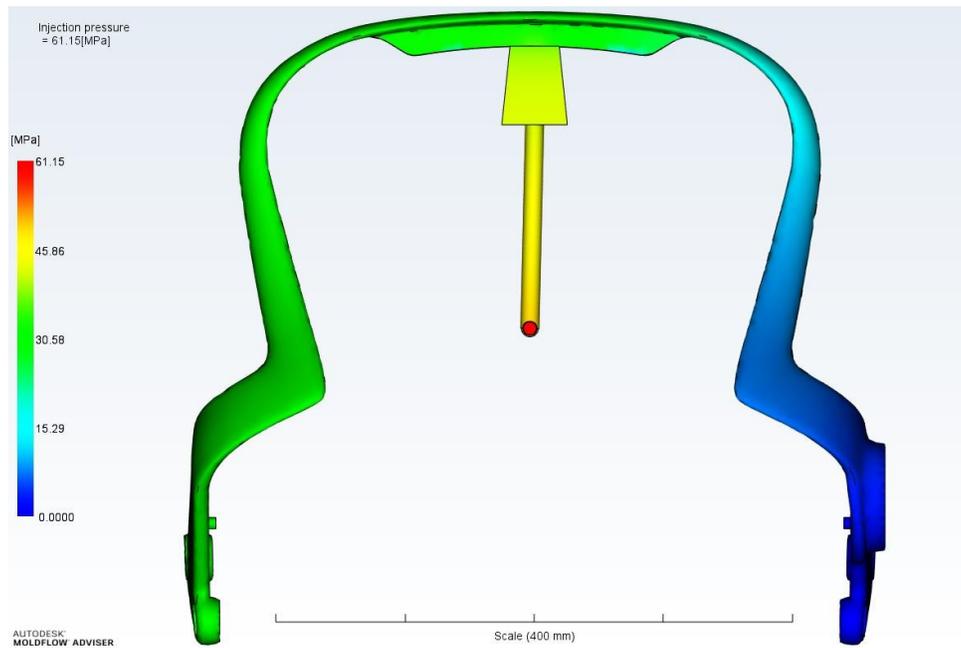
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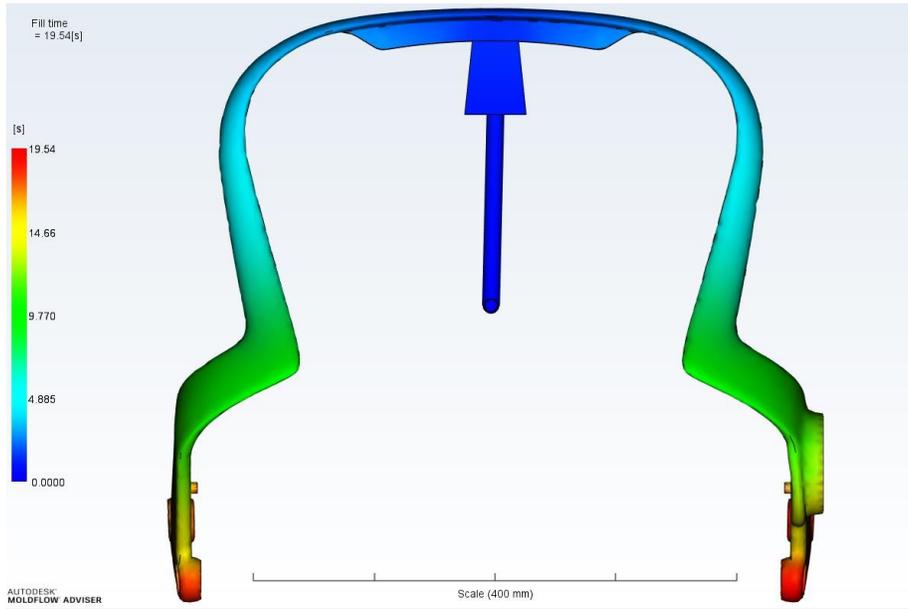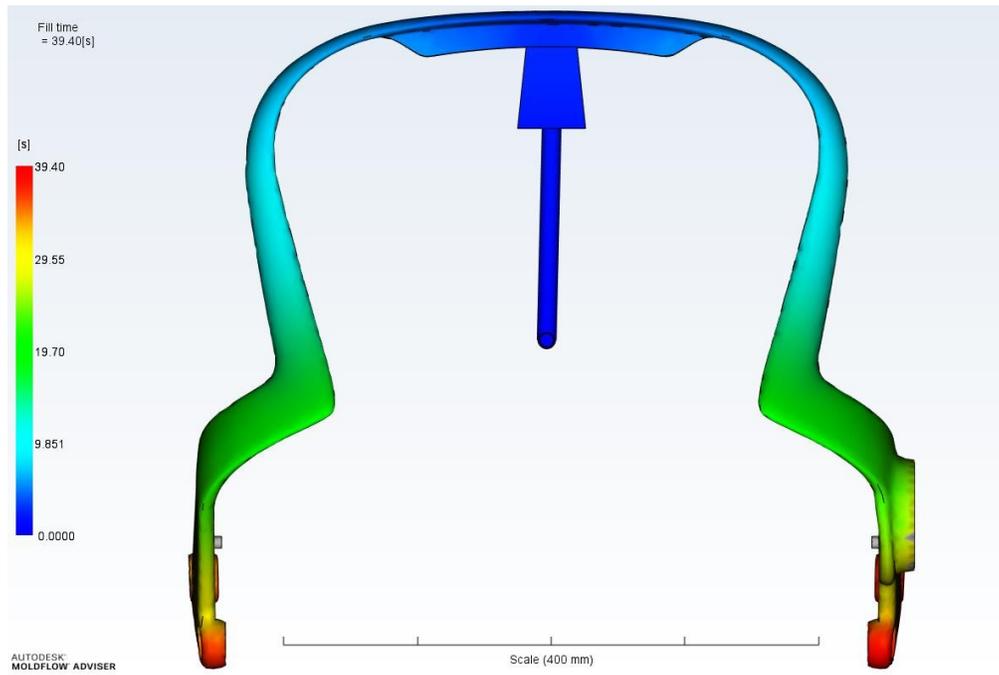

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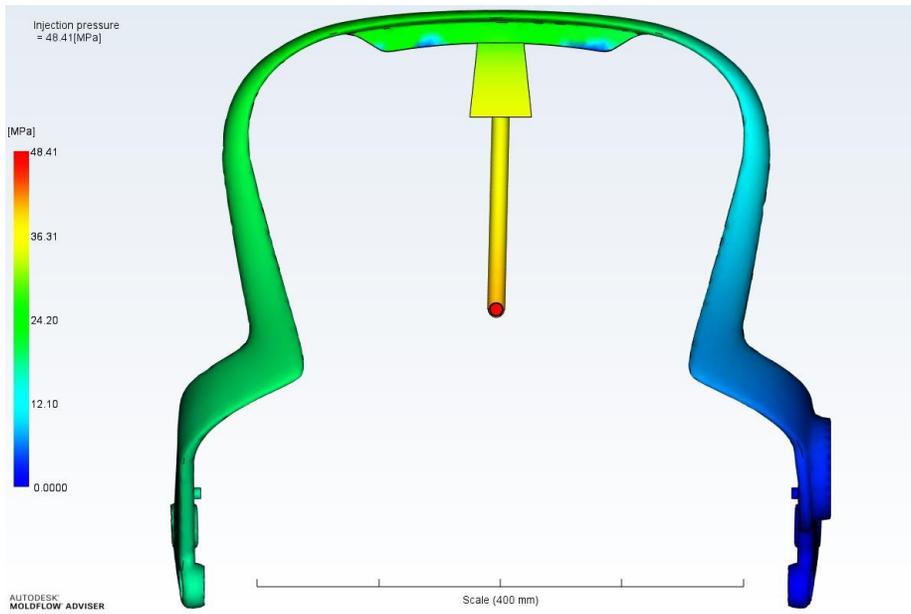
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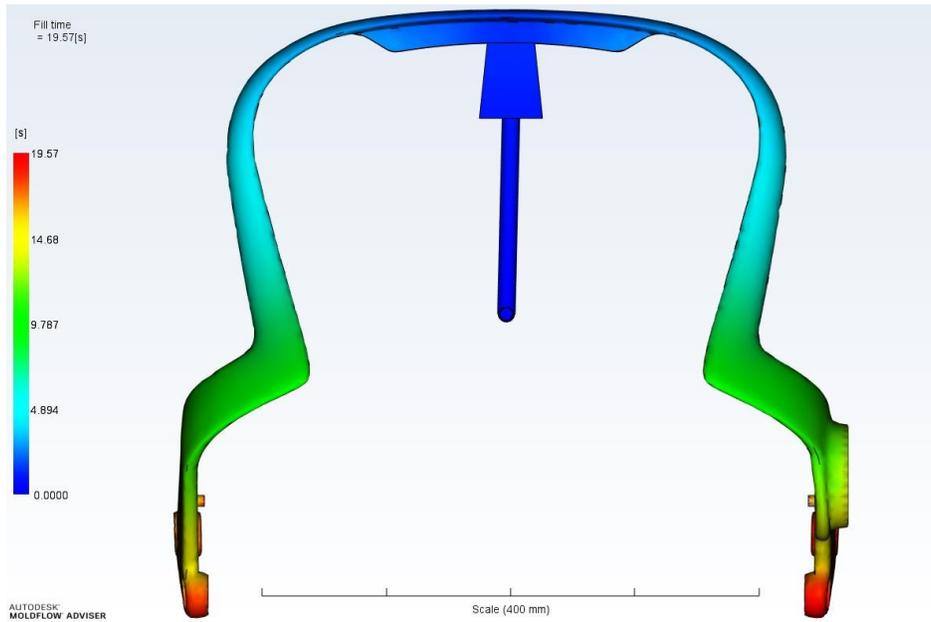
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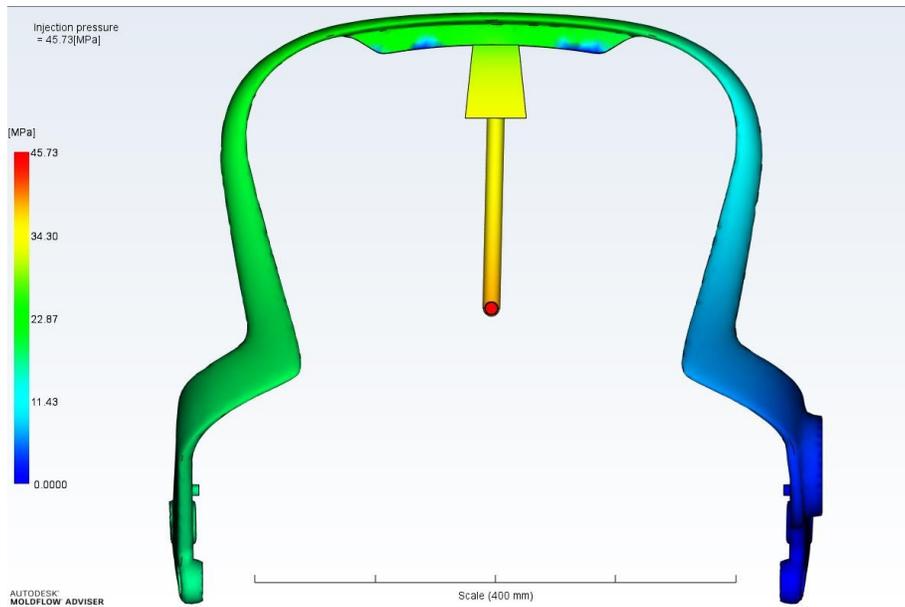
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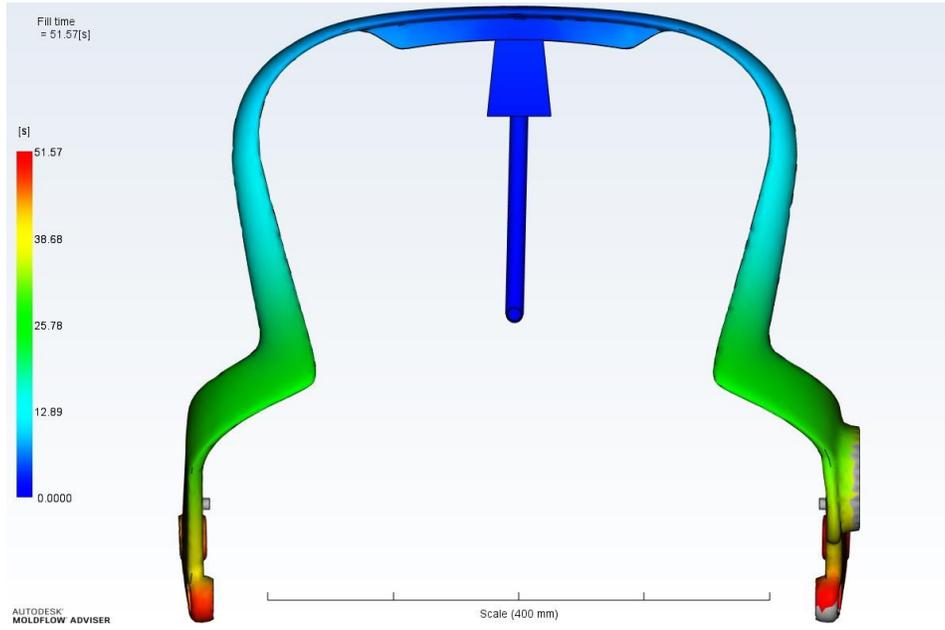
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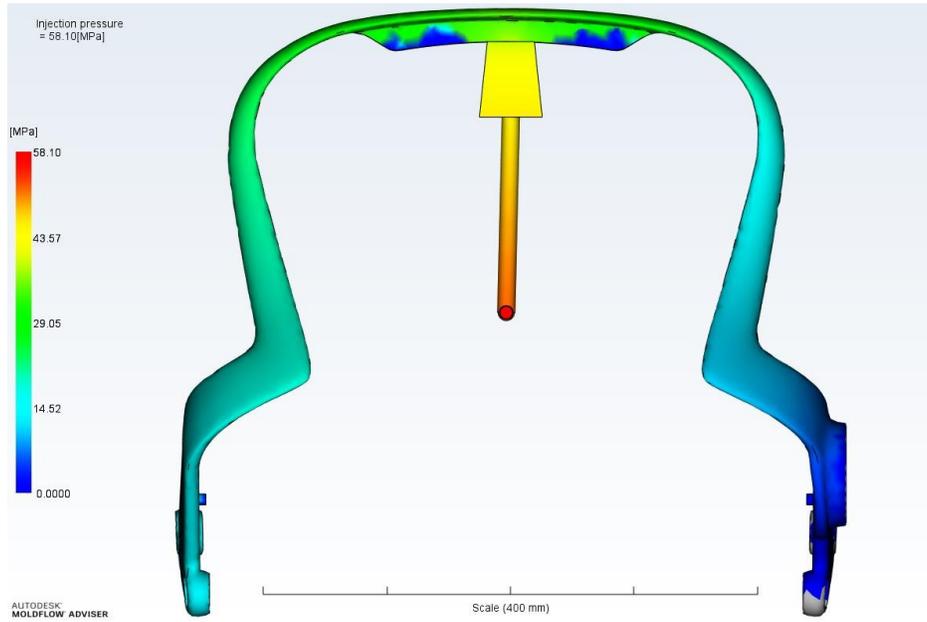
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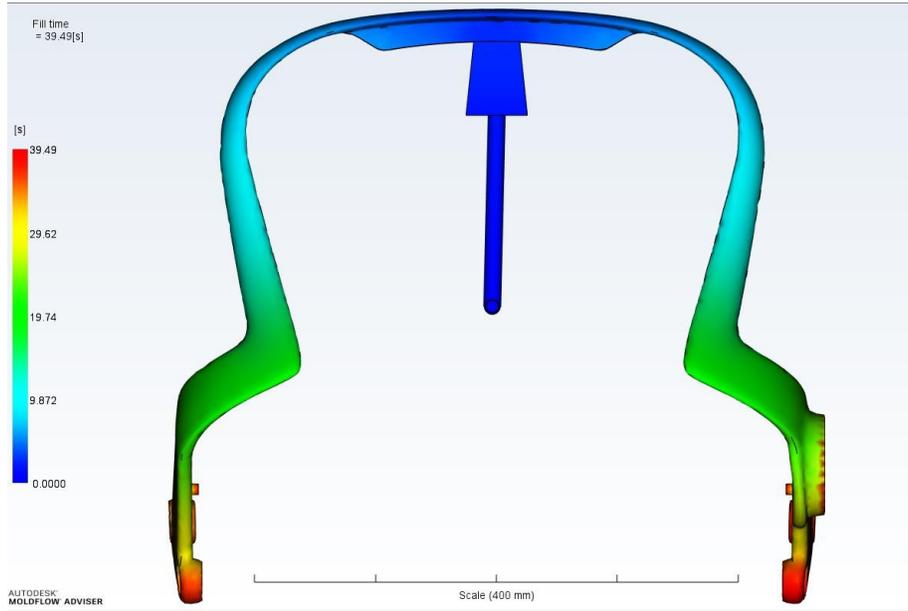
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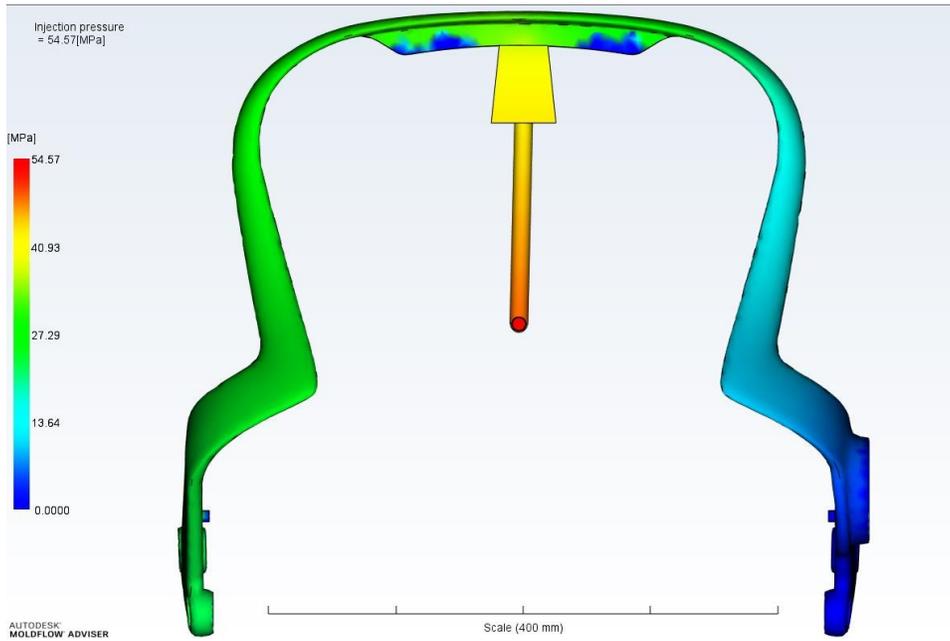
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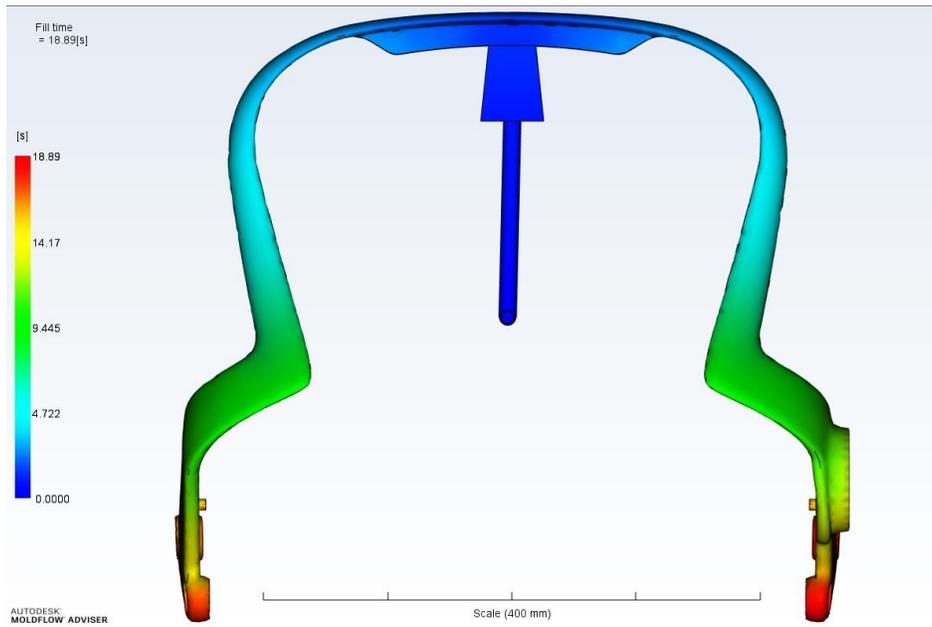
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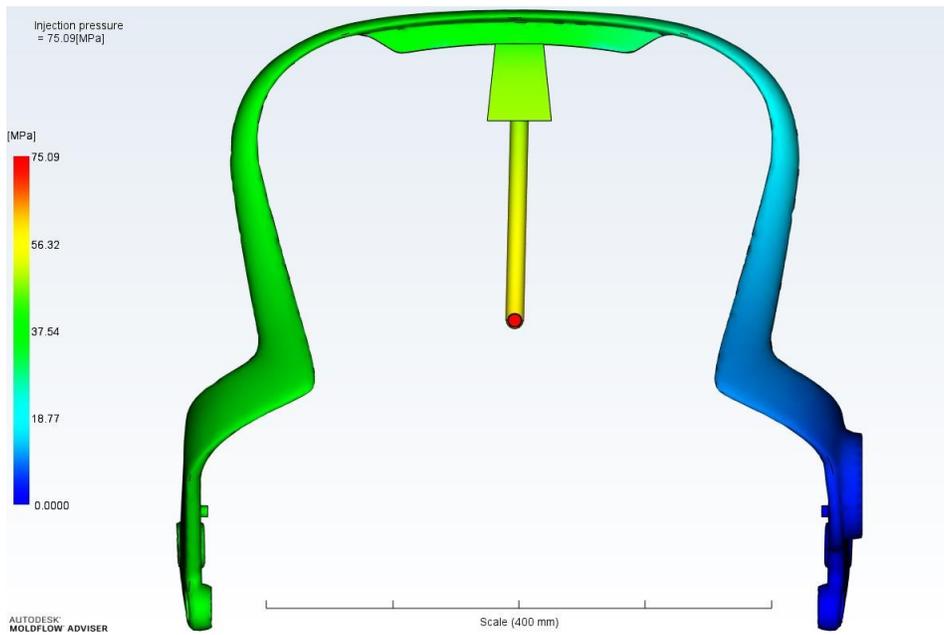
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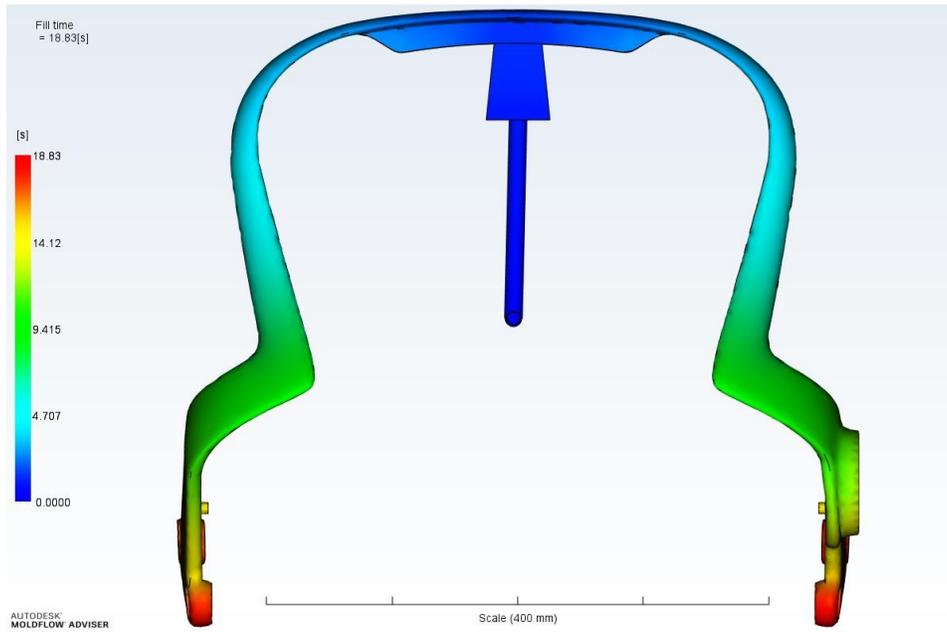
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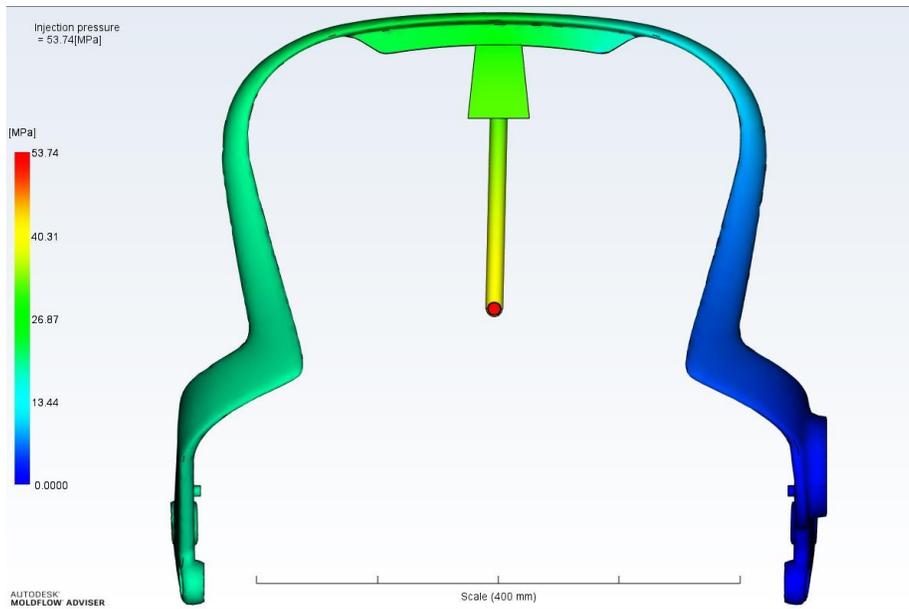
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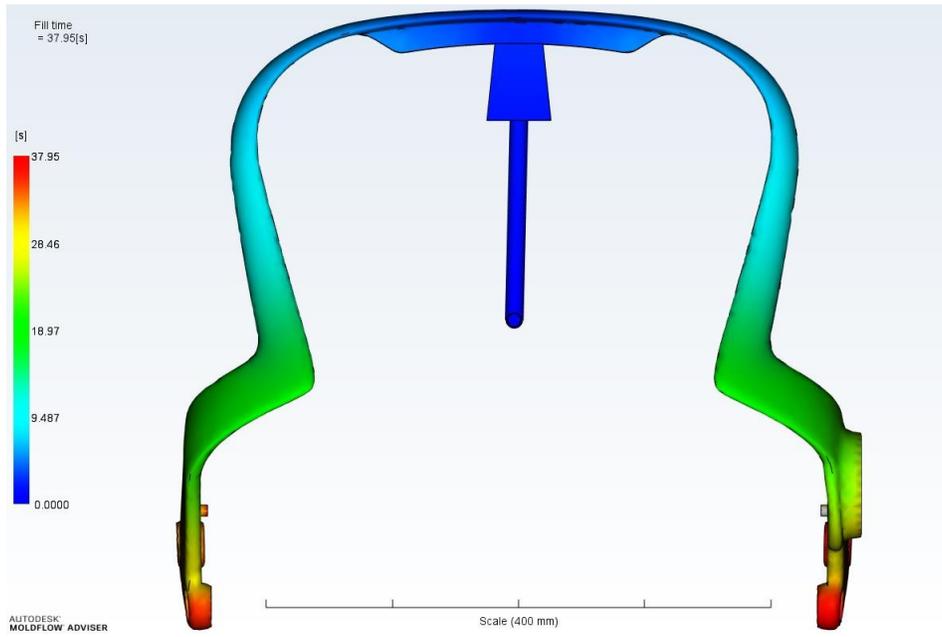
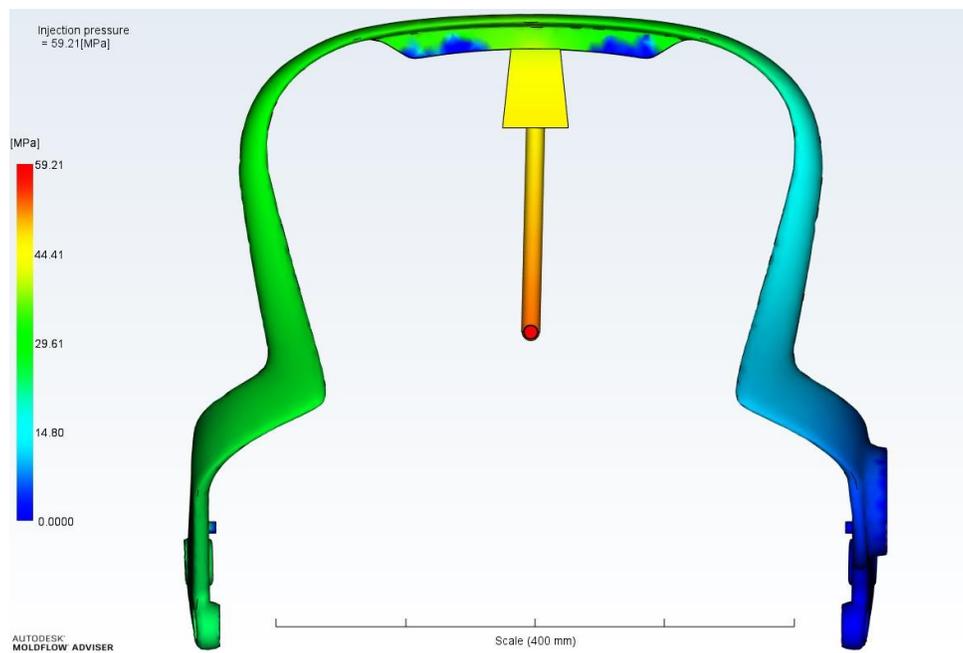Sample #22 Injection pressure
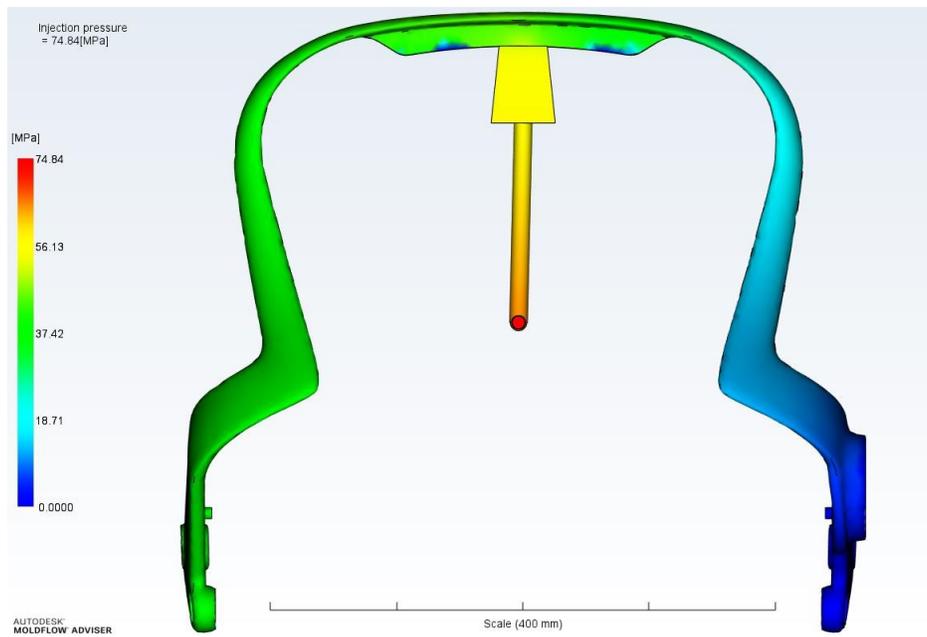
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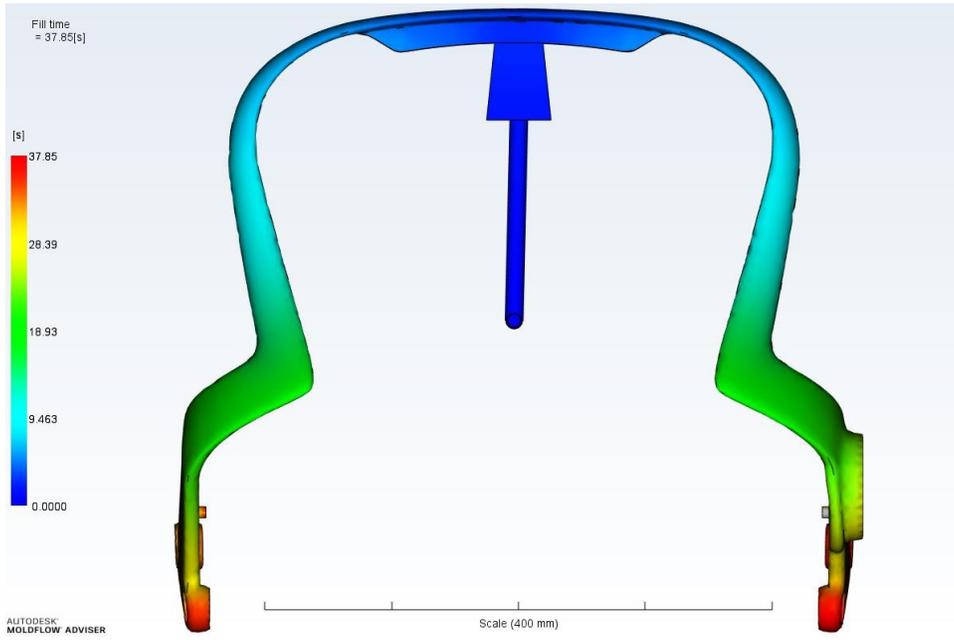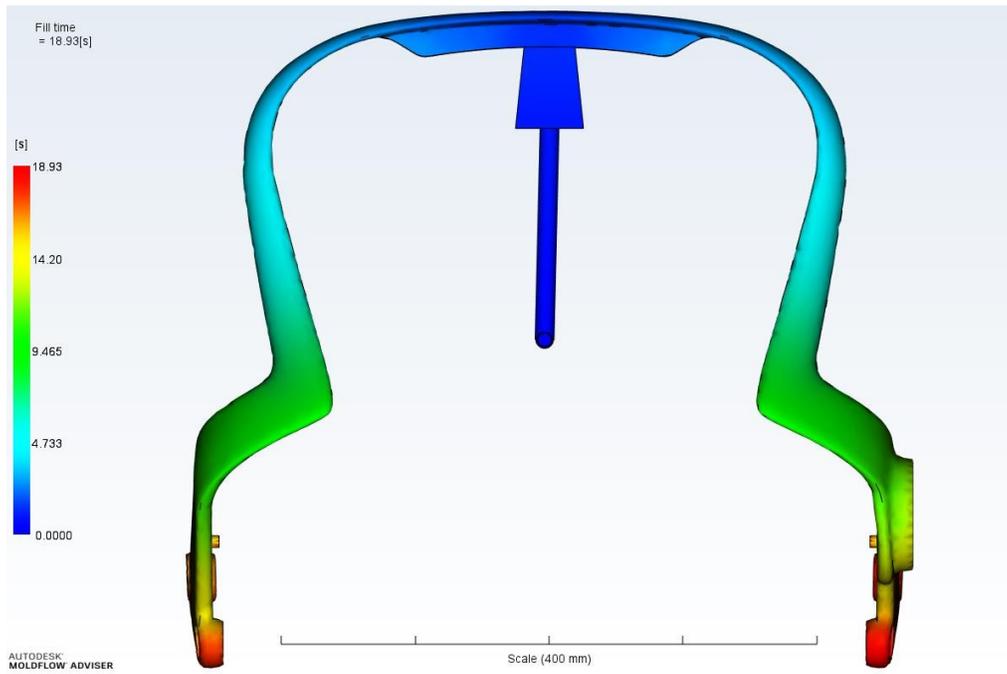

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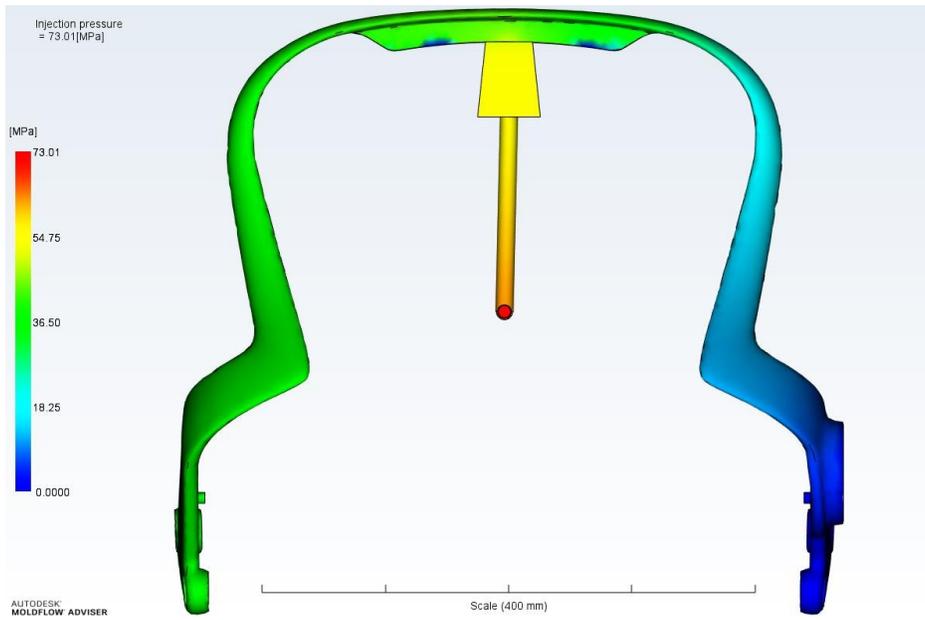
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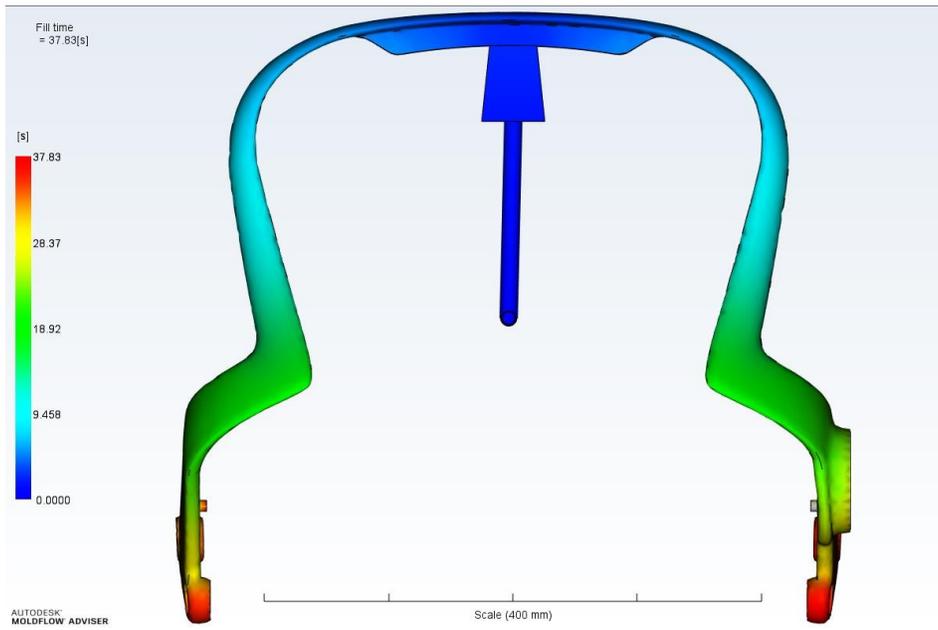
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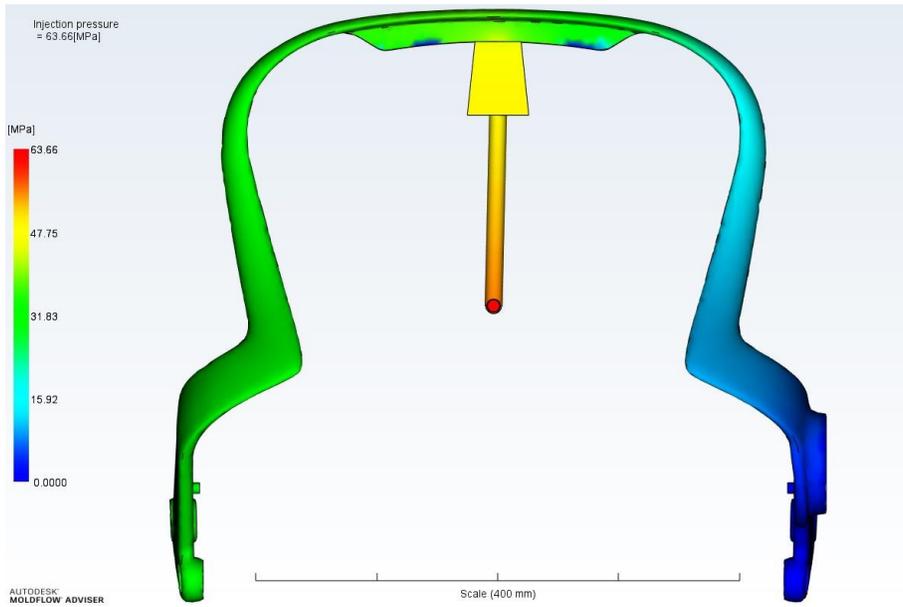
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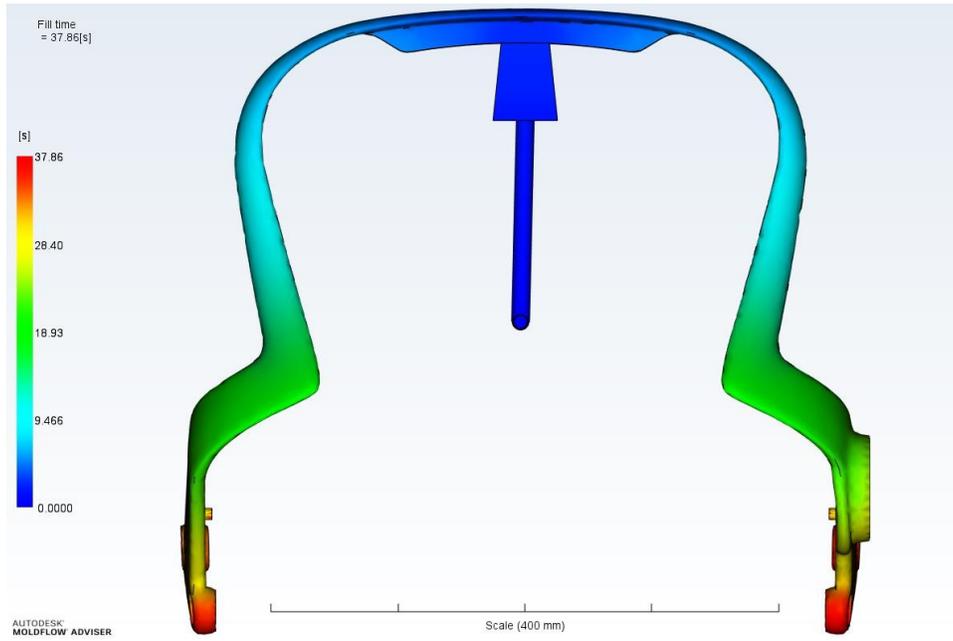
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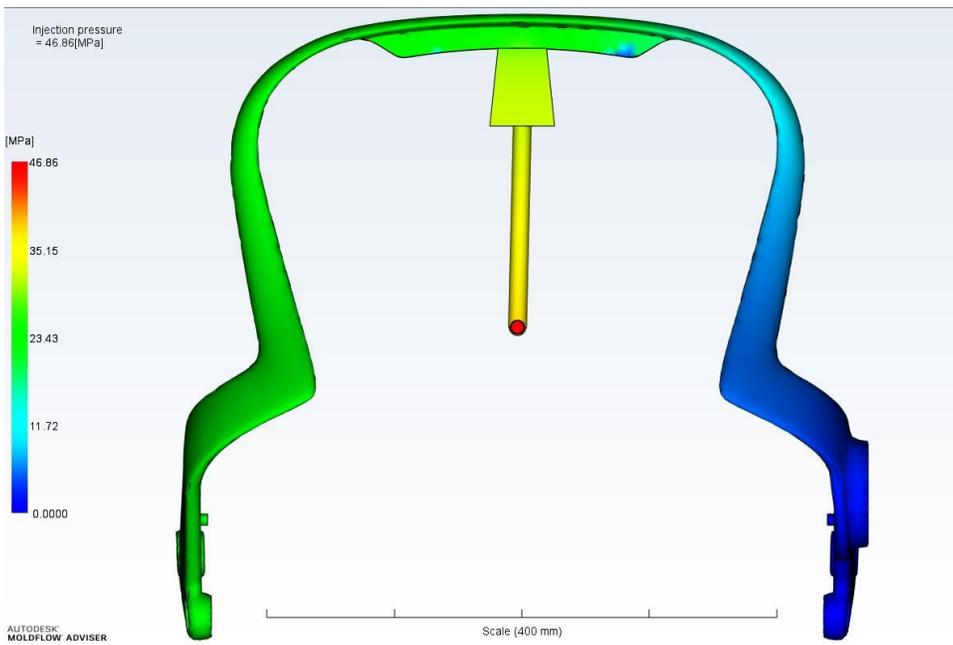
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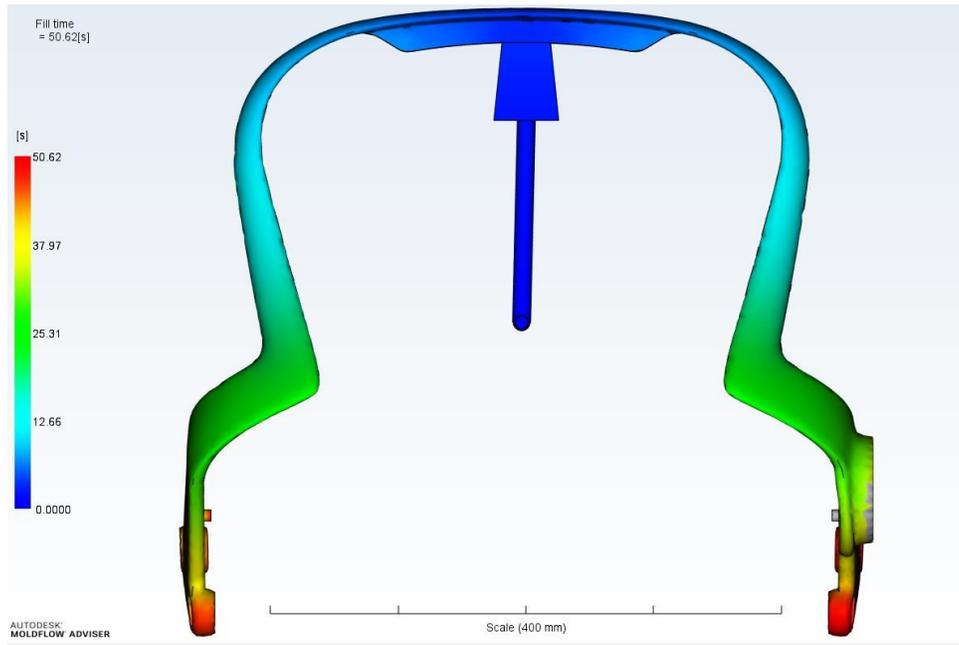
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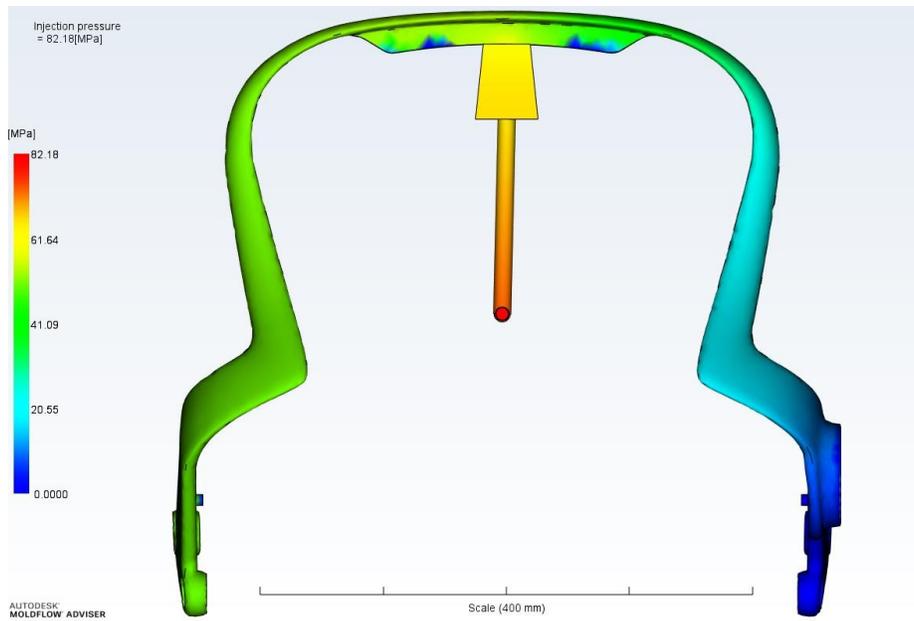
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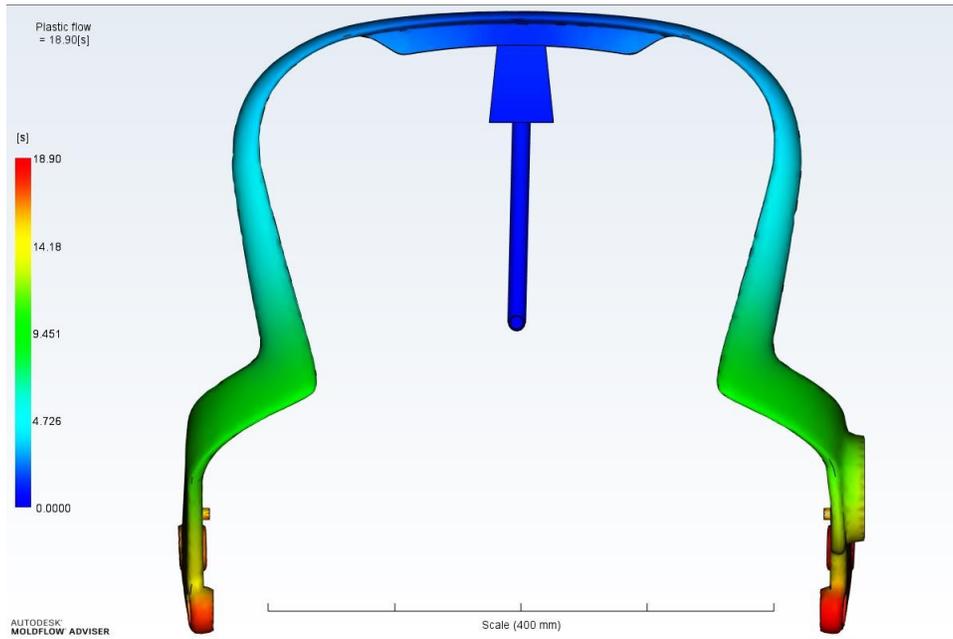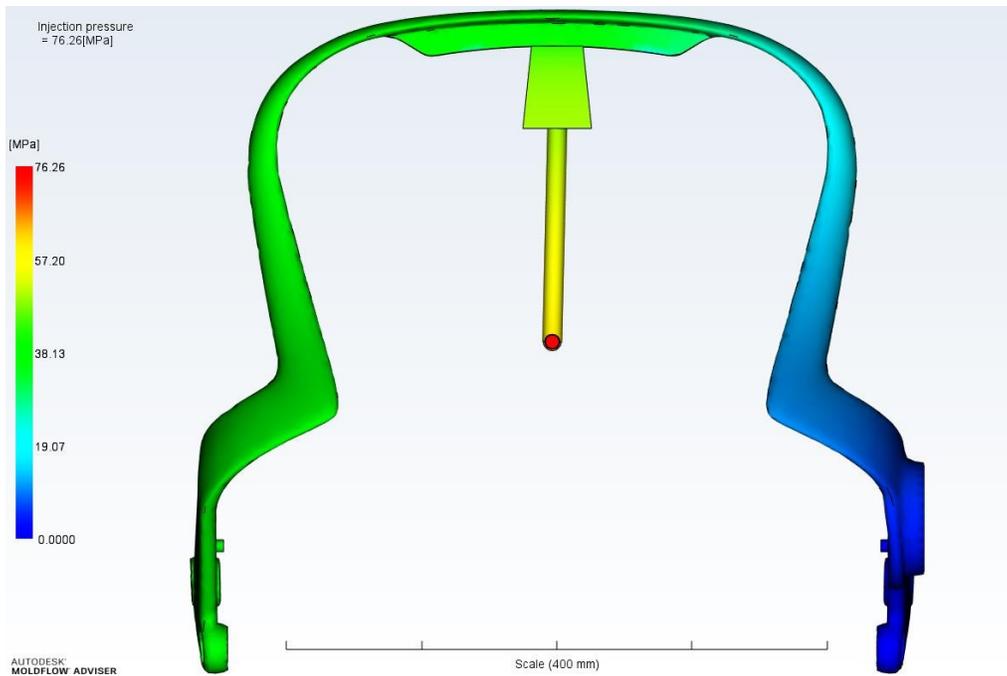

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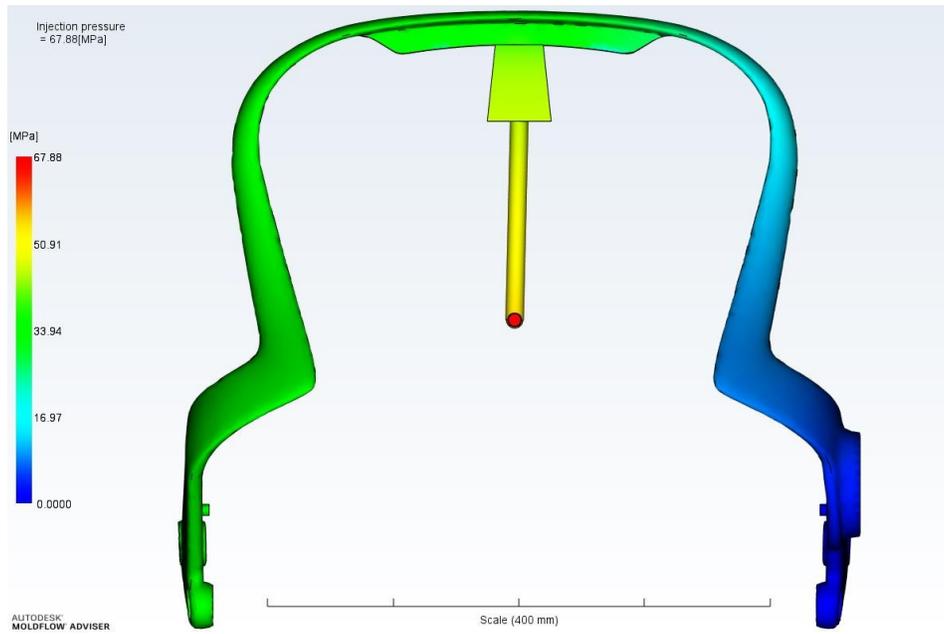
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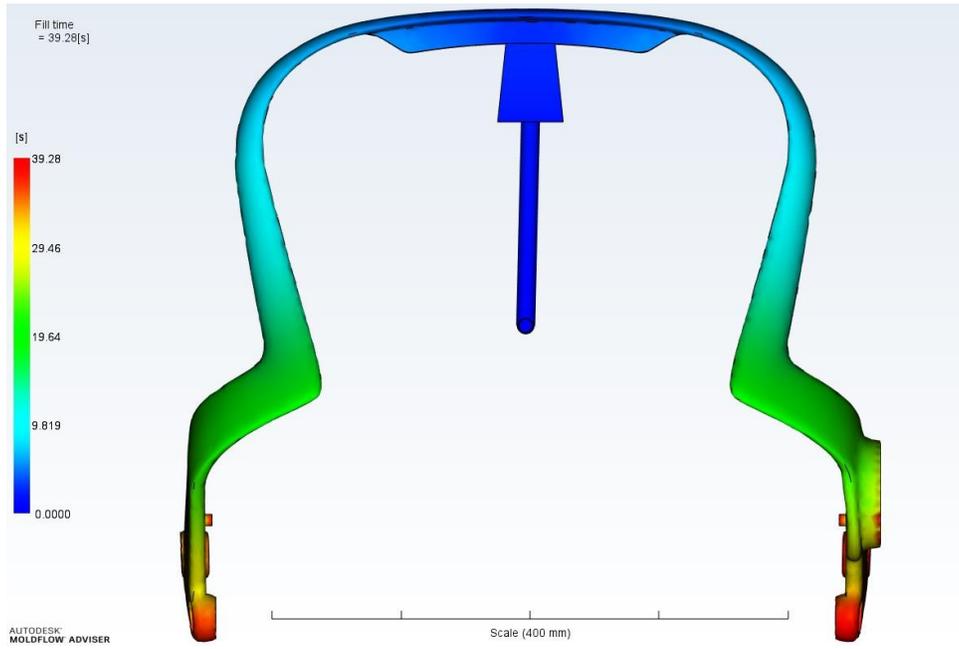
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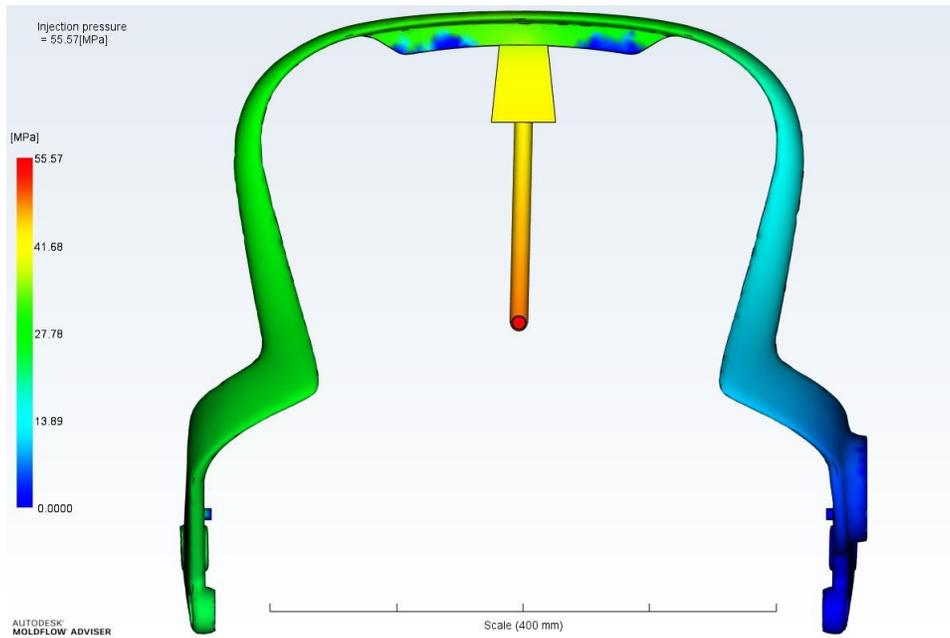
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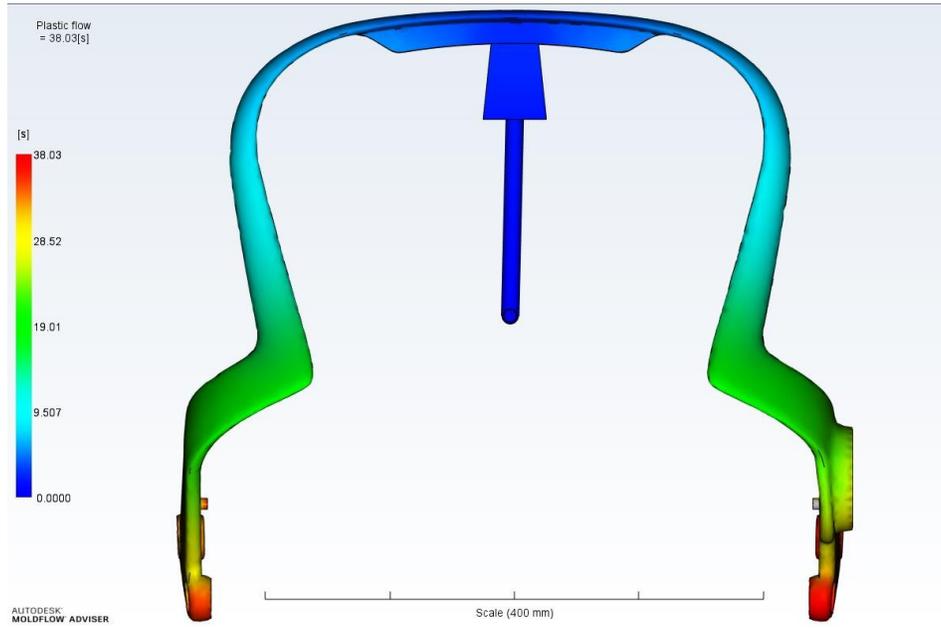
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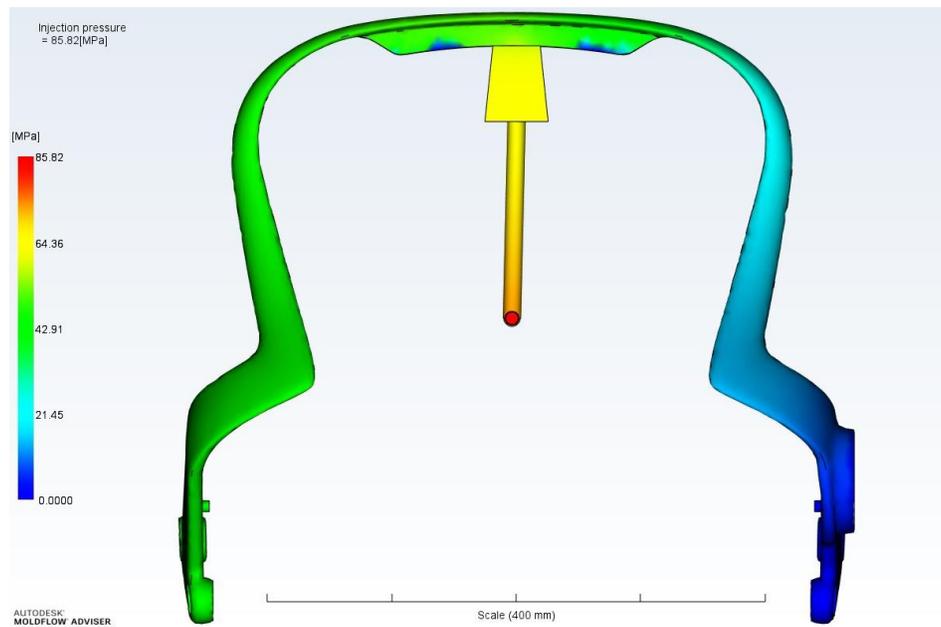
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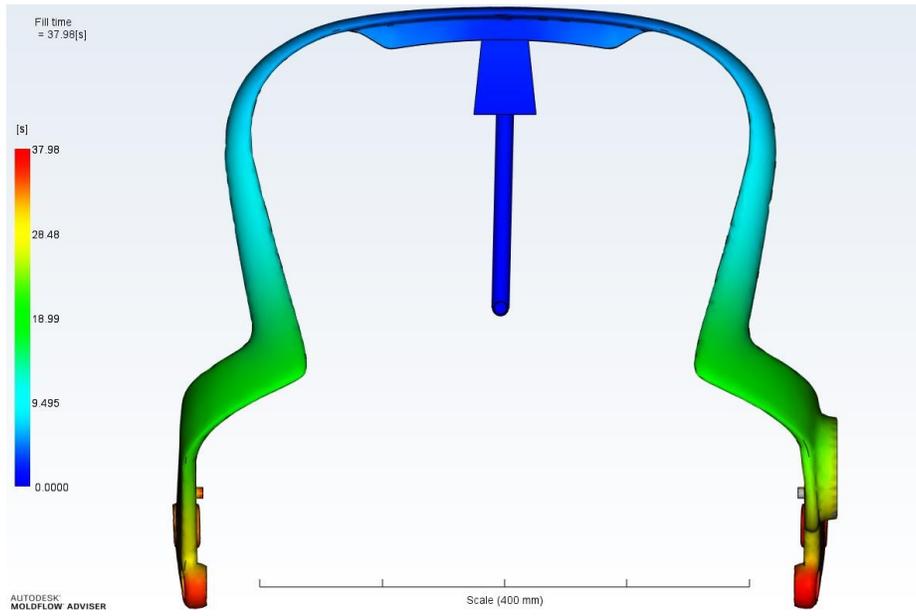
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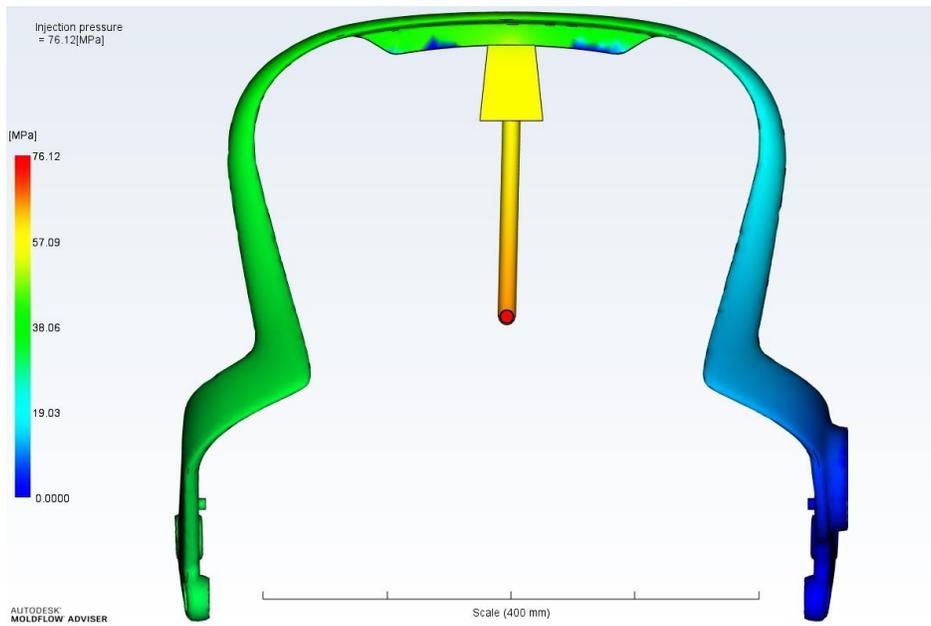
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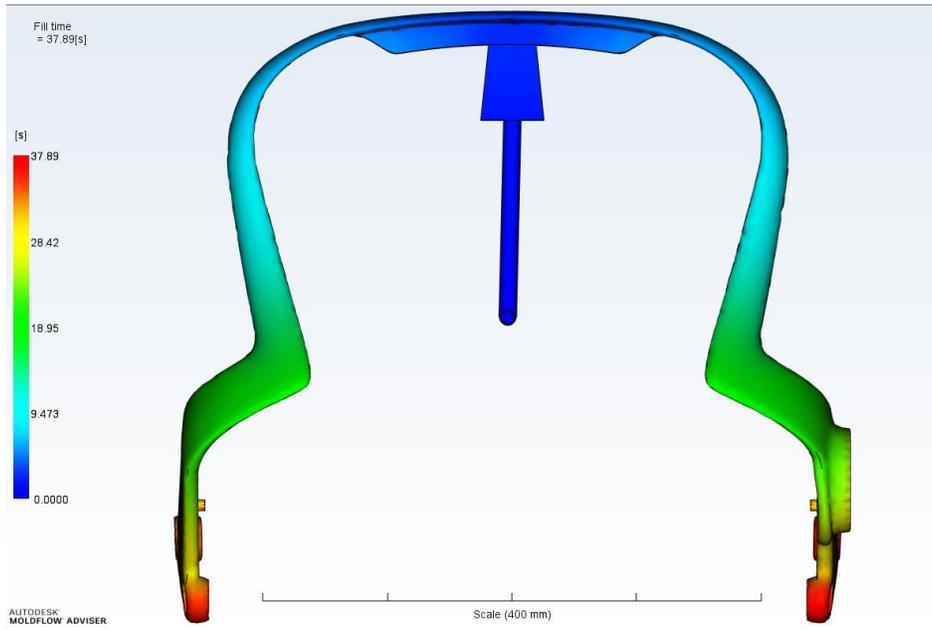
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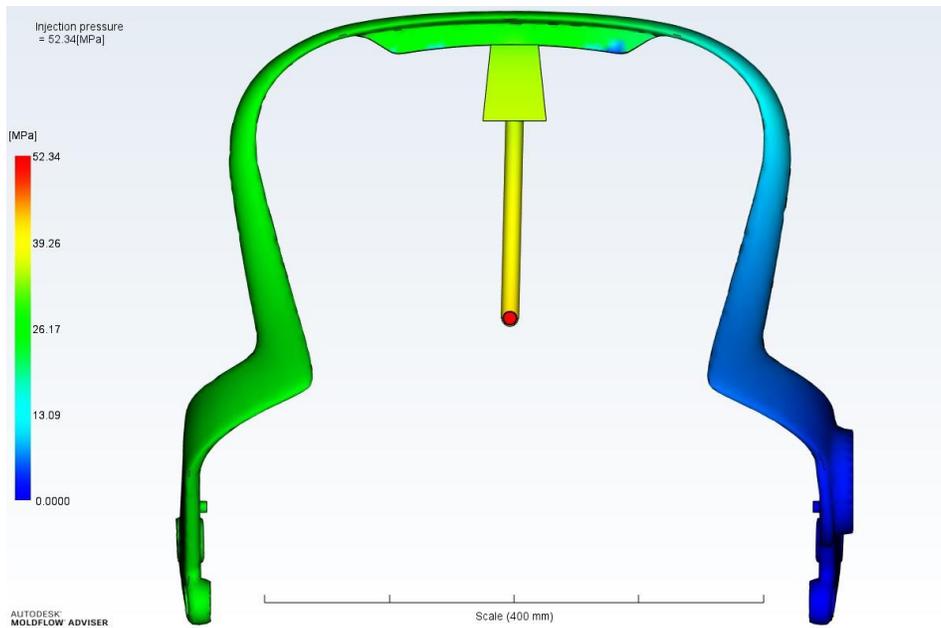
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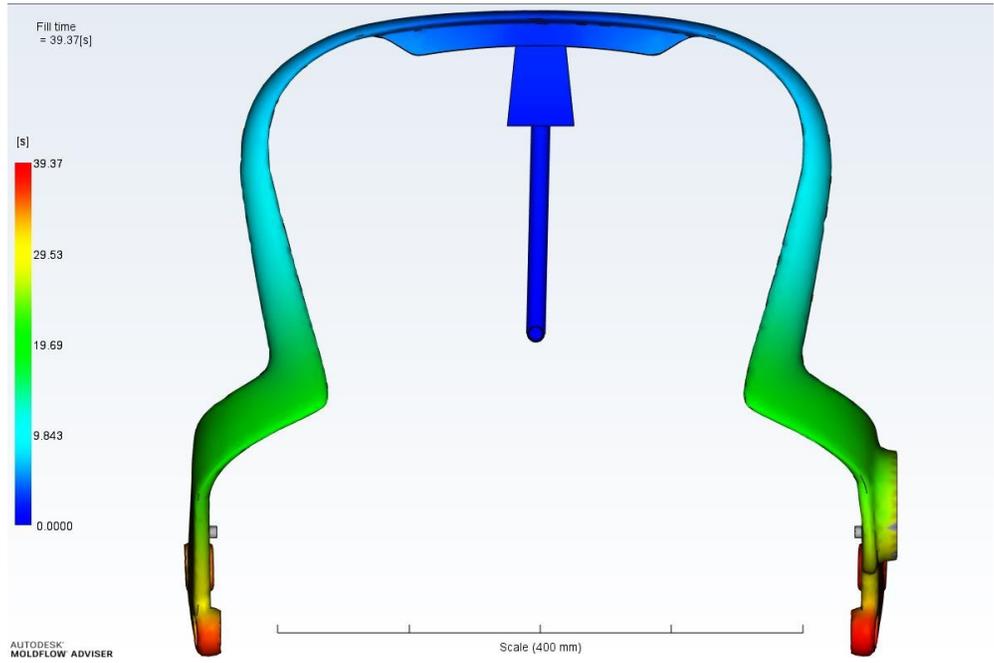
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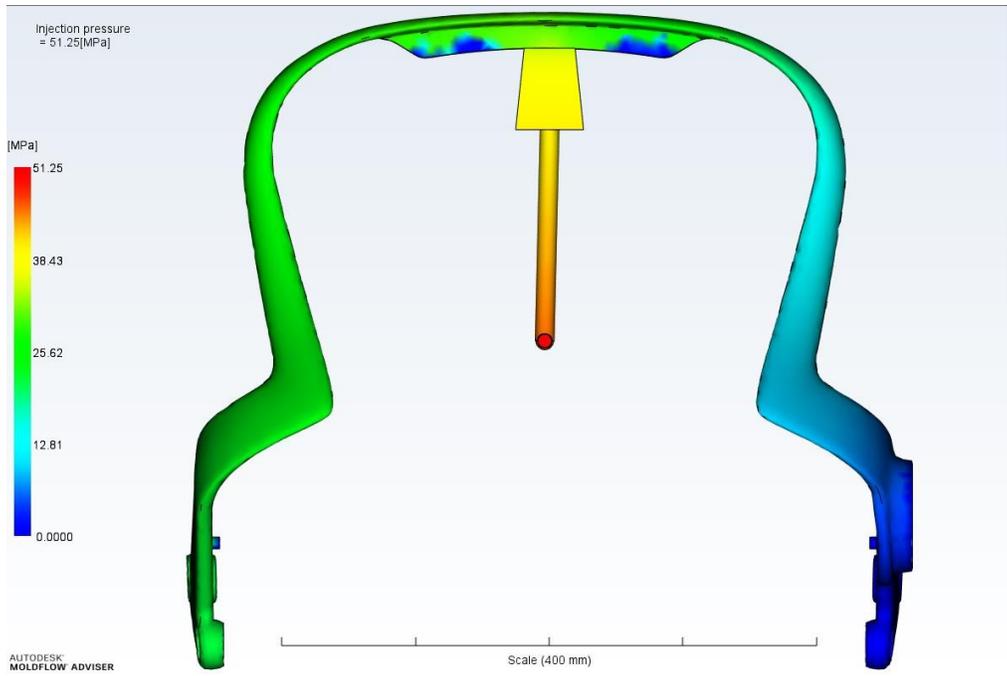
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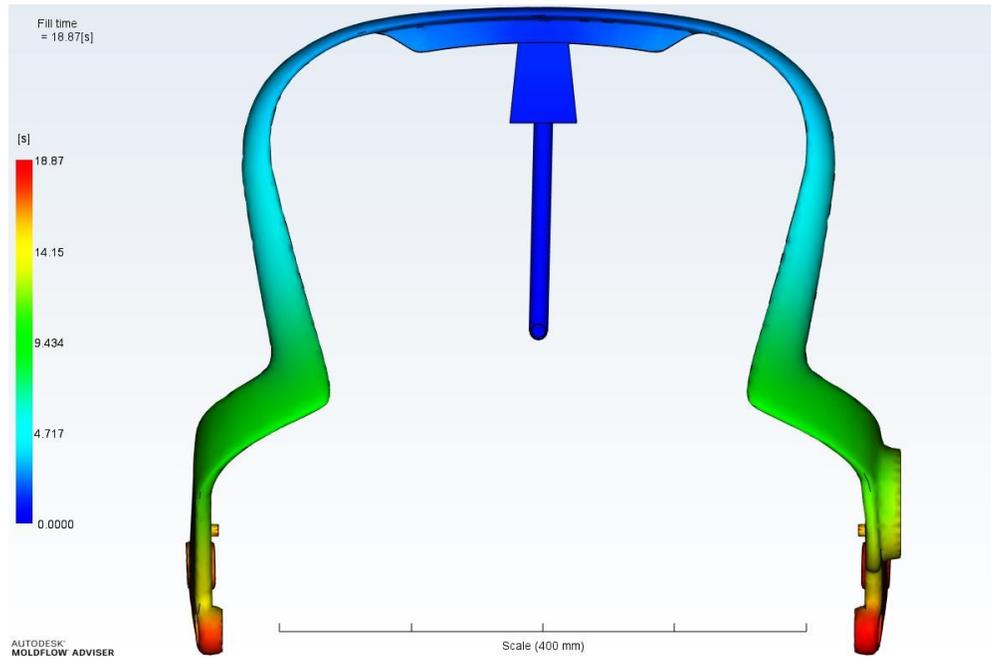
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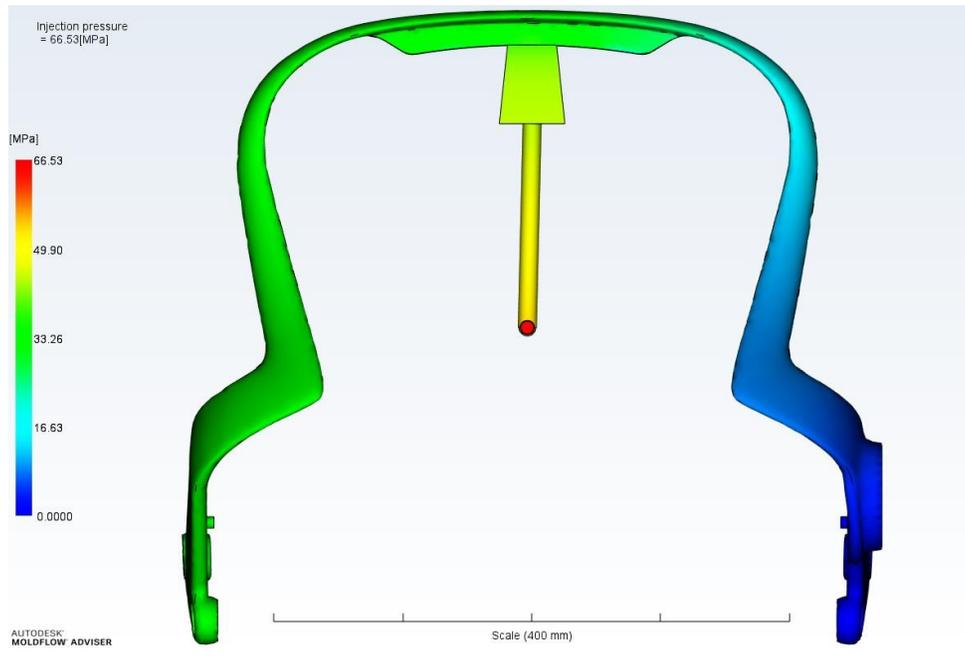
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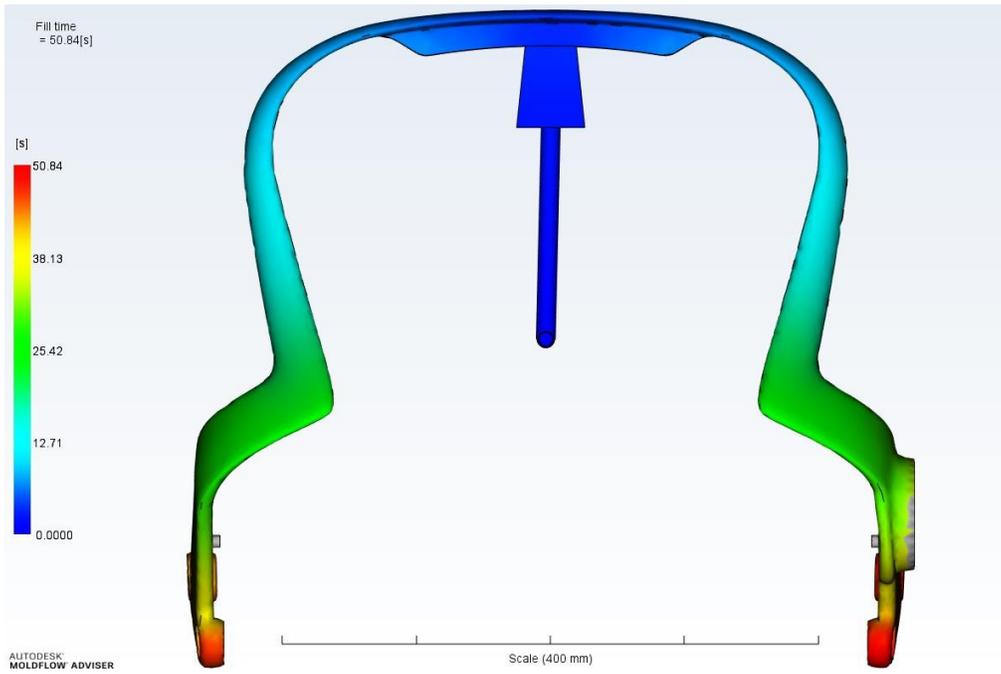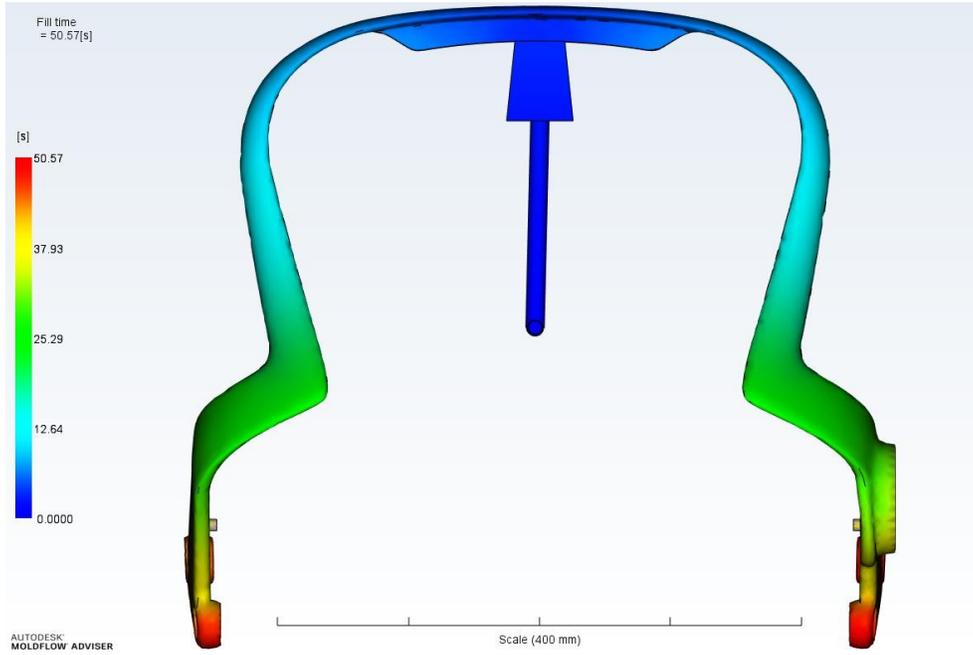

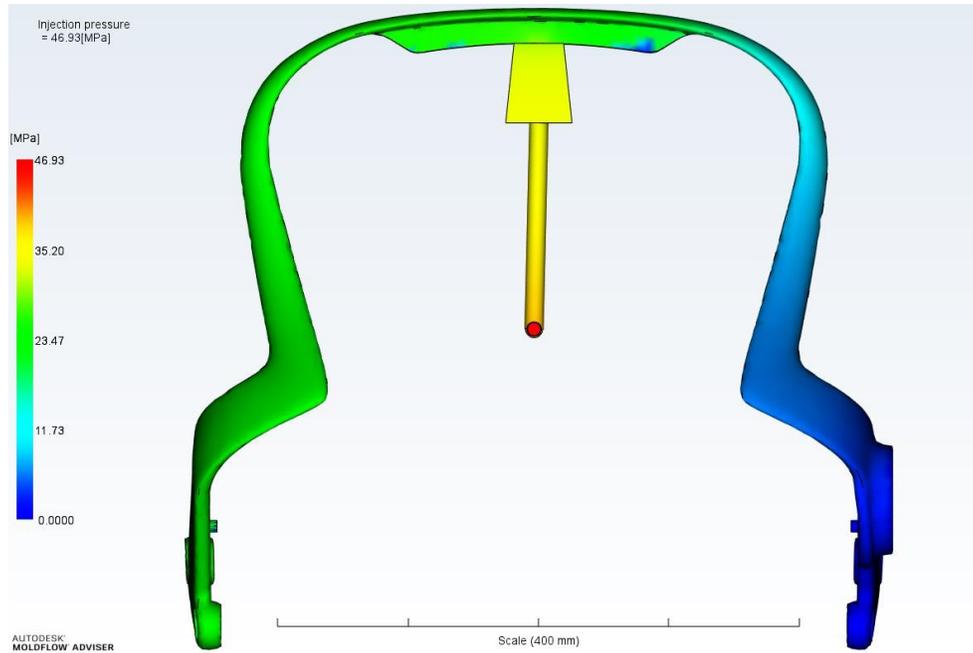Sample #34 Injection pressure
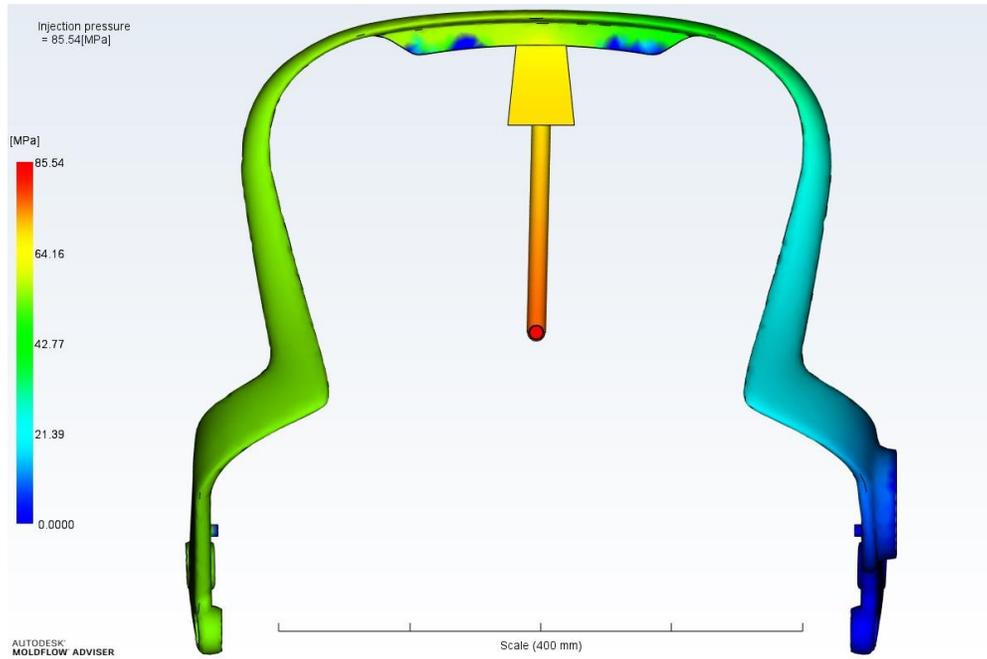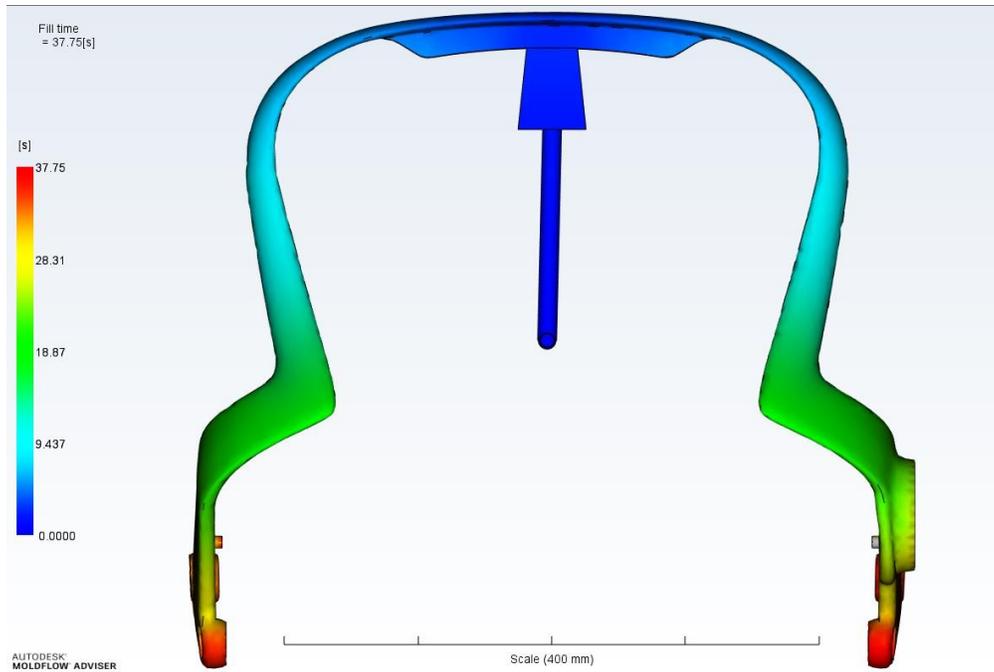
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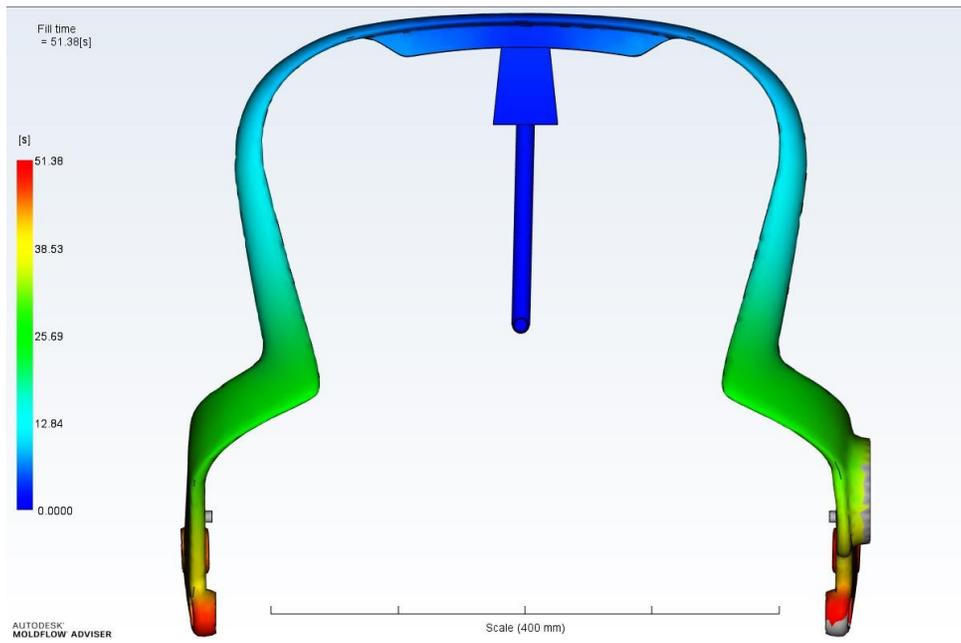
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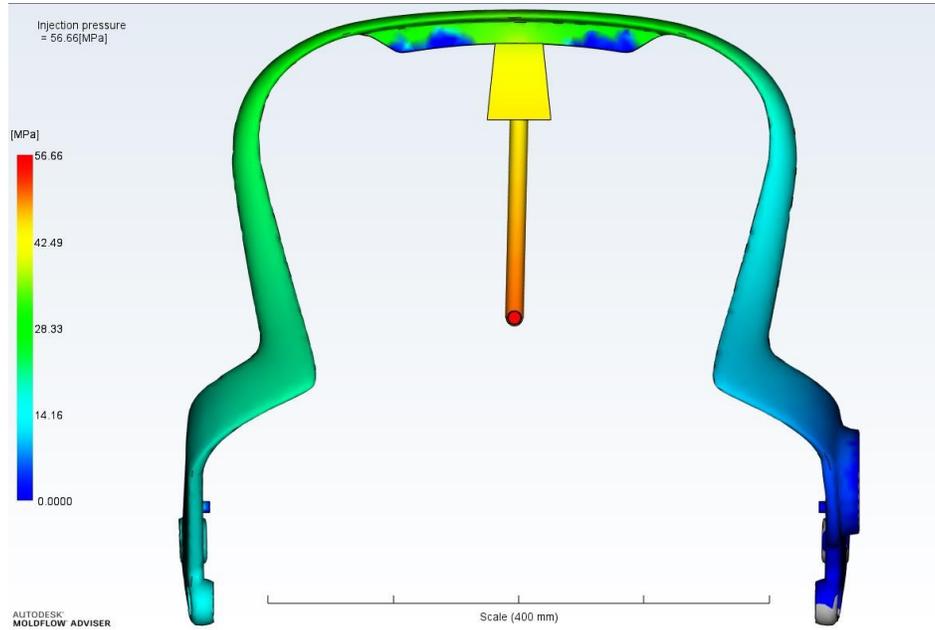
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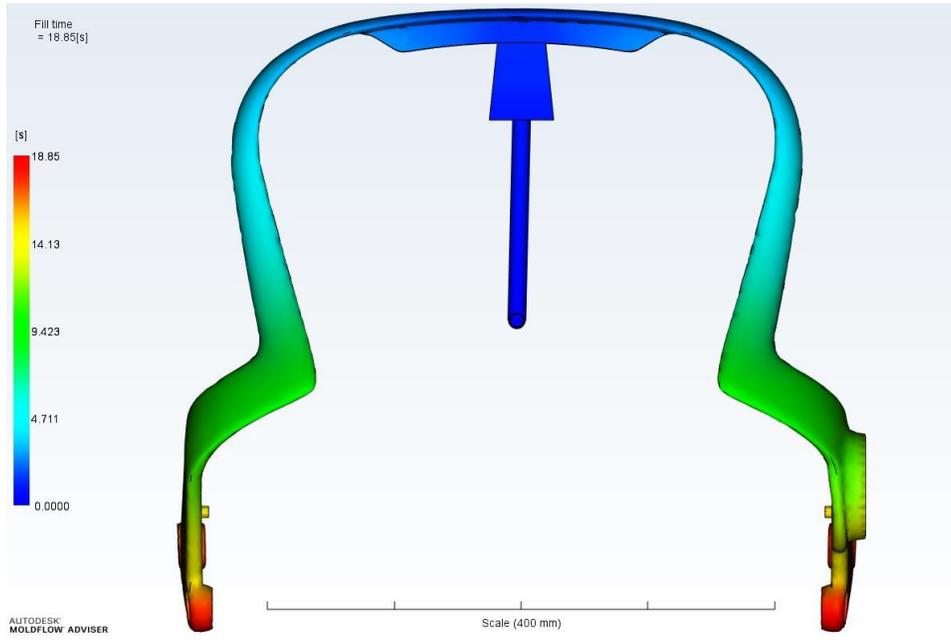
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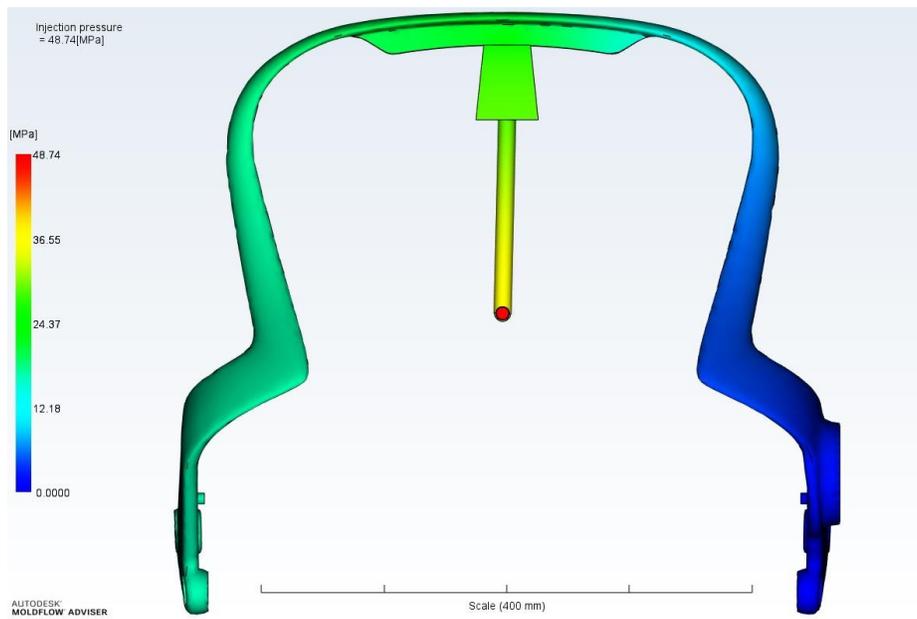
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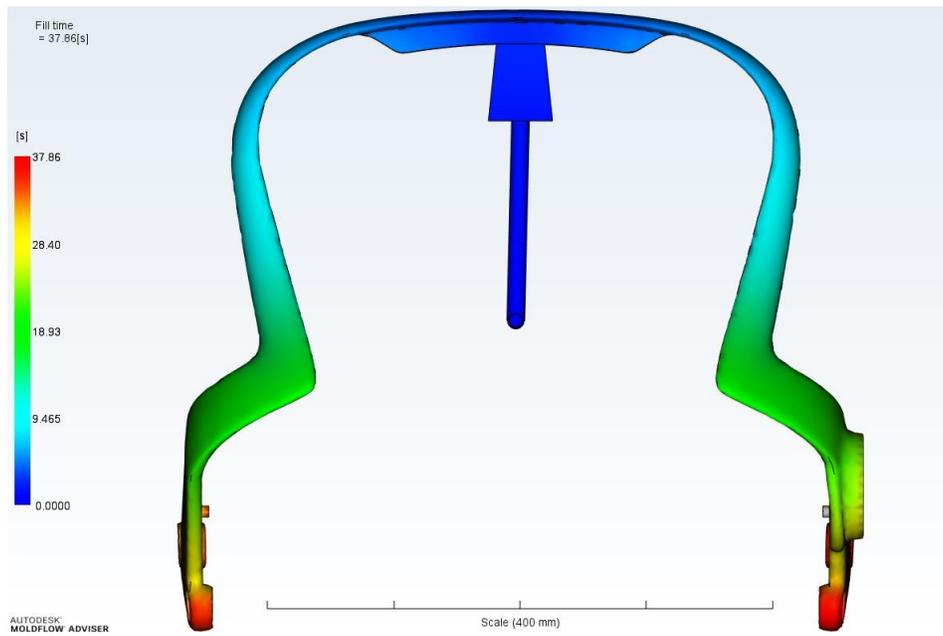
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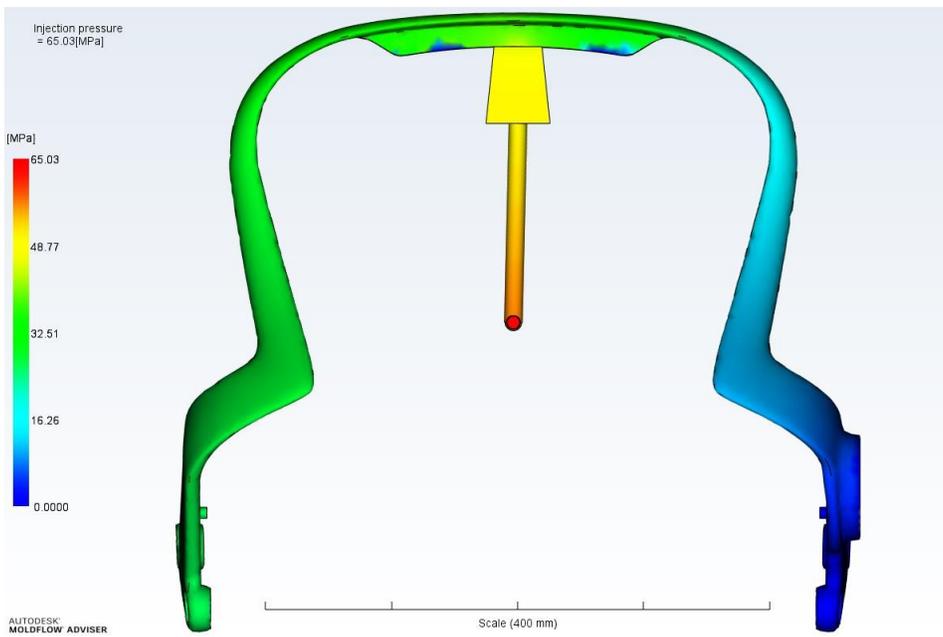
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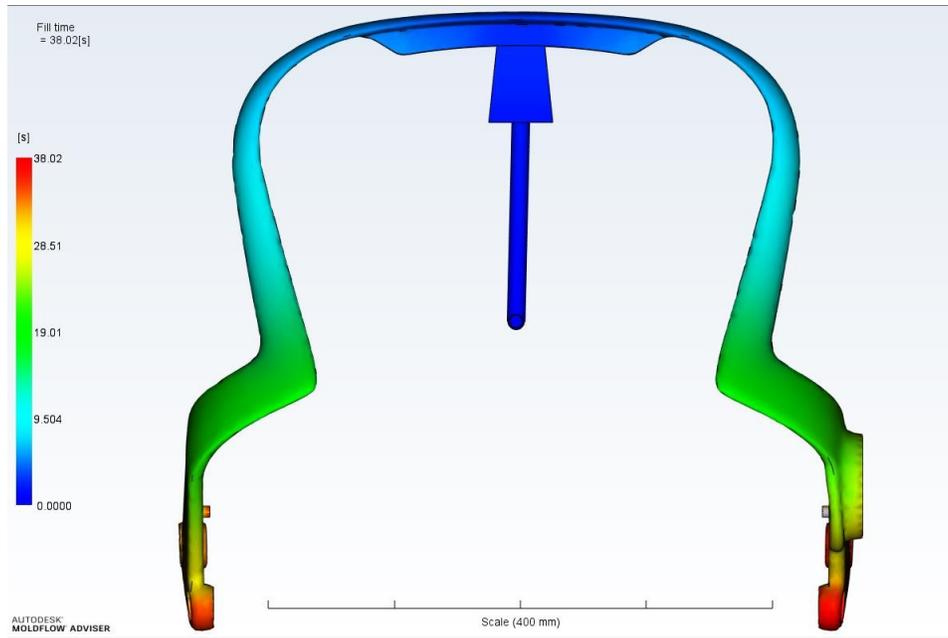
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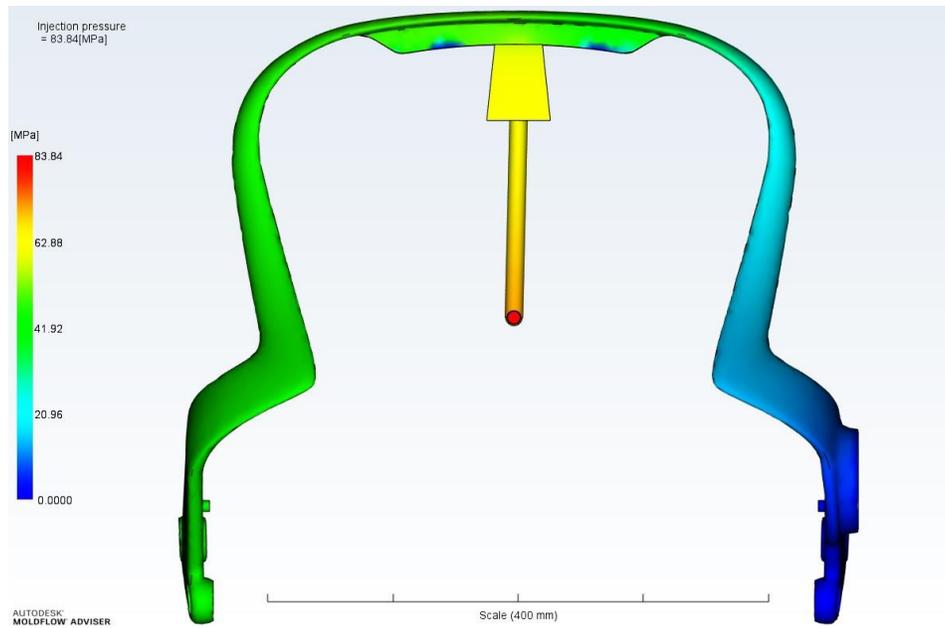
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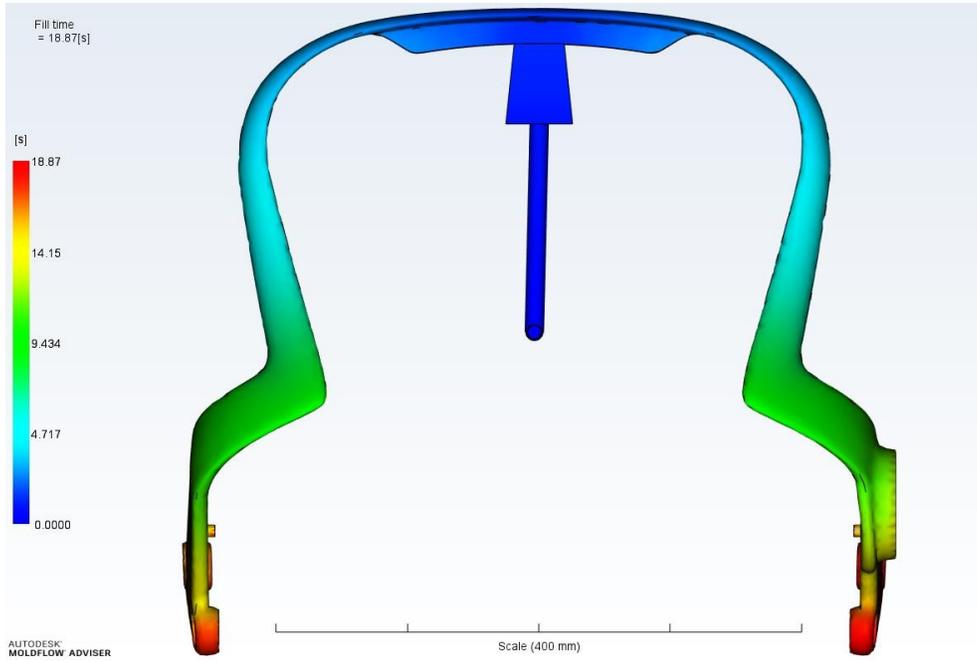
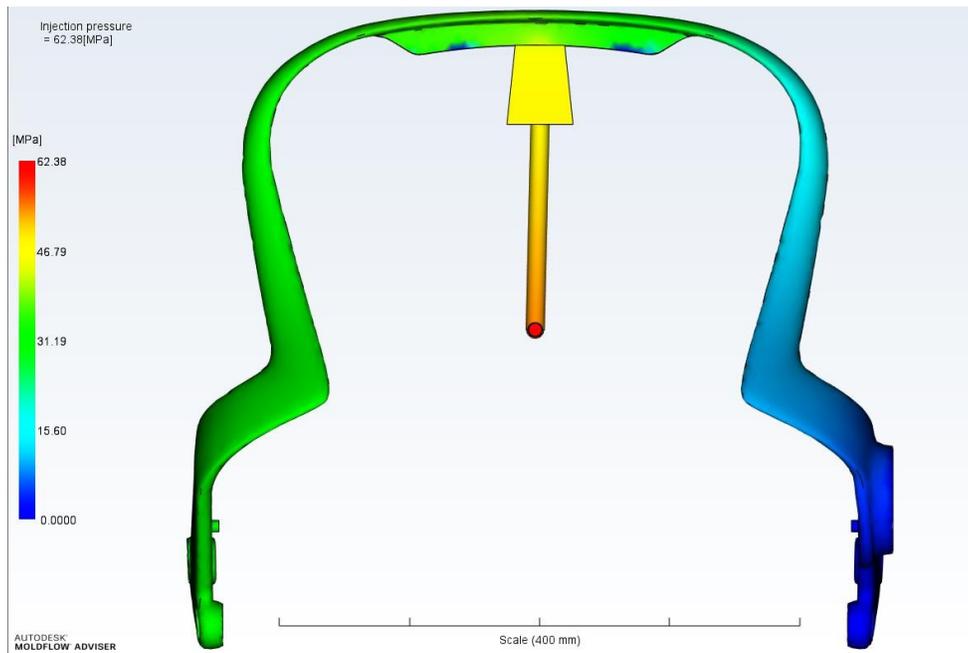Sample #39 Injection pressure
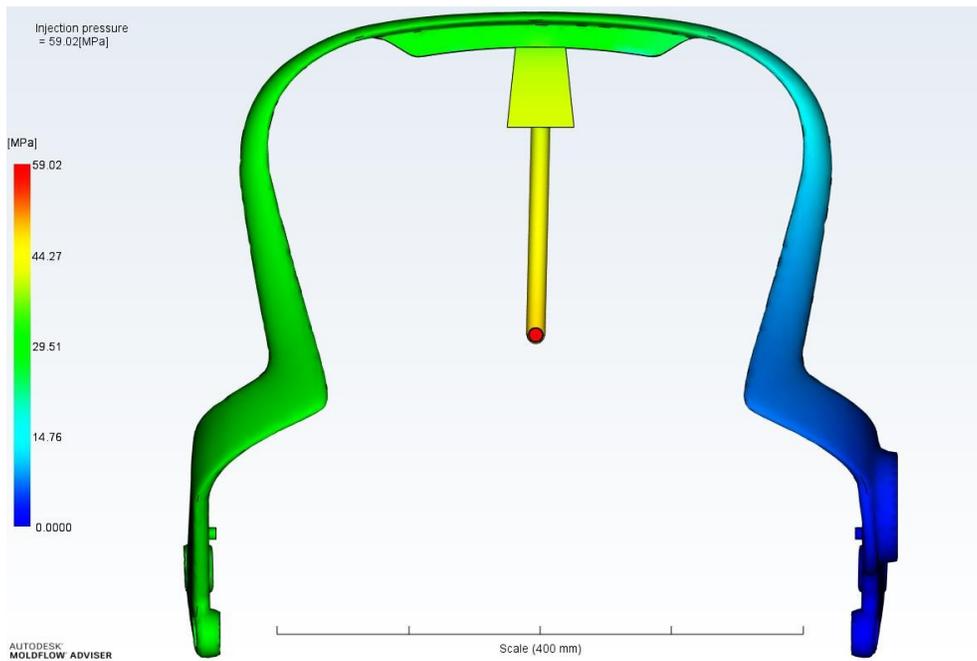
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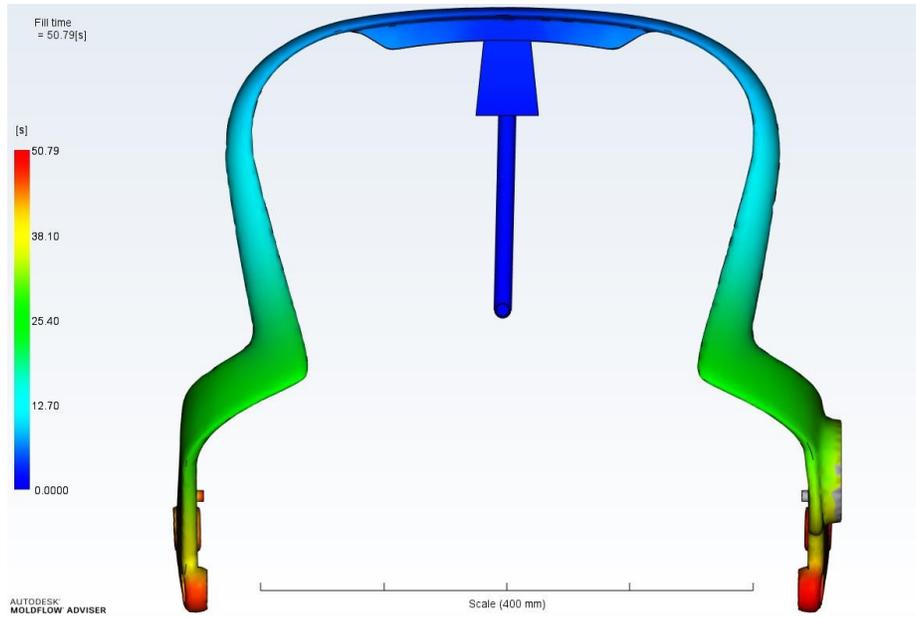
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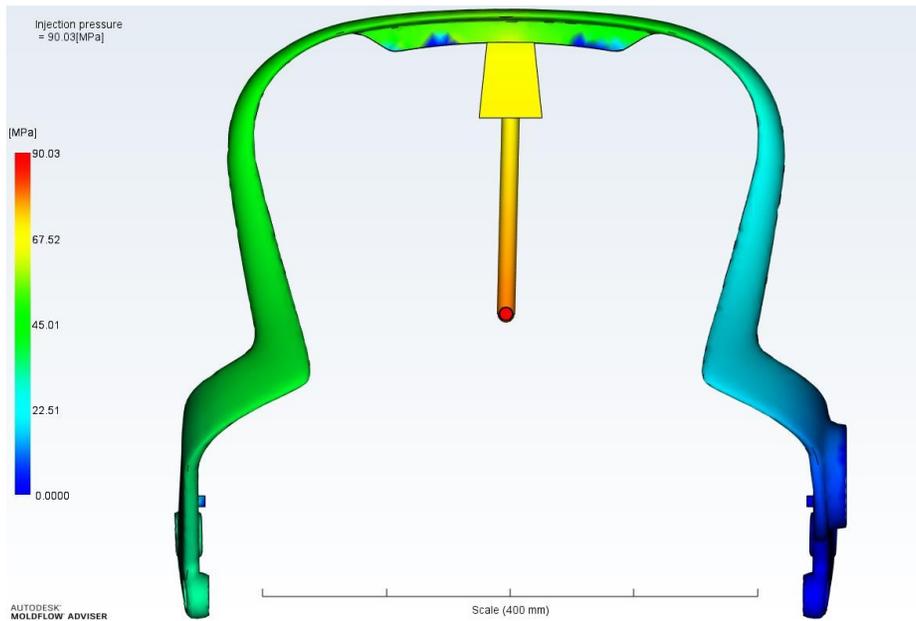
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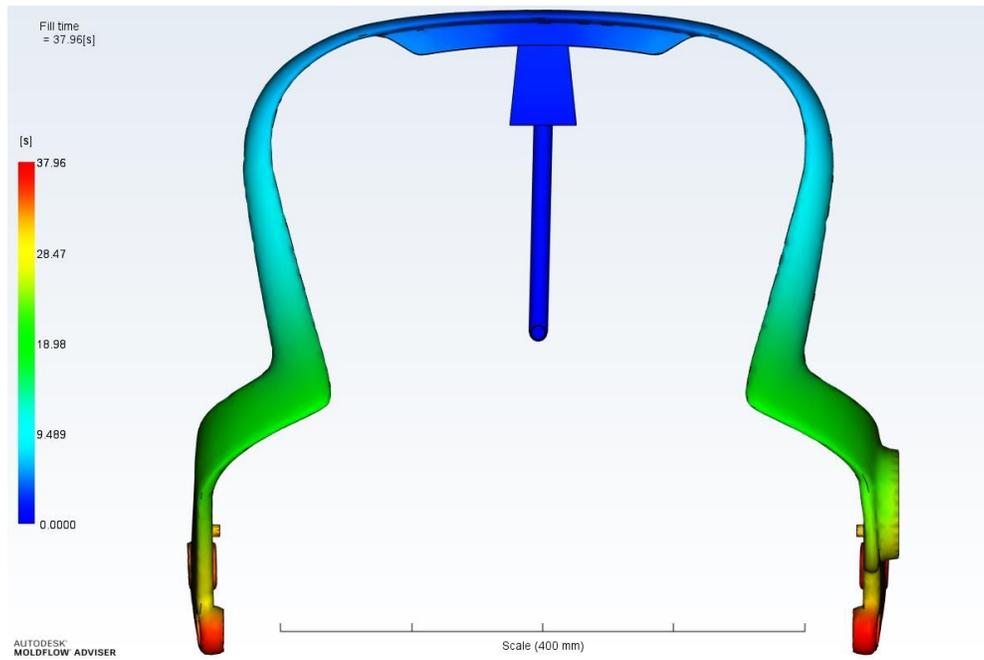
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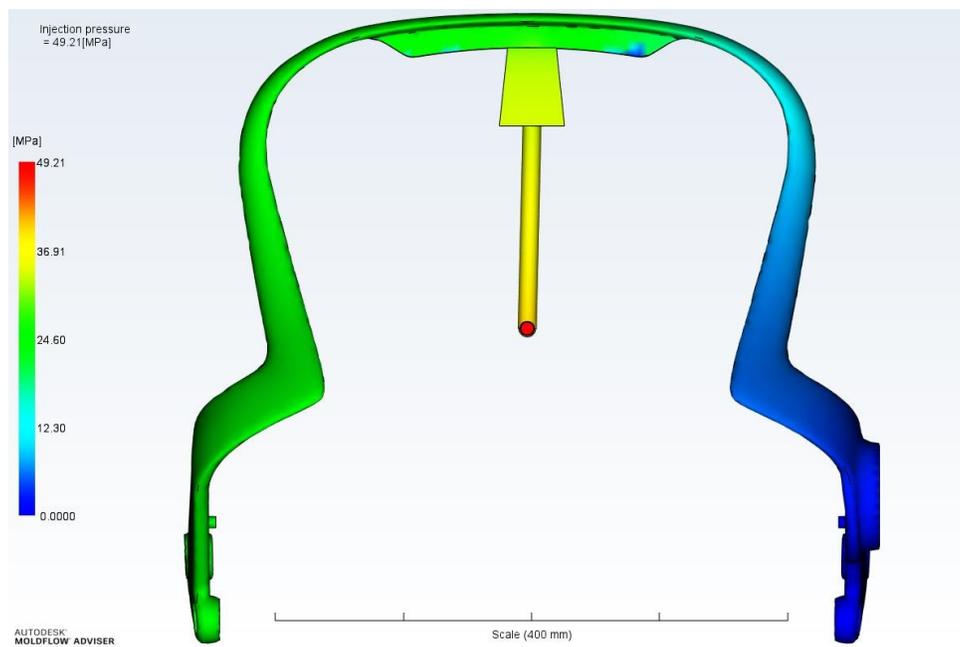
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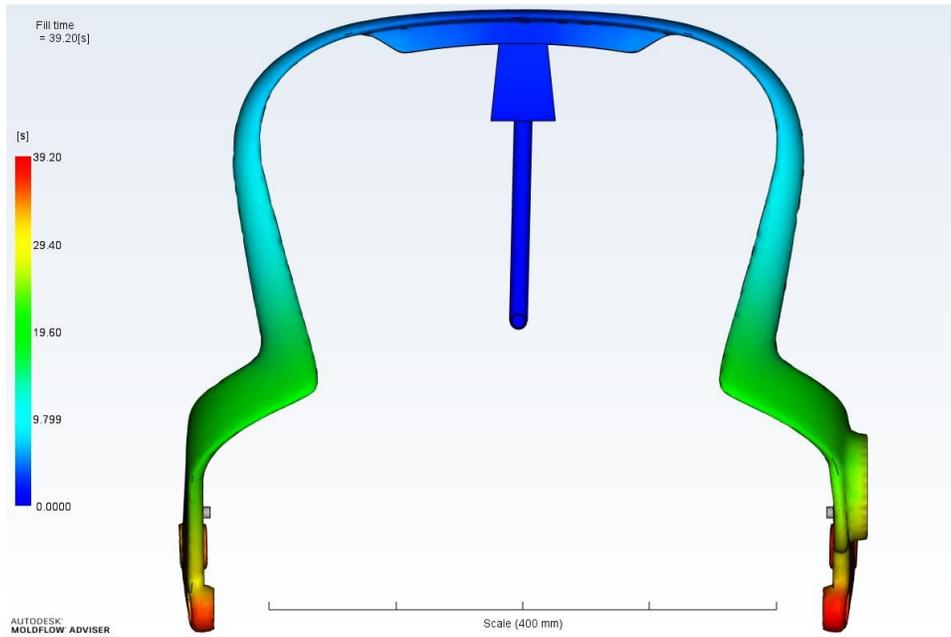
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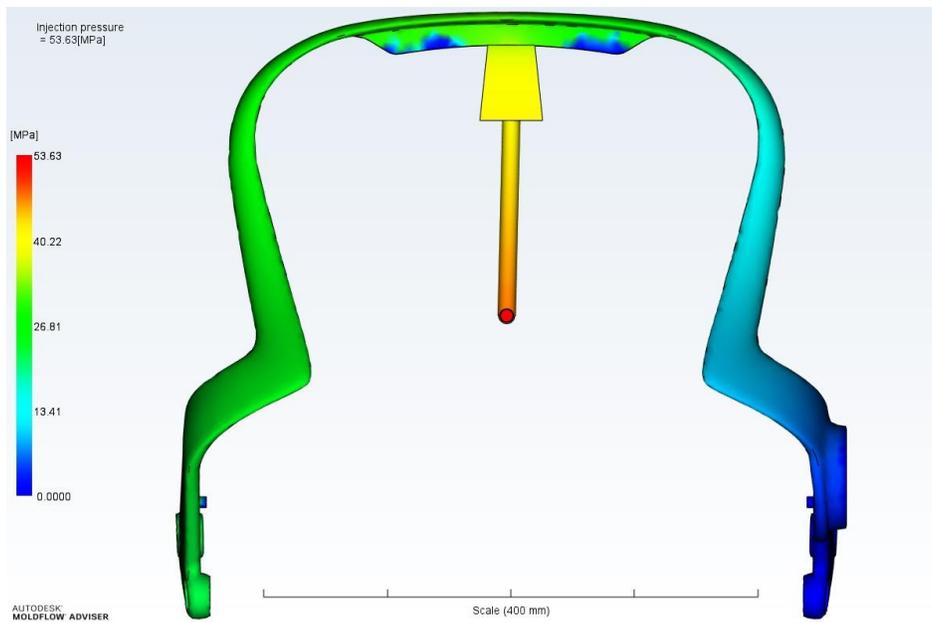
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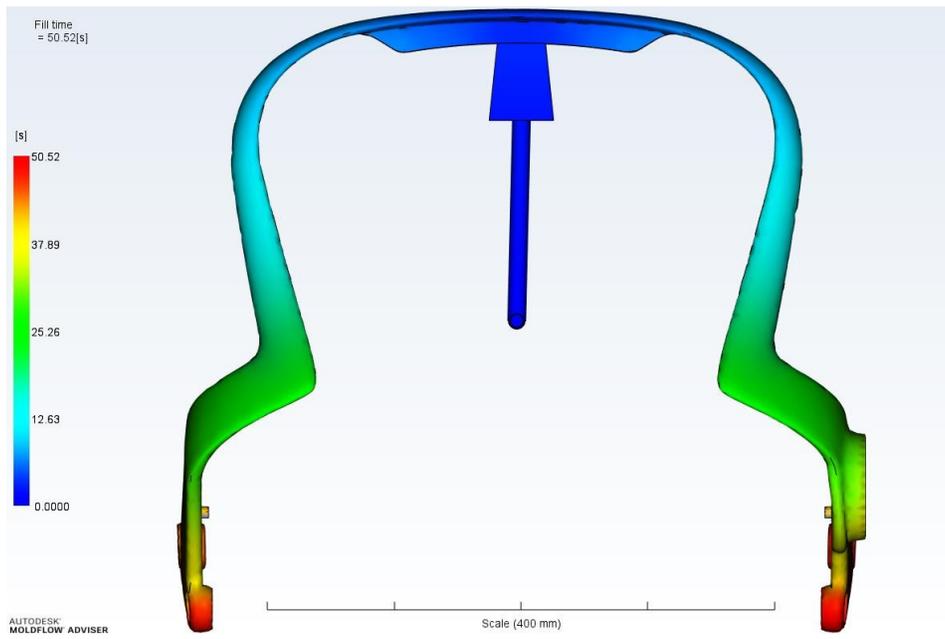
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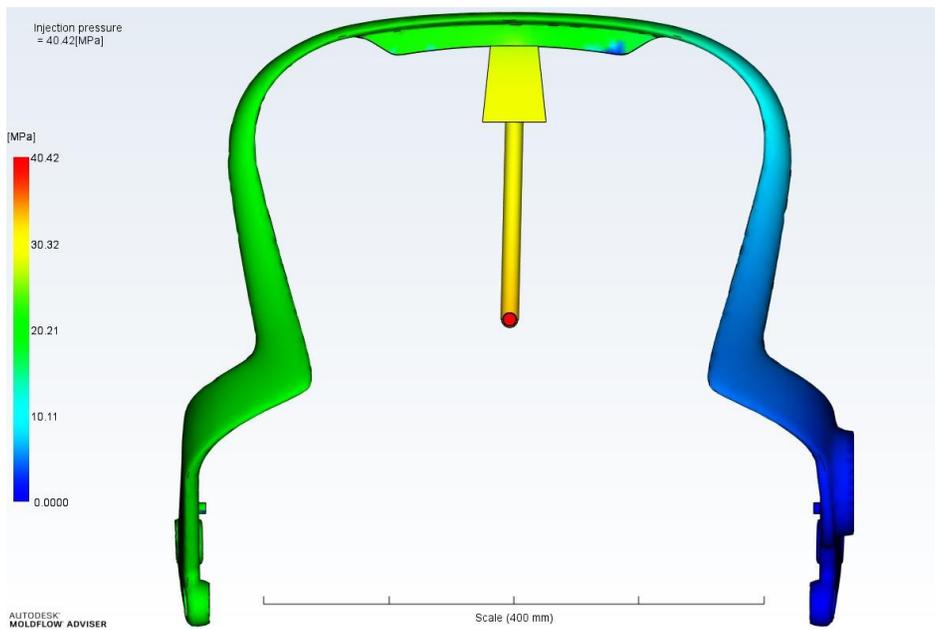
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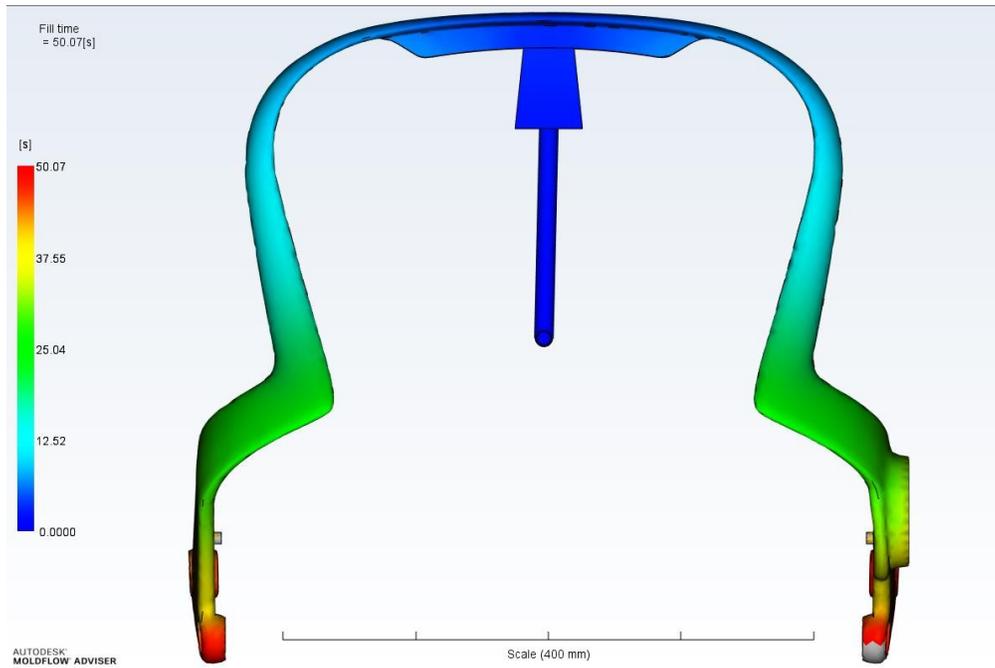
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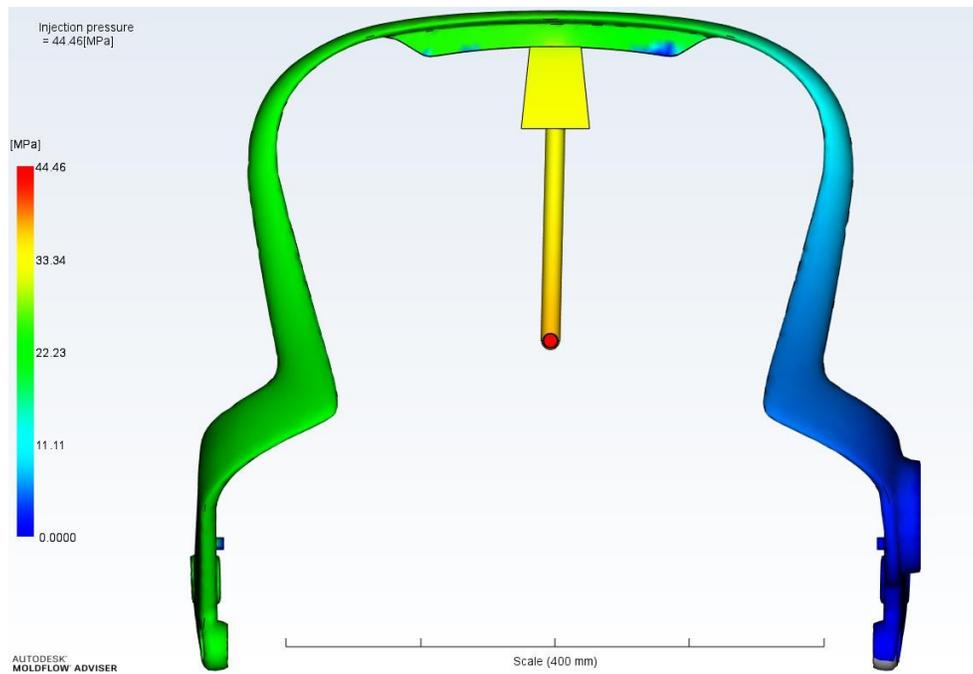
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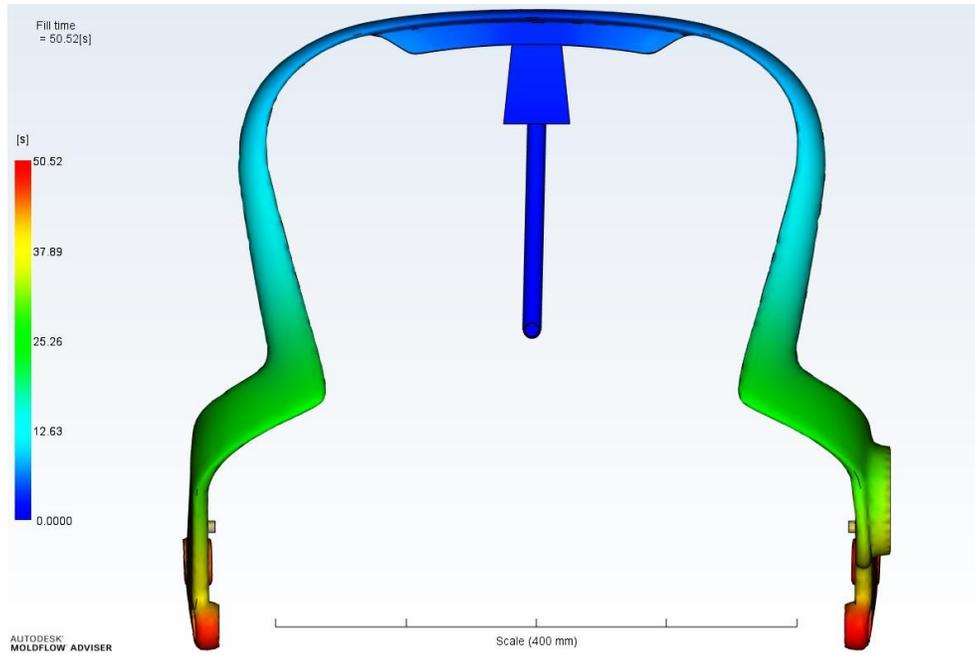
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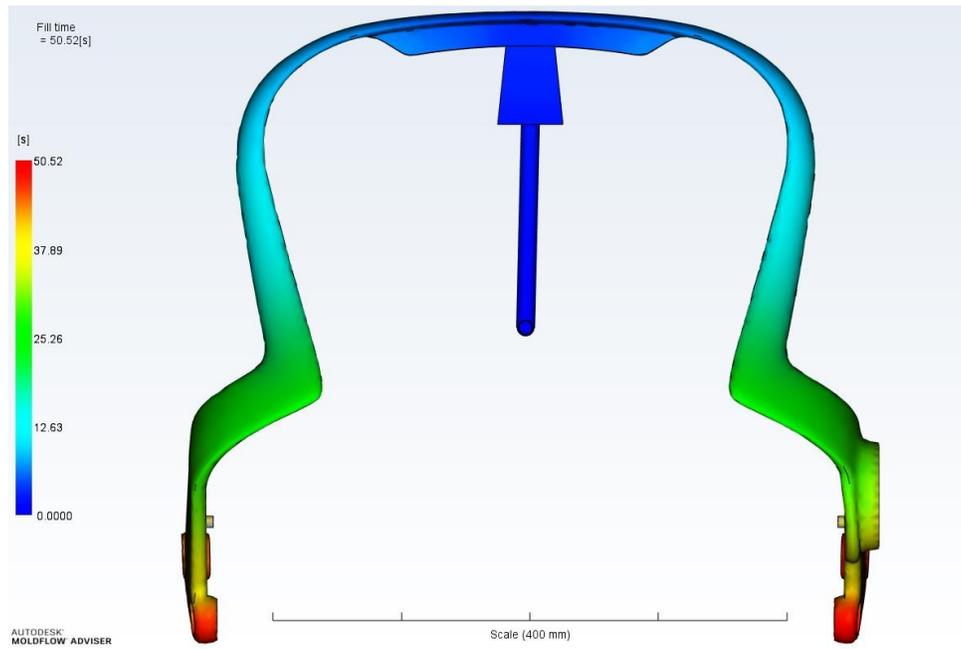
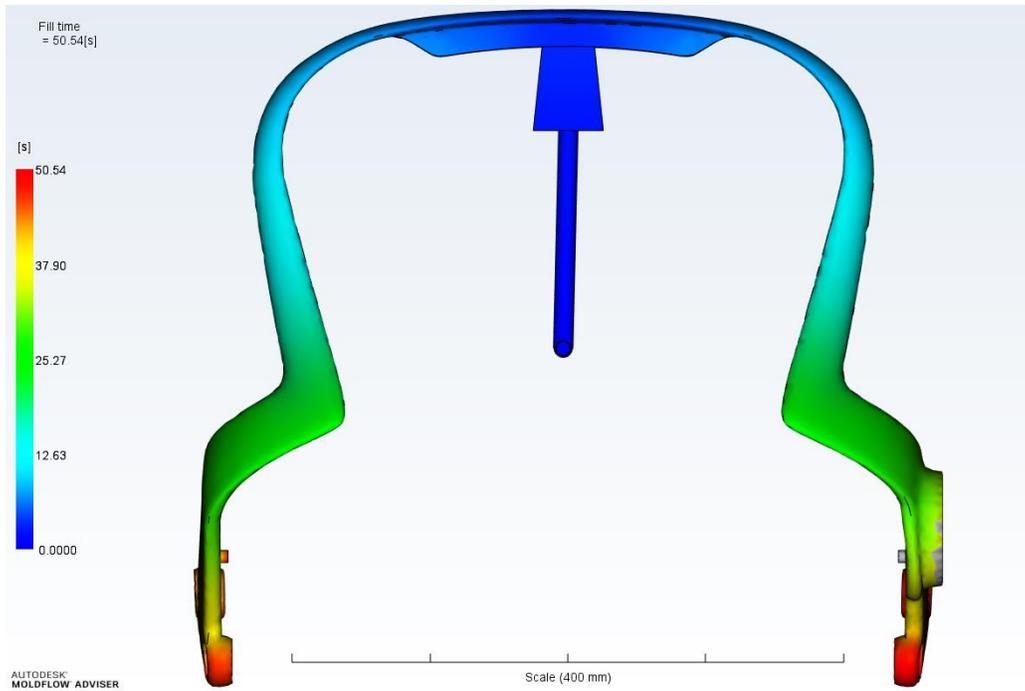## Sample #46 Fill time
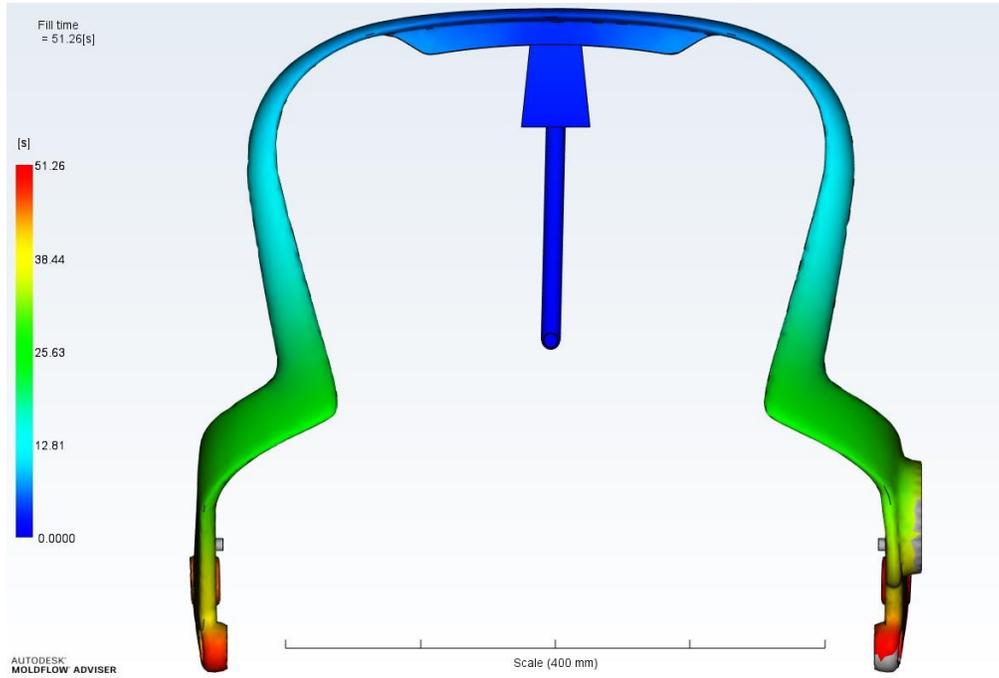
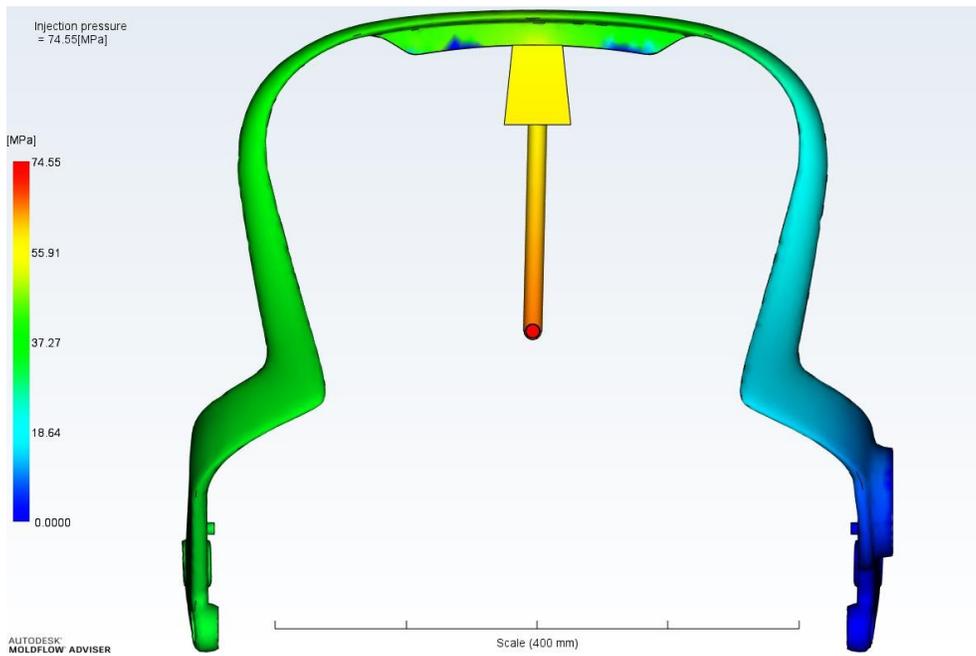## Sample #46 Injection pressure
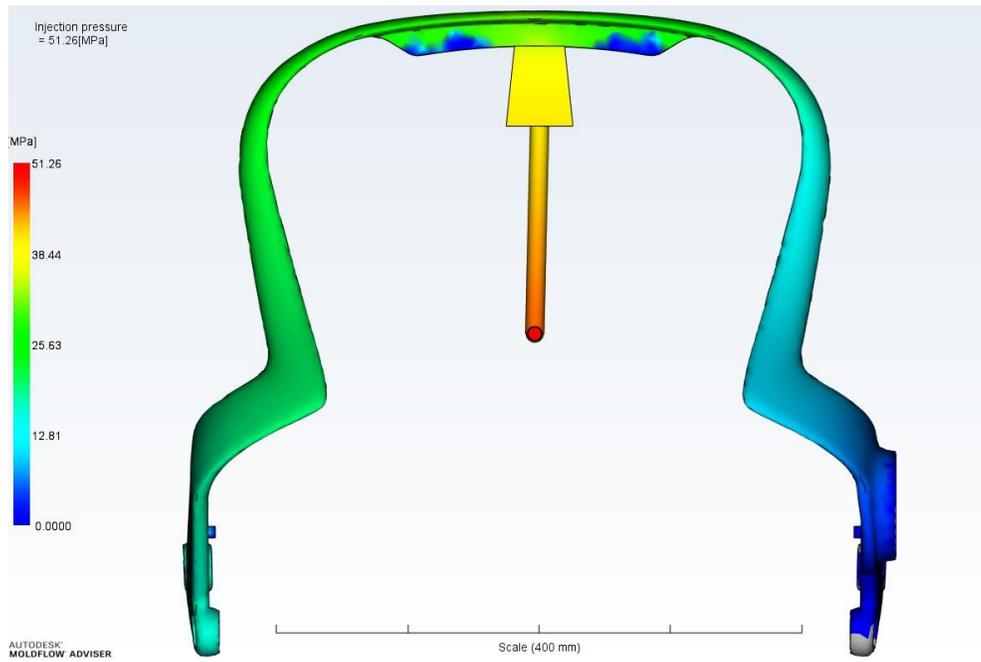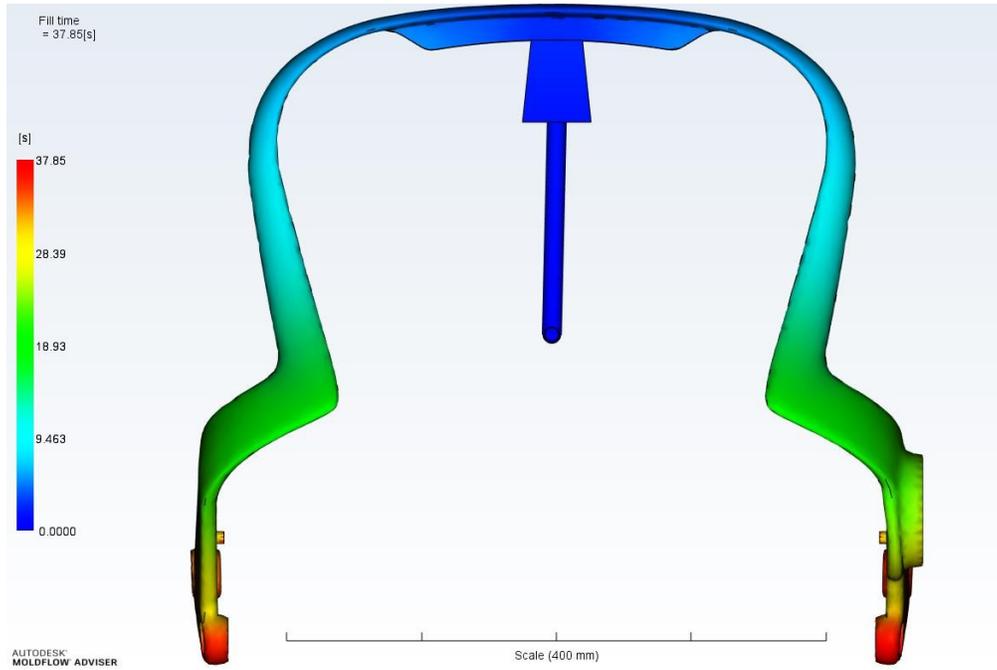
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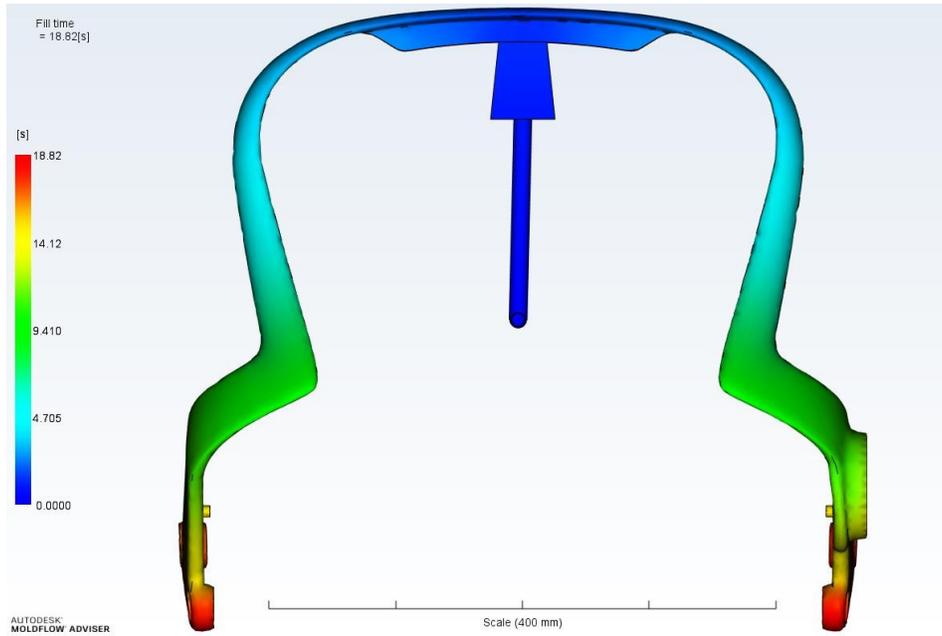
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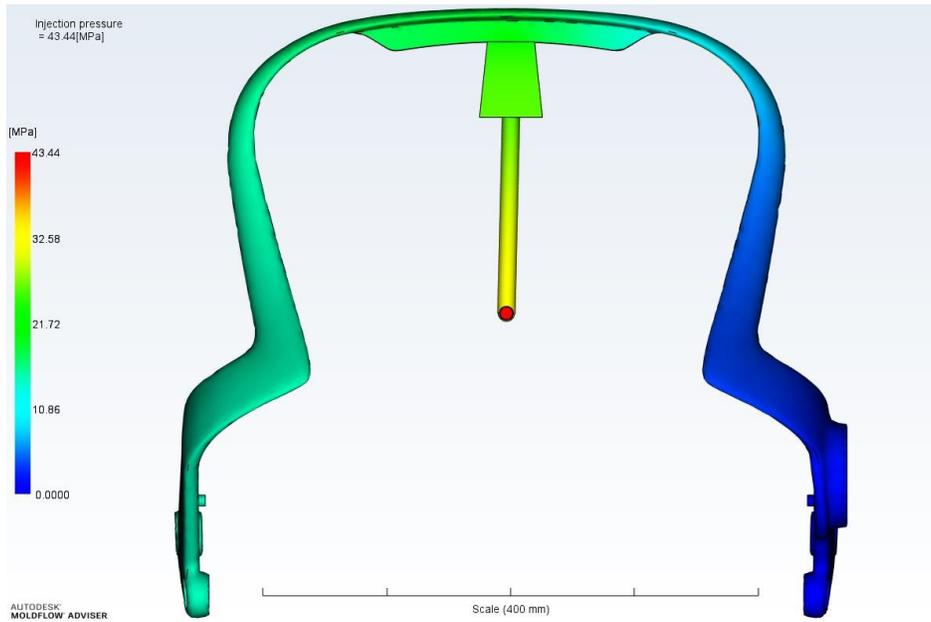
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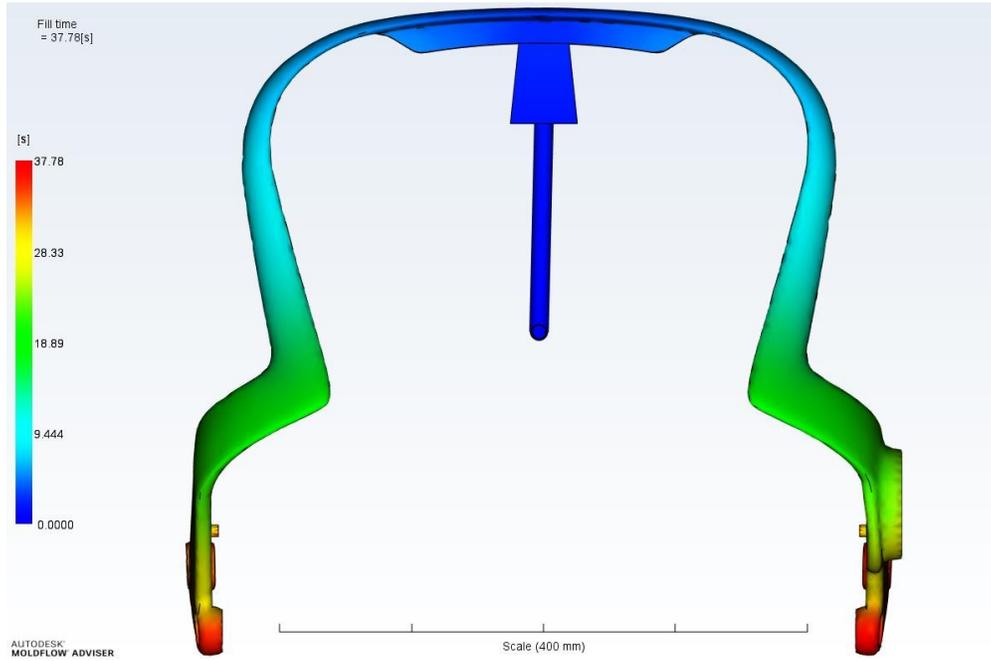
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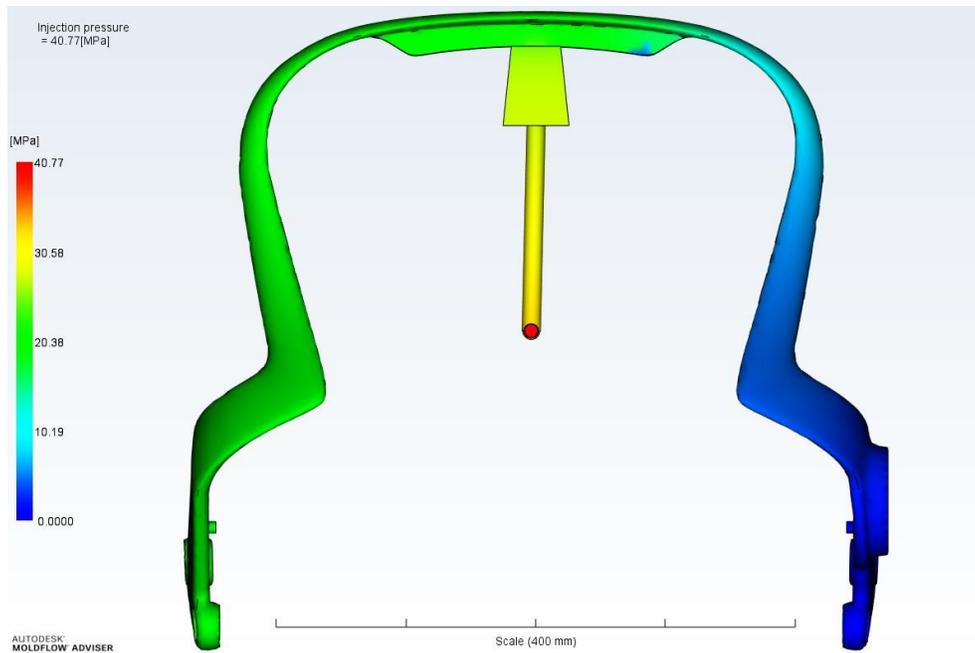
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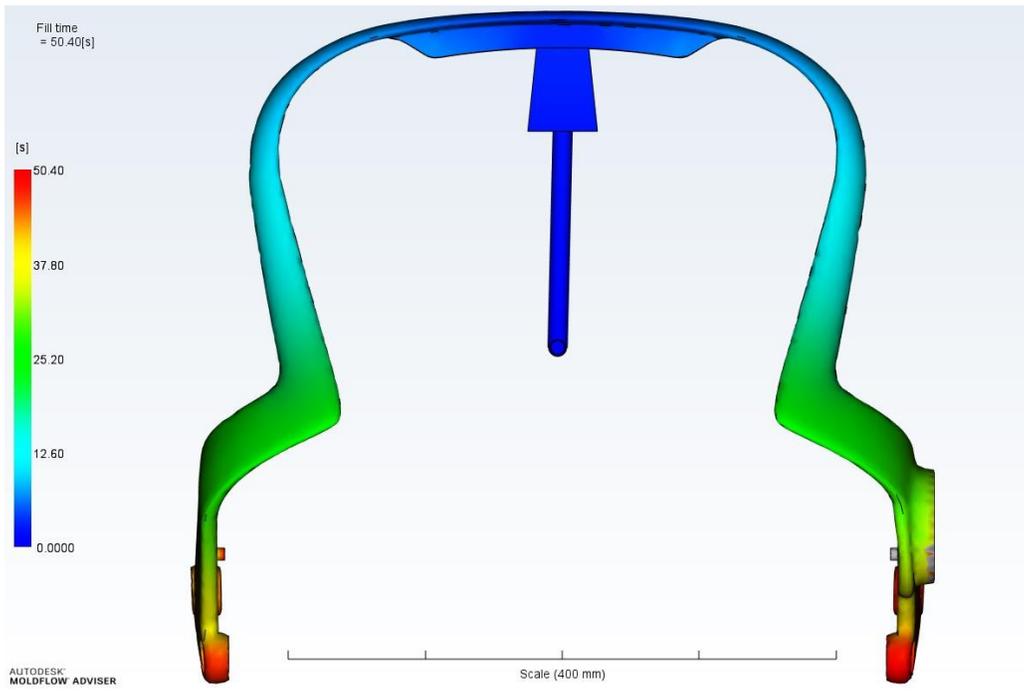
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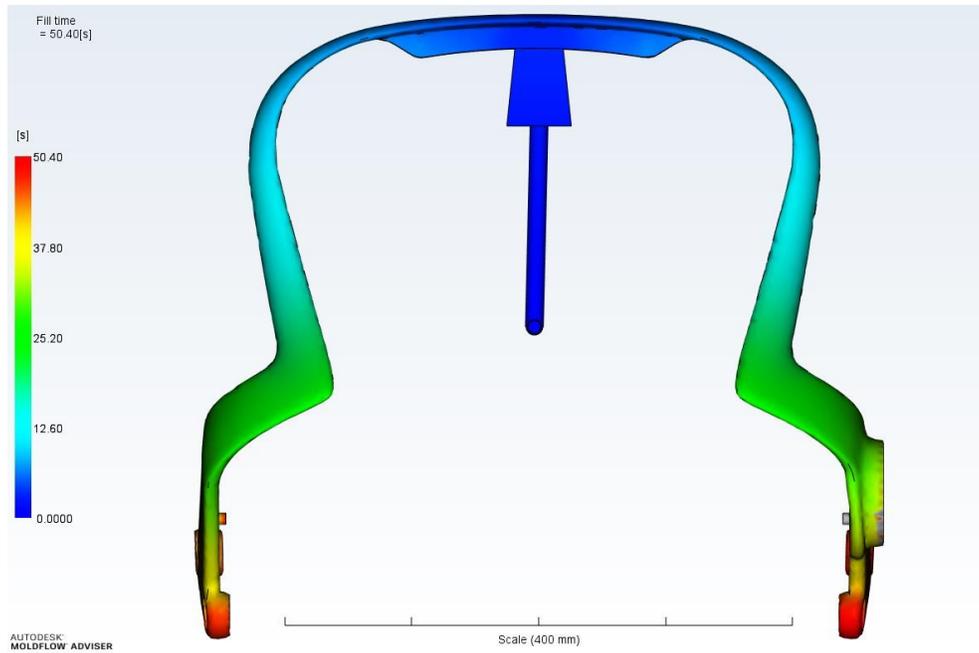
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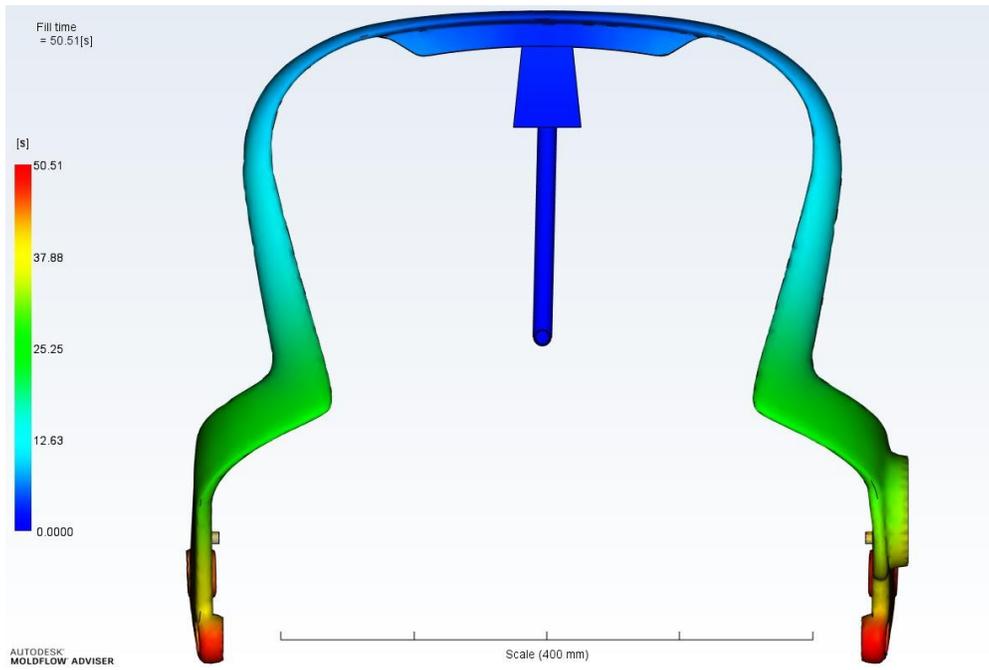
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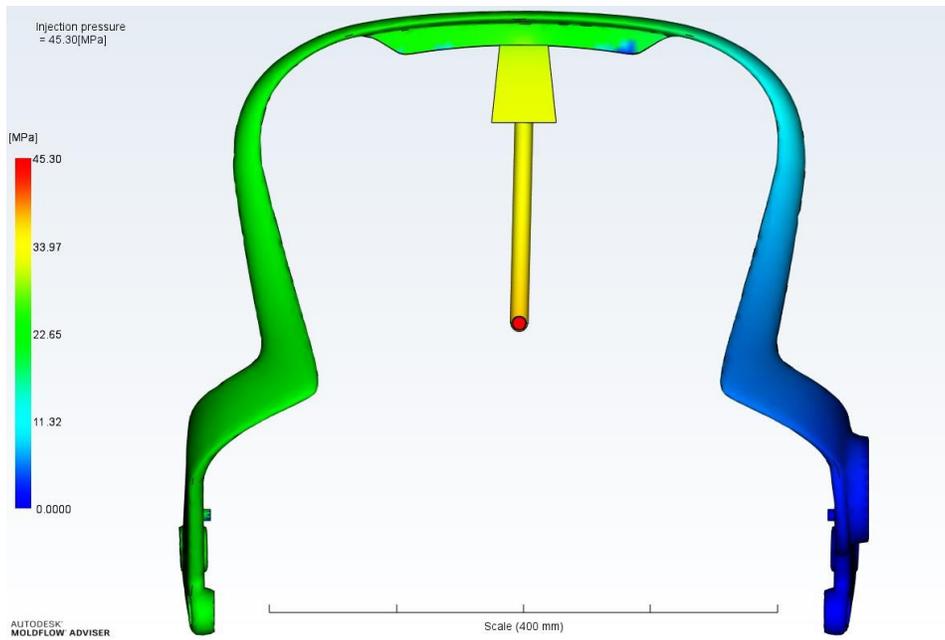
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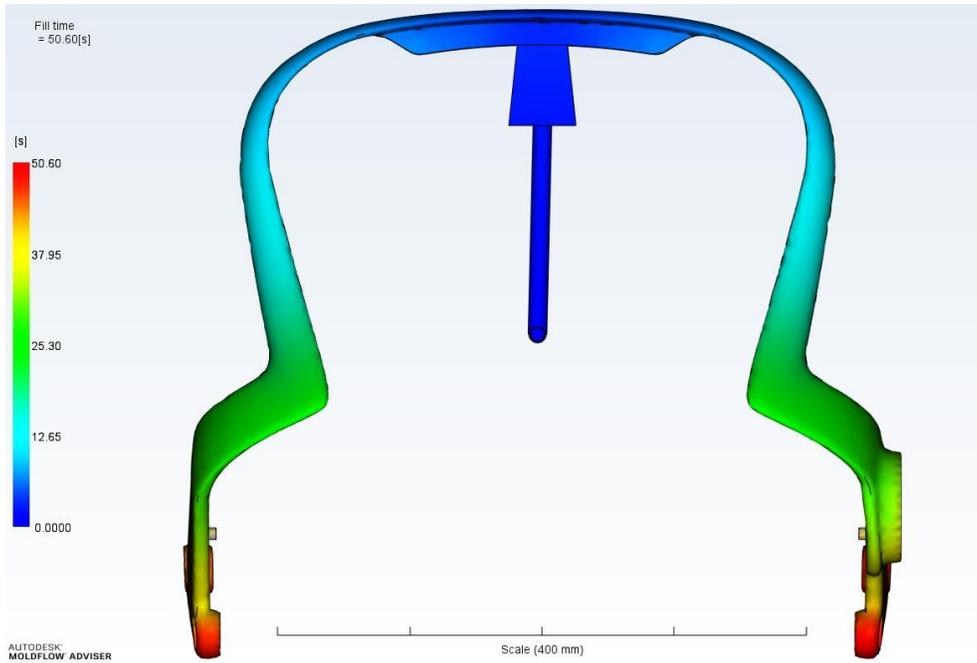
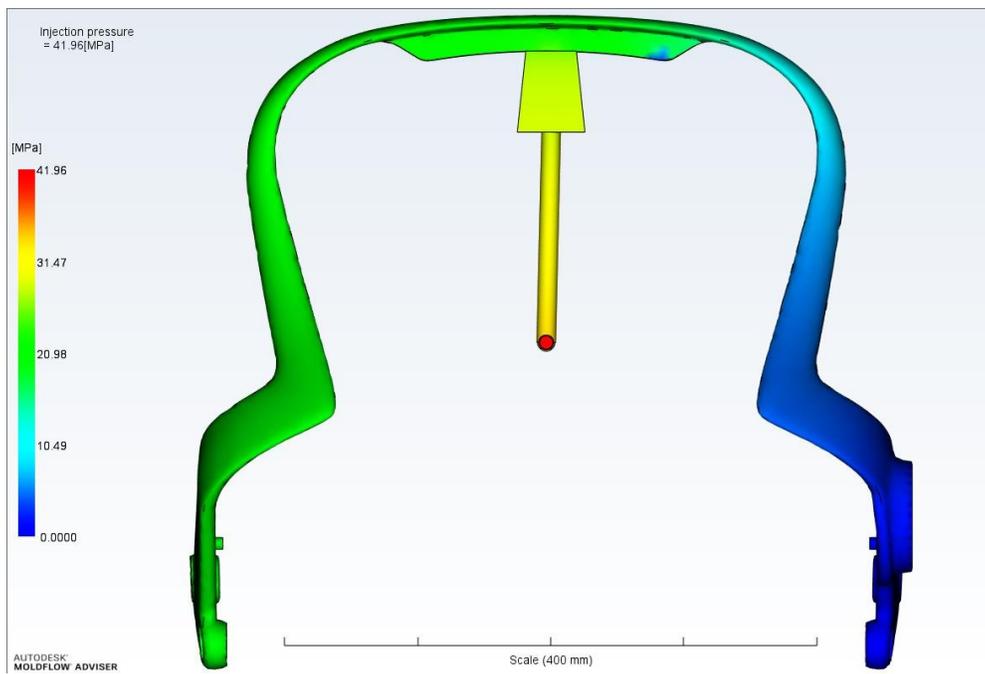Sample #51 Injection pressure
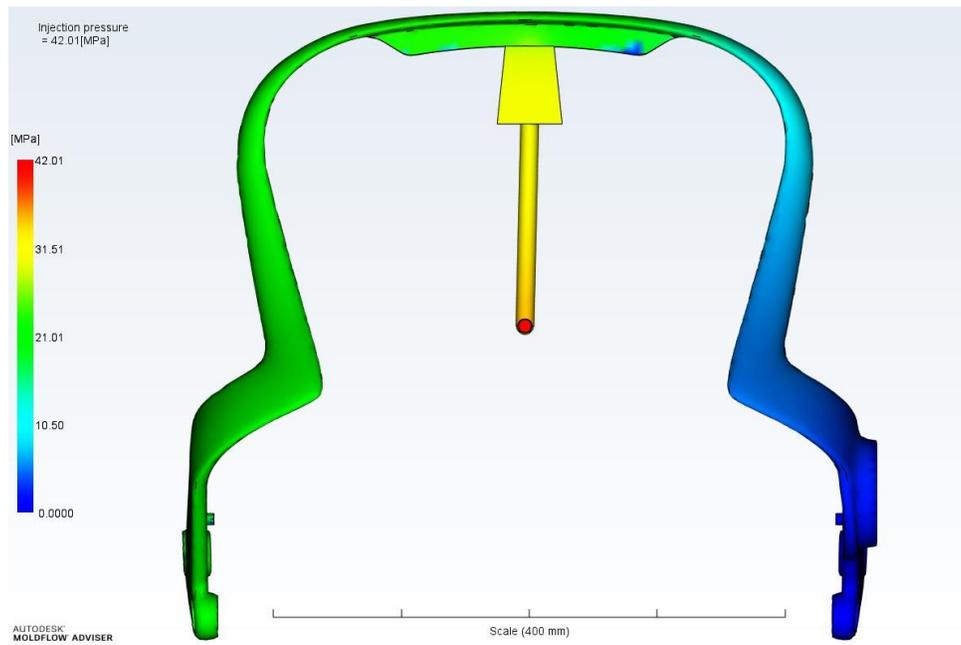
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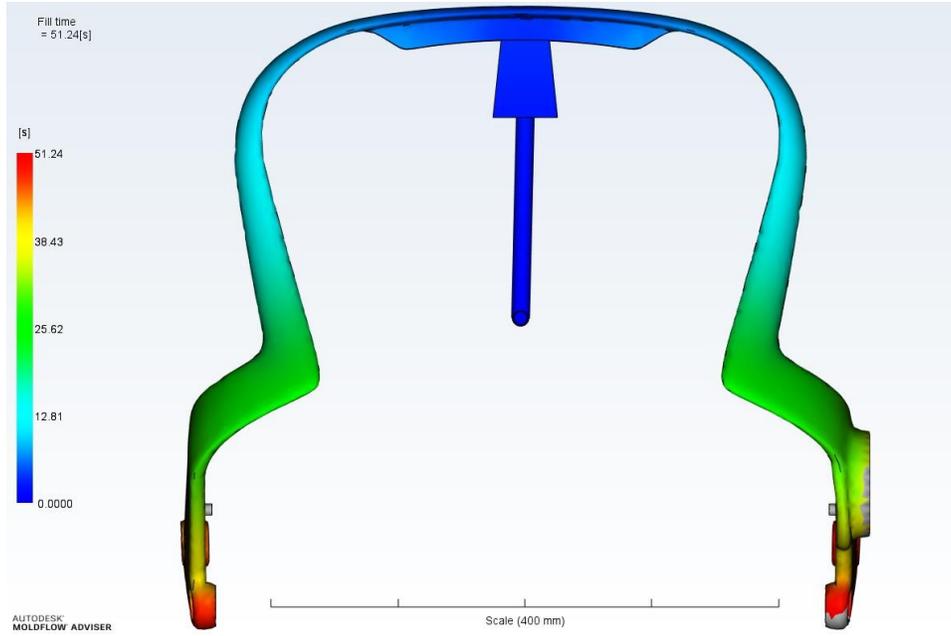
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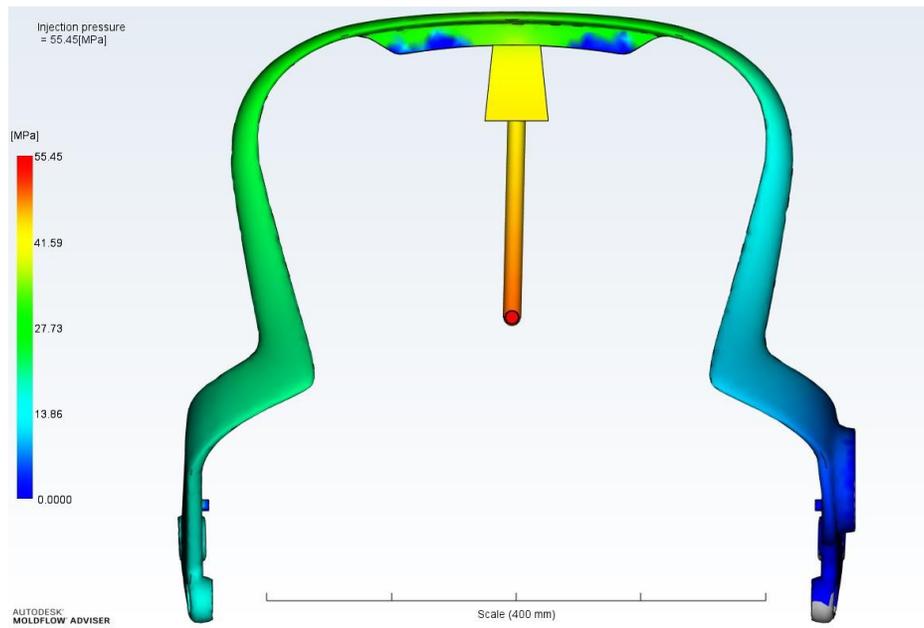
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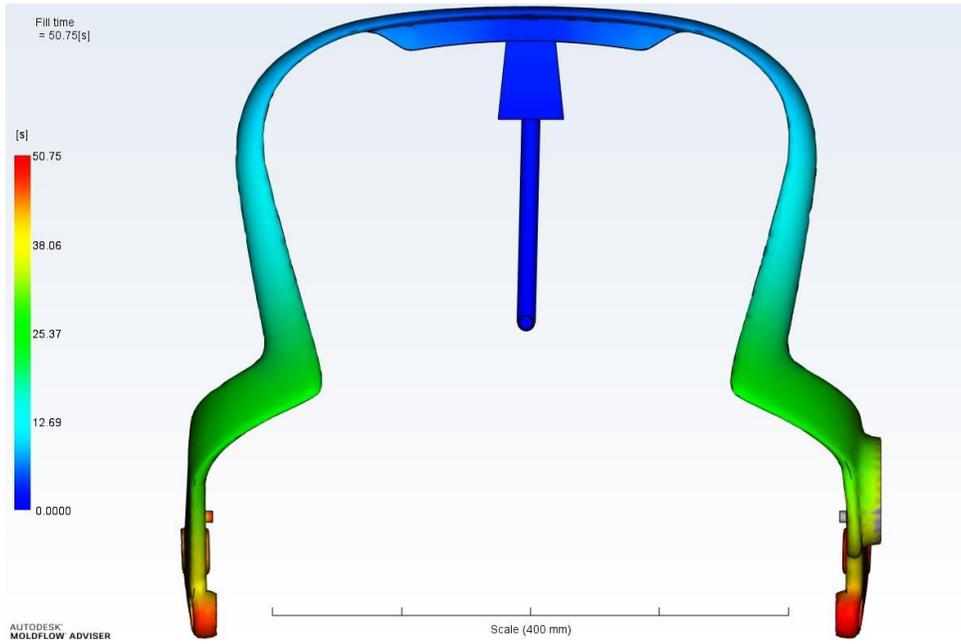
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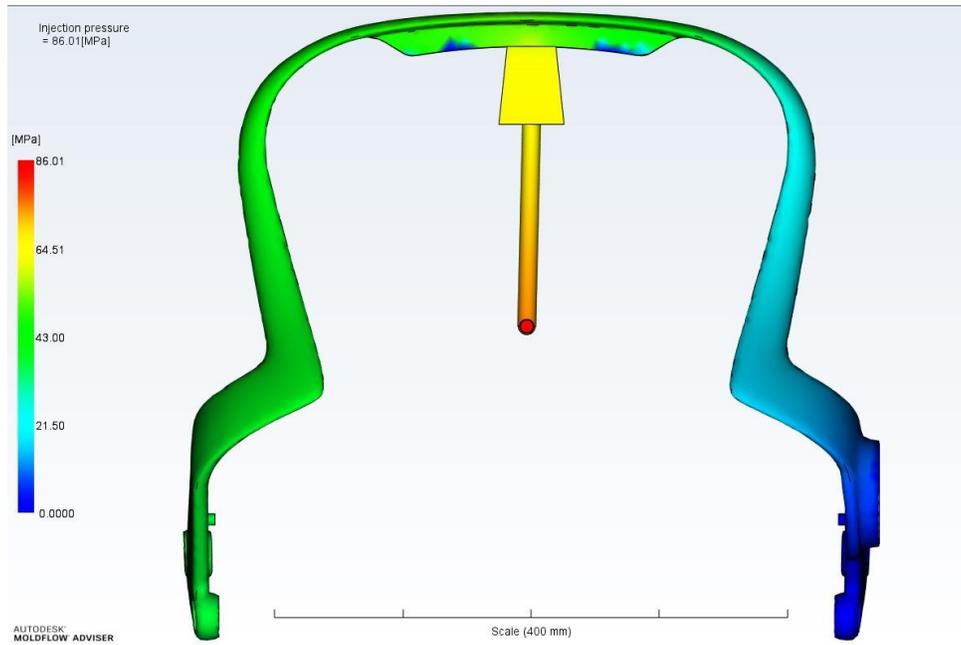
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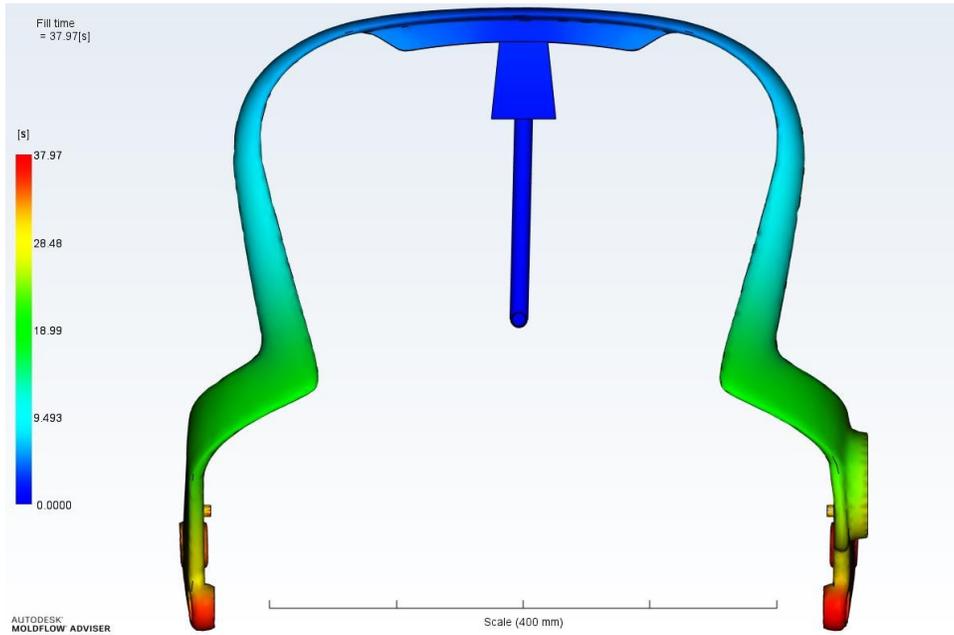
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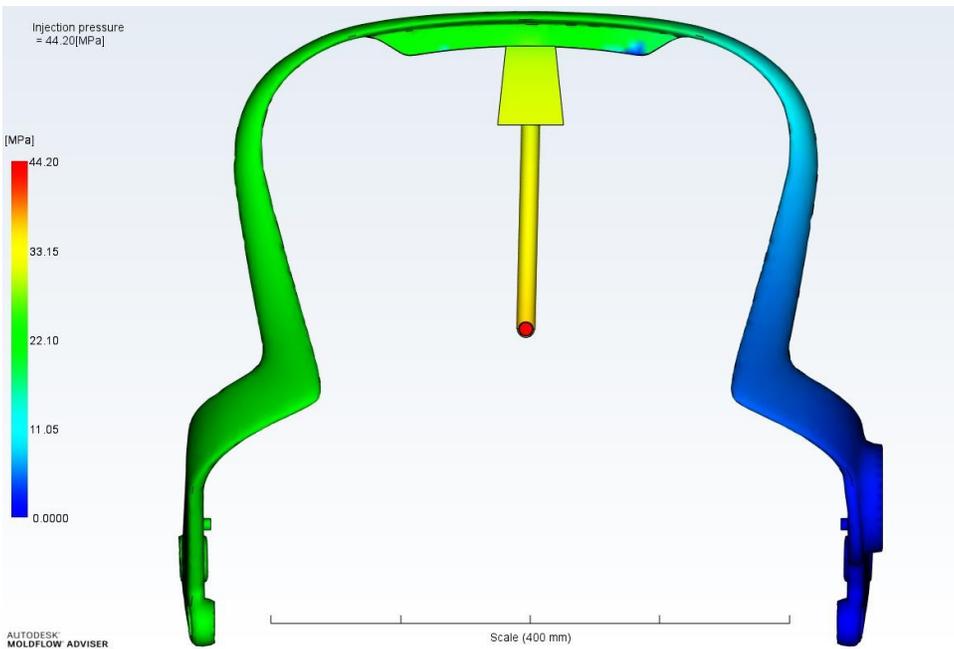
Sample #55 Fill time
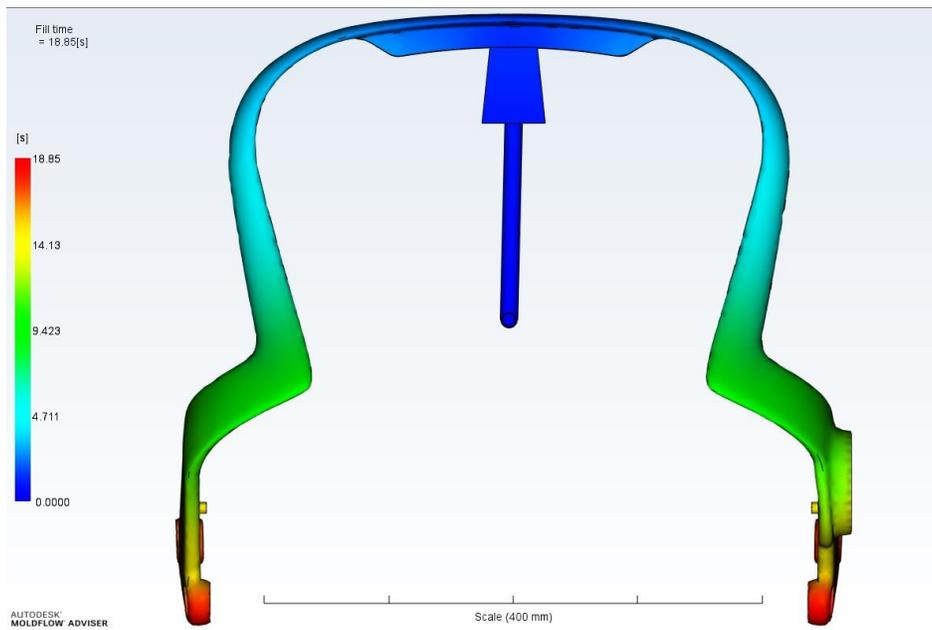
Sample #55 Injection pressure
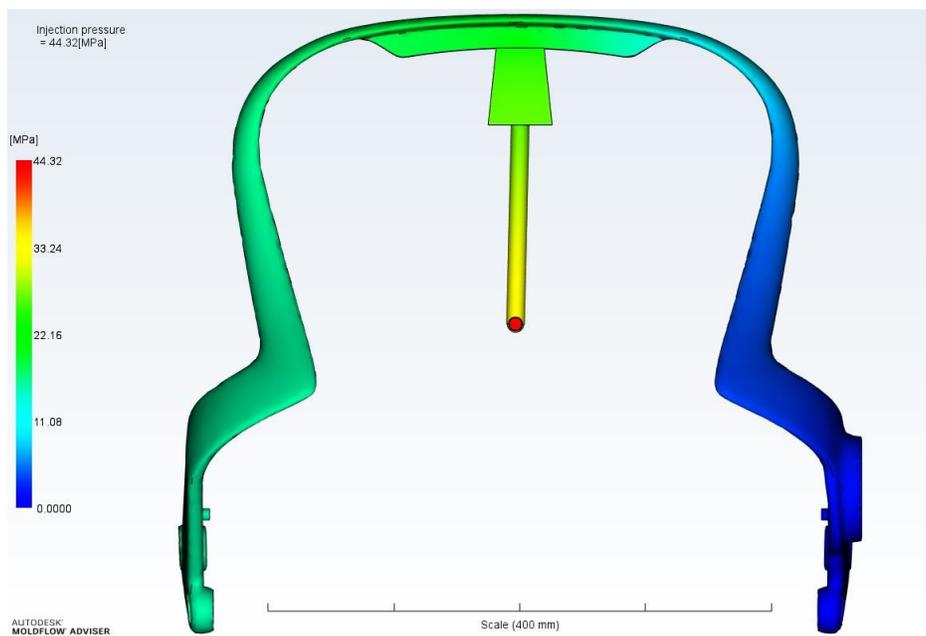
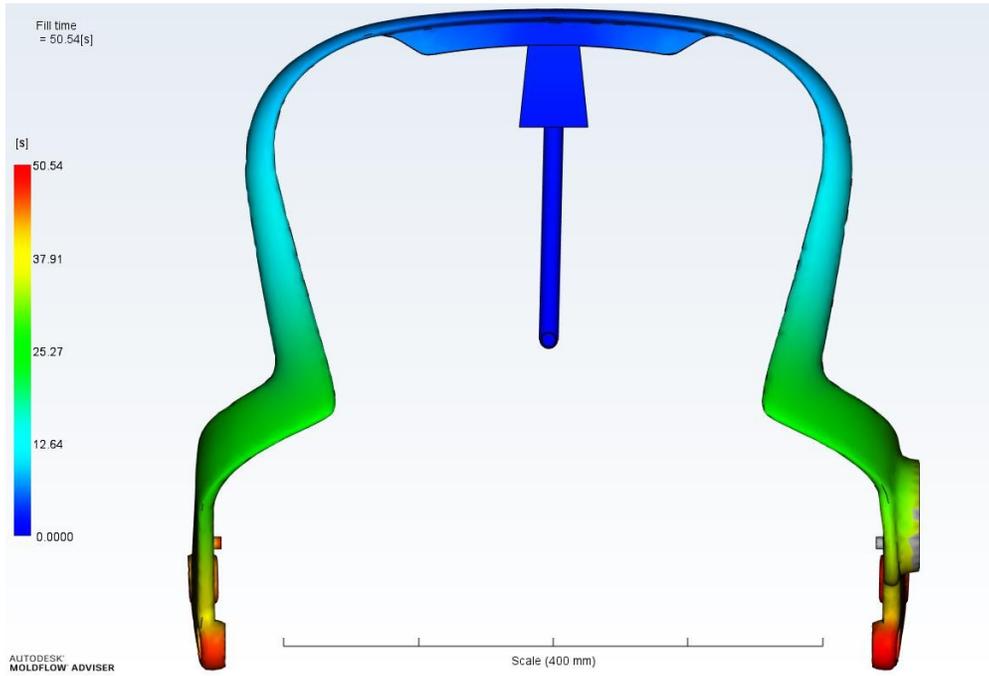Sample #56 Fill time
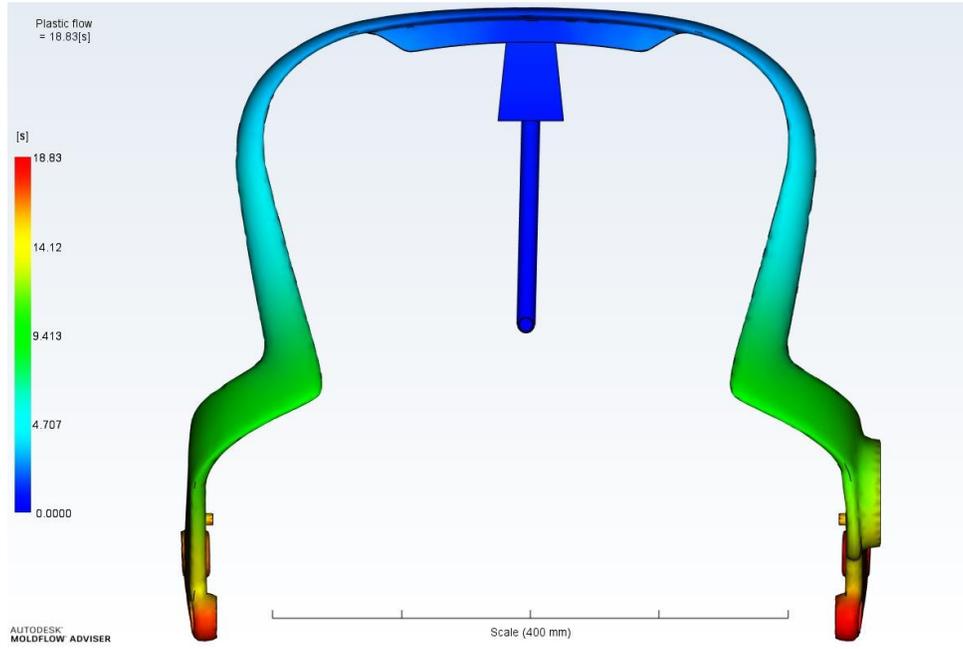
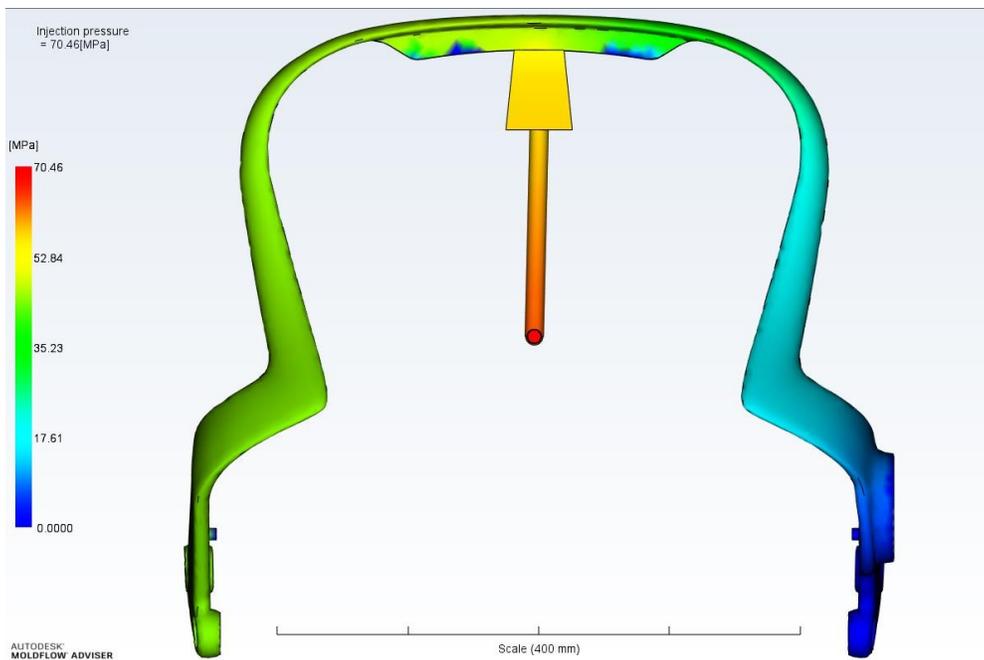Sample #56 Injection pressure
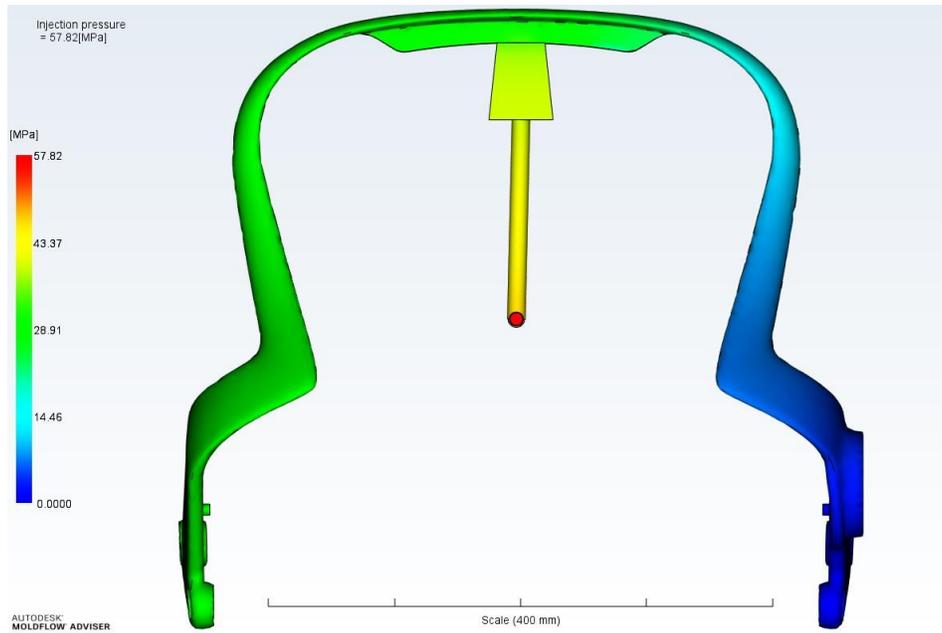
Sample #57 Fill time
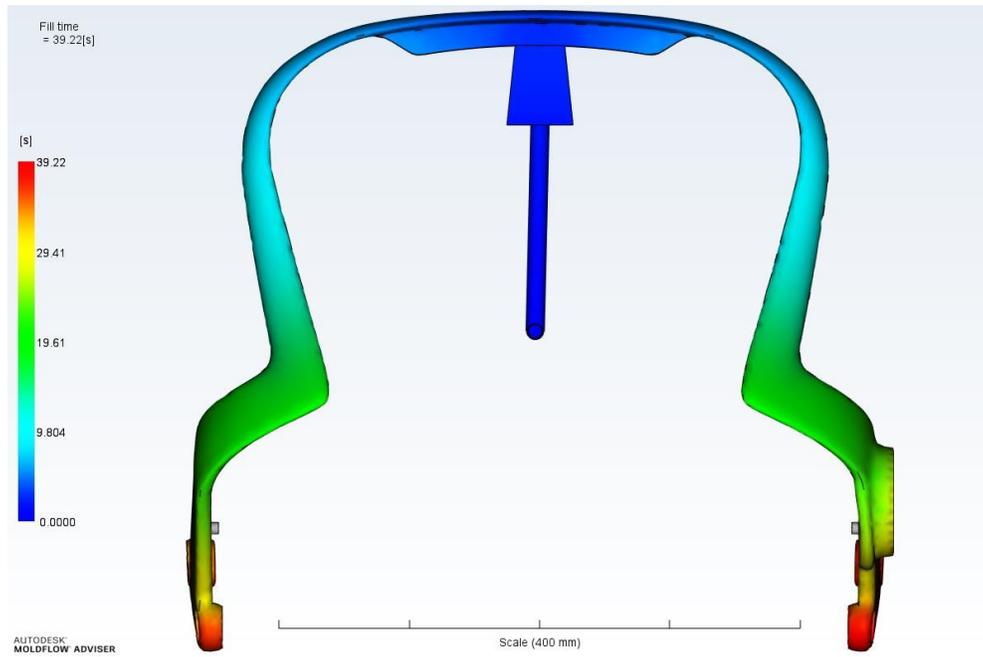
Sample #57 Injection pressure
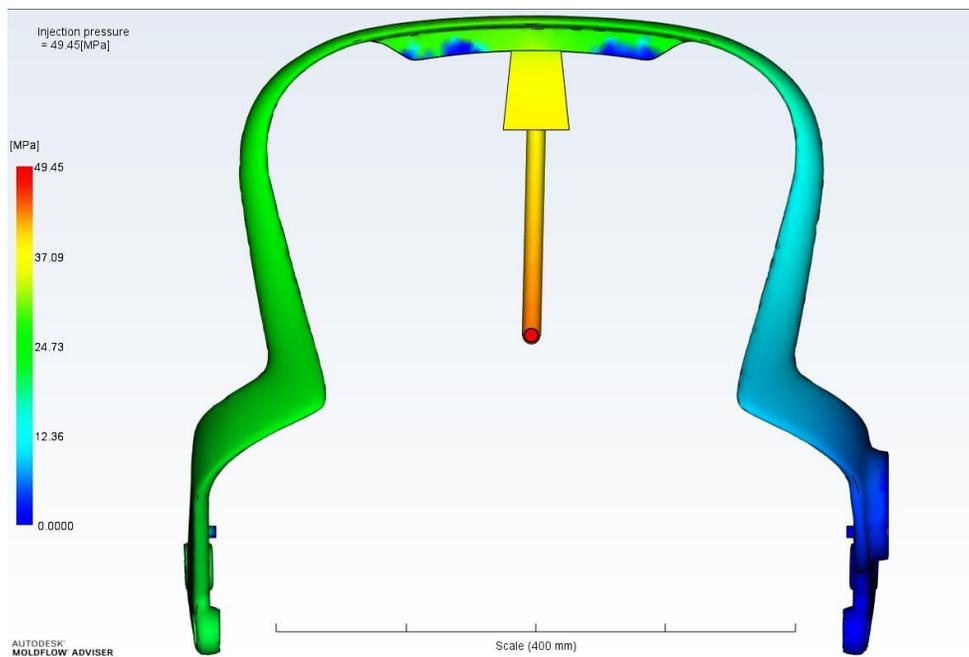
Sample #58 Fill time
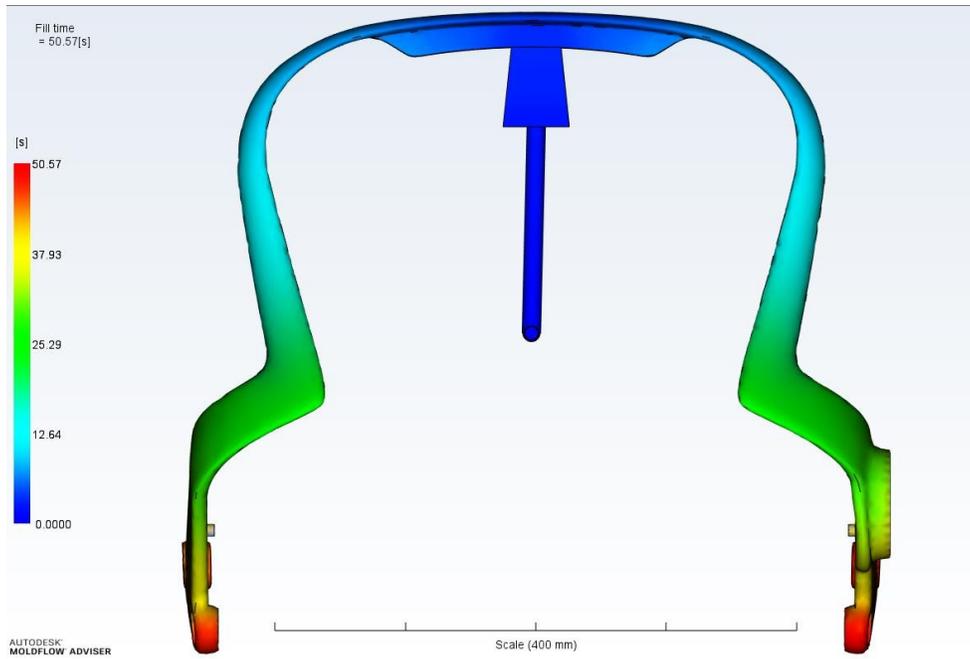
Sample #58 Injection pressure
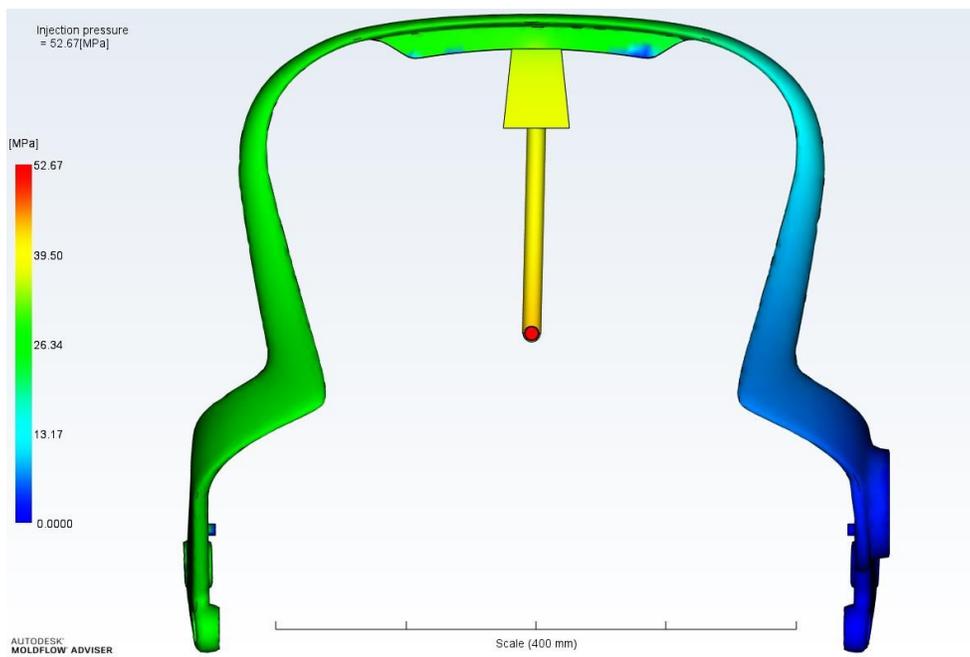
Sample #59 Fill time
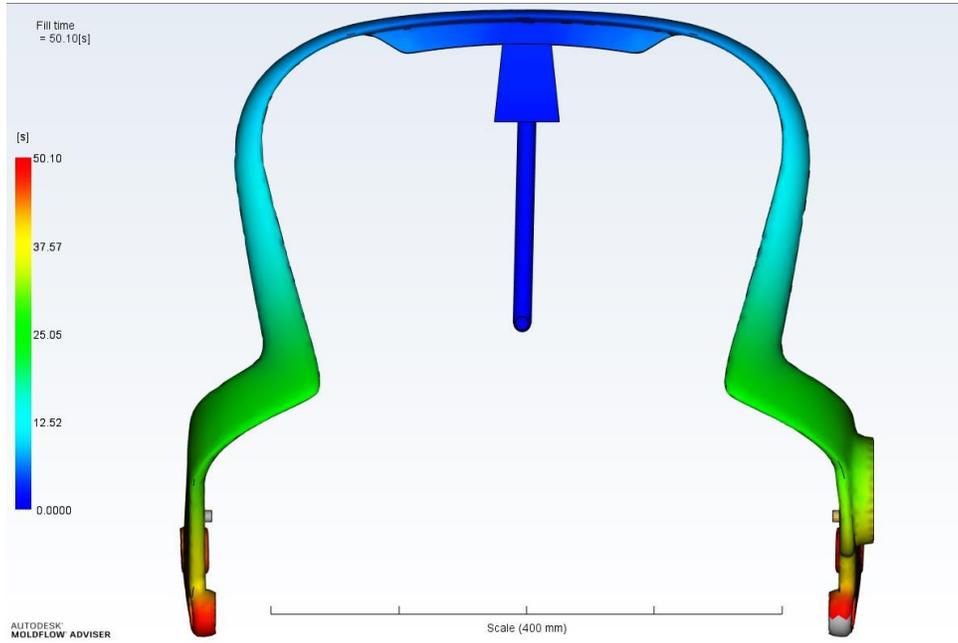
Sample #59 Injection pressure
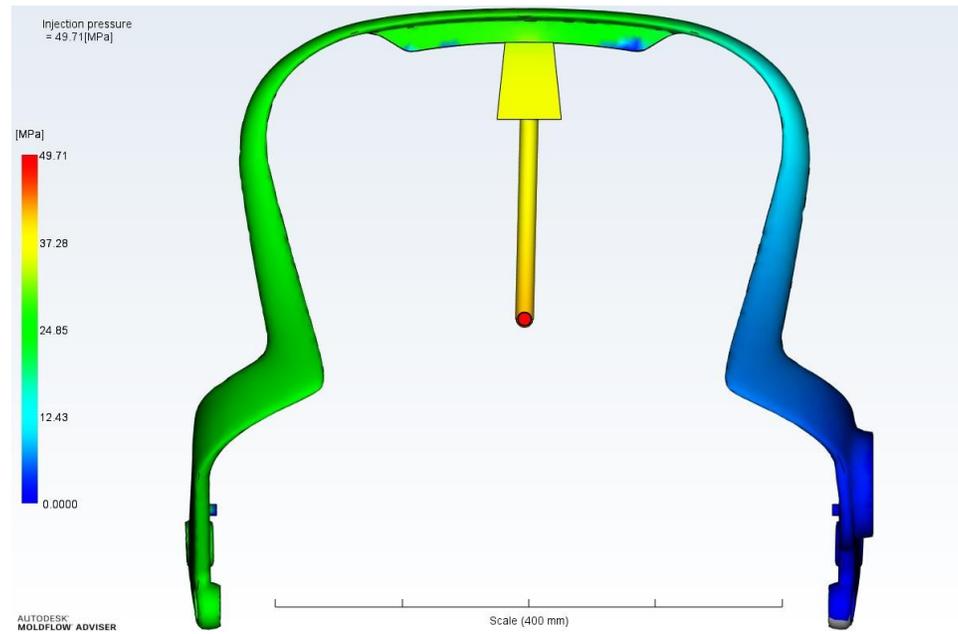
Sample #60 Fill time
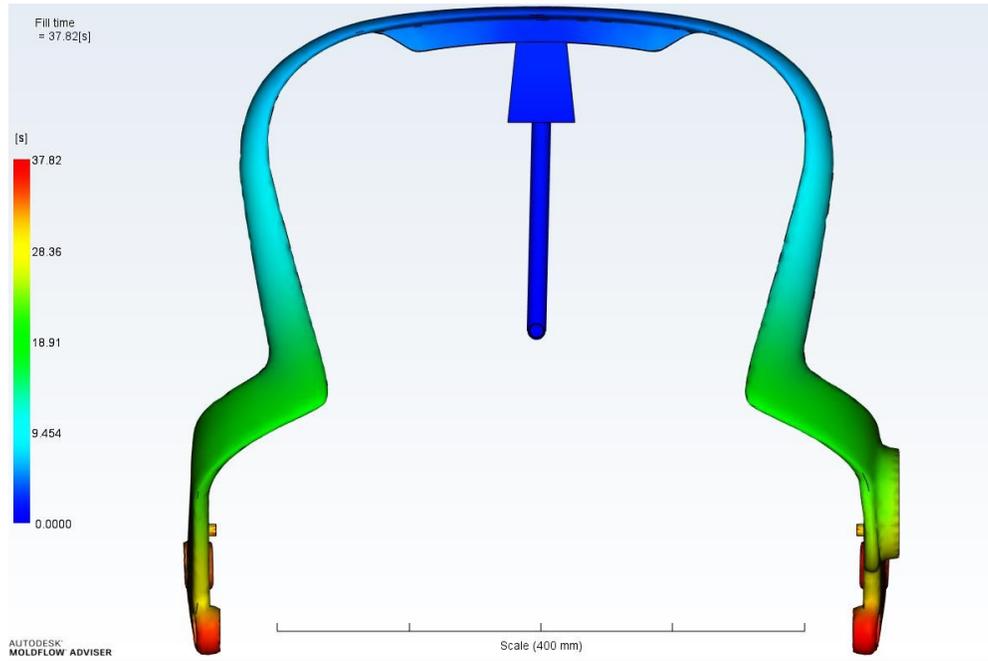
Sample #60 Injection pressure
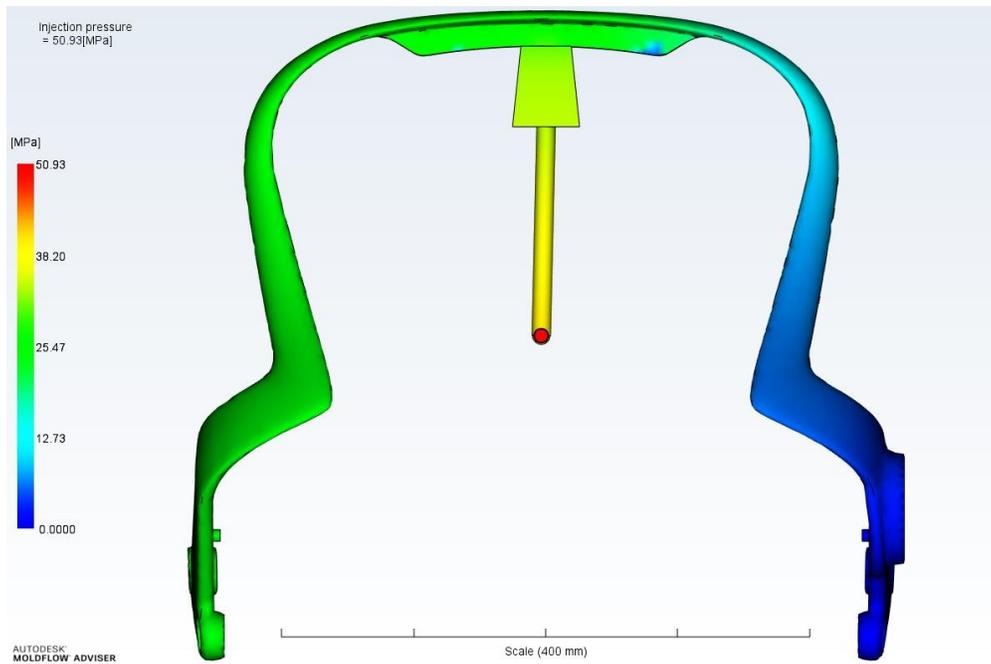
Sample #61 Fill time
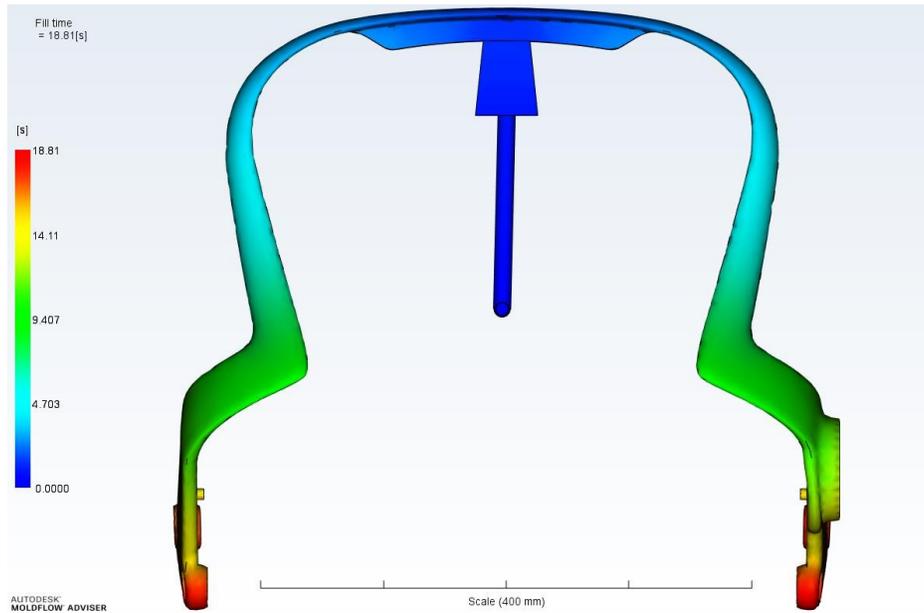
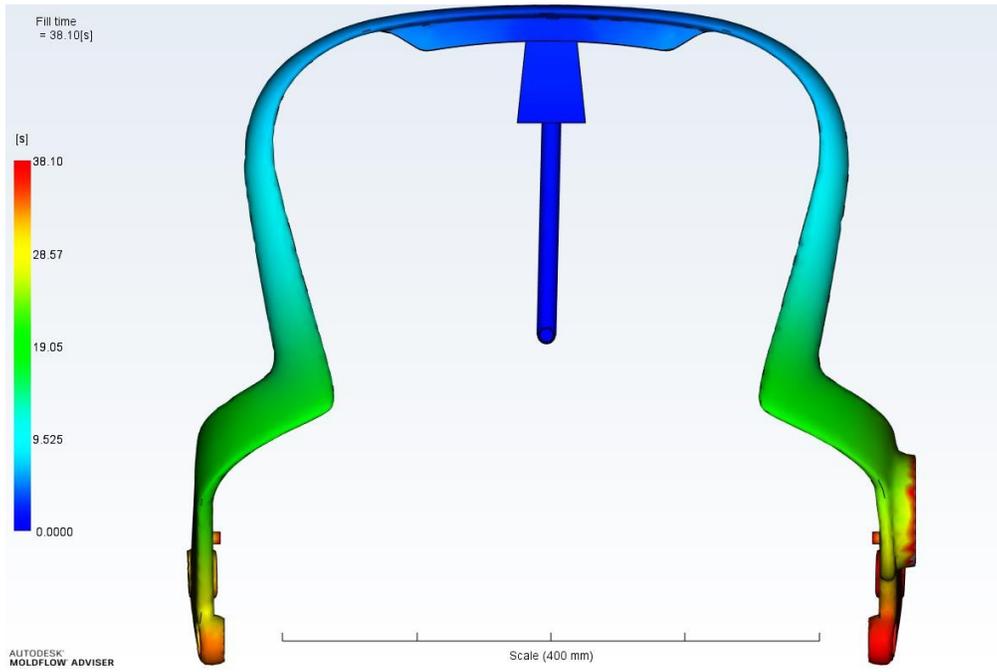## Sample #61 Injection pressure
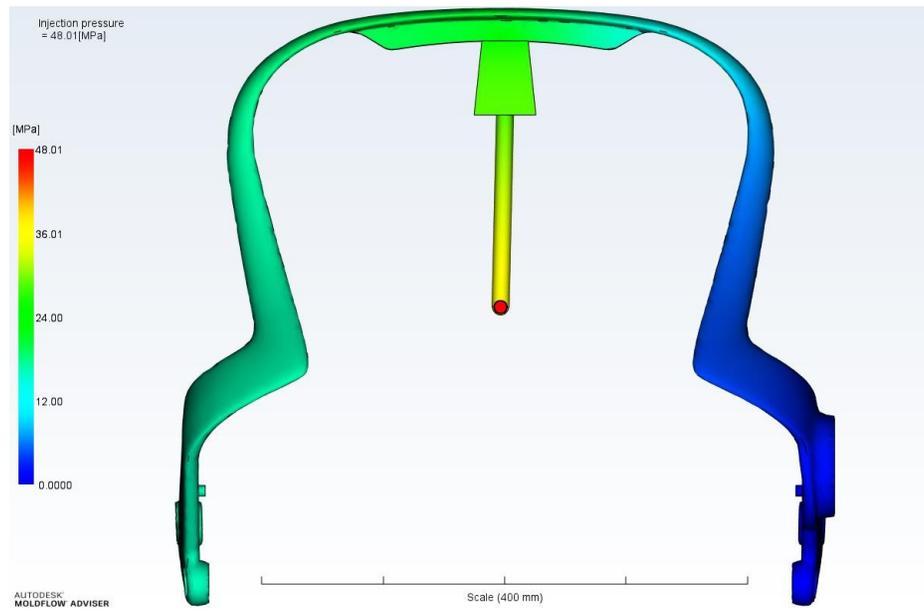
Sample #62 Fill time
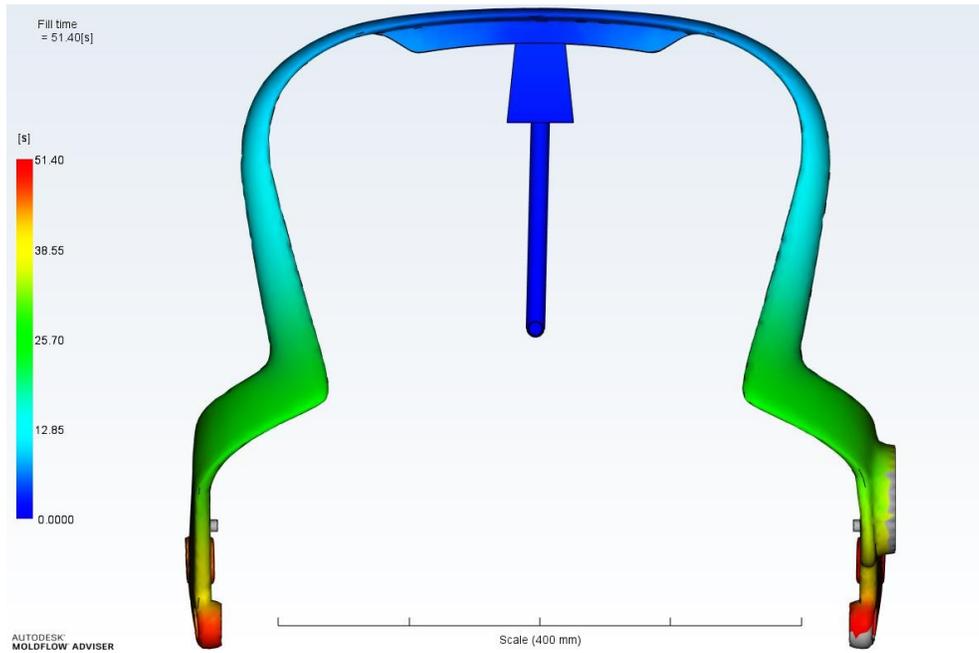
Sample #62 Injection pressure
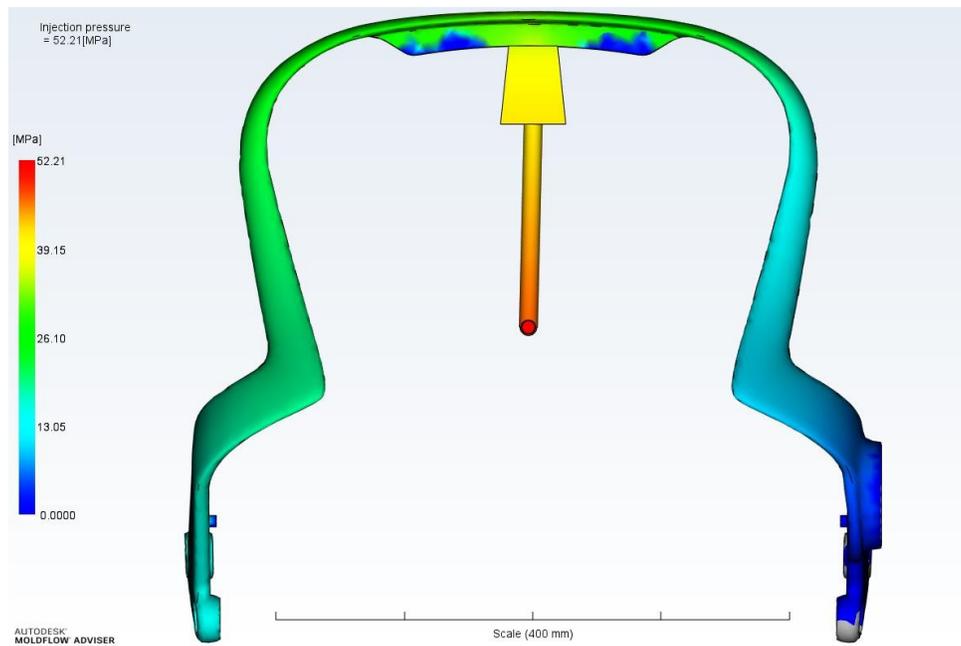
Sample #63 Fill time
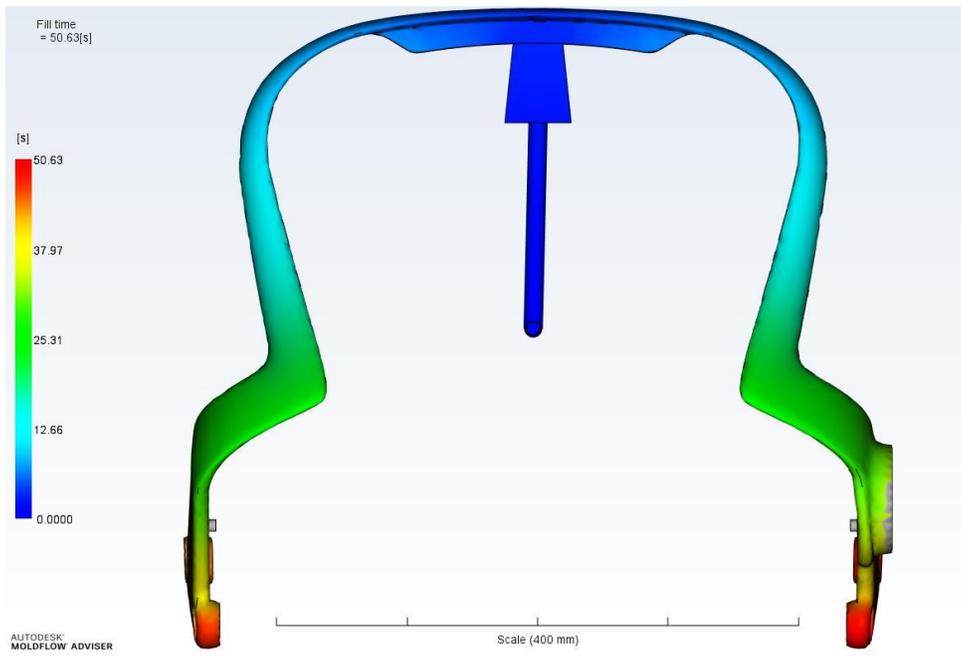
Sample #63 Injection pressure
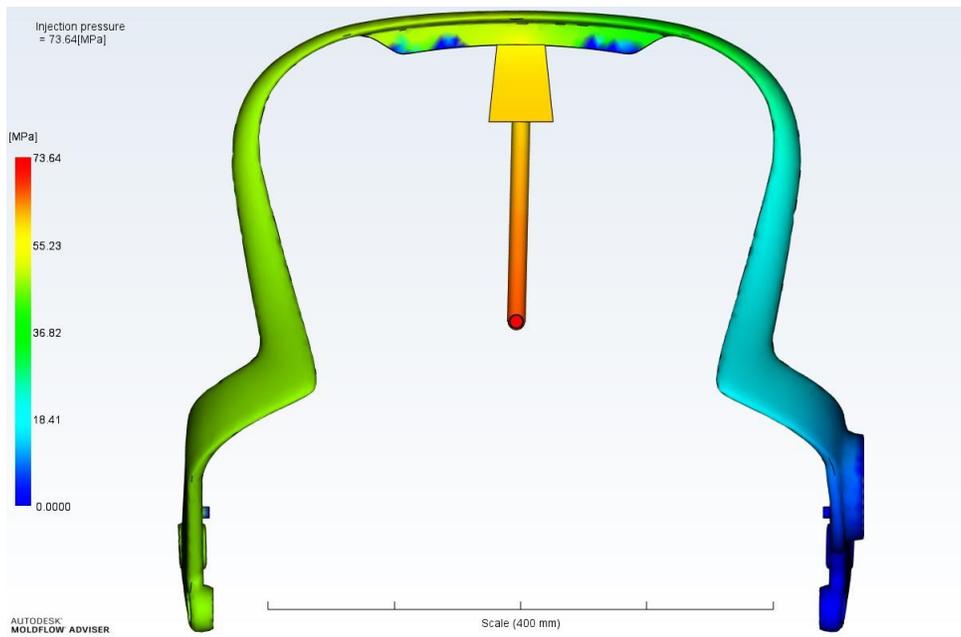
Sample #64 Fill time
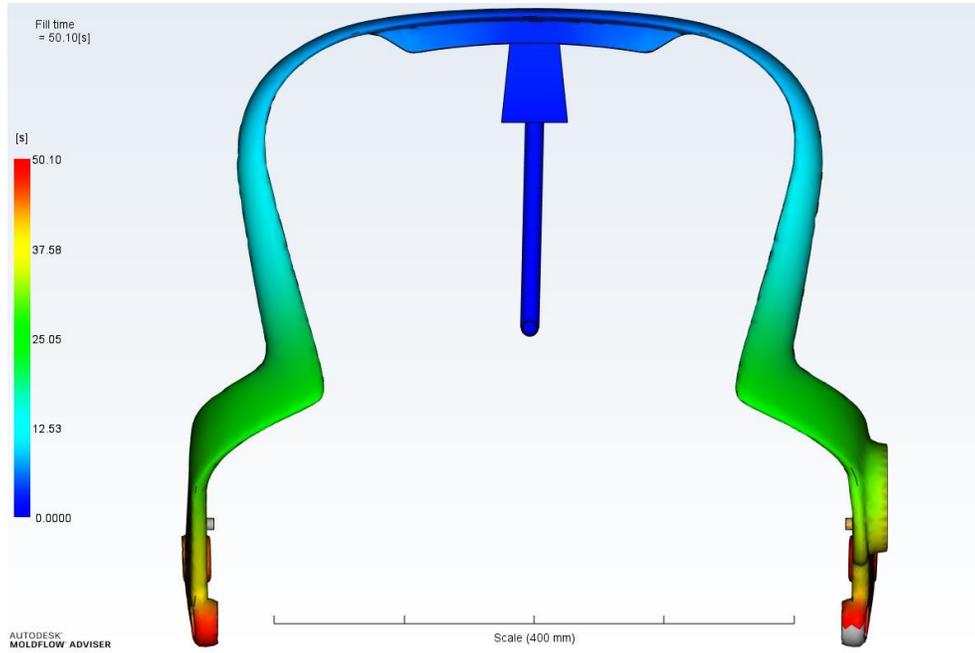
Sample #64 Injection pressure
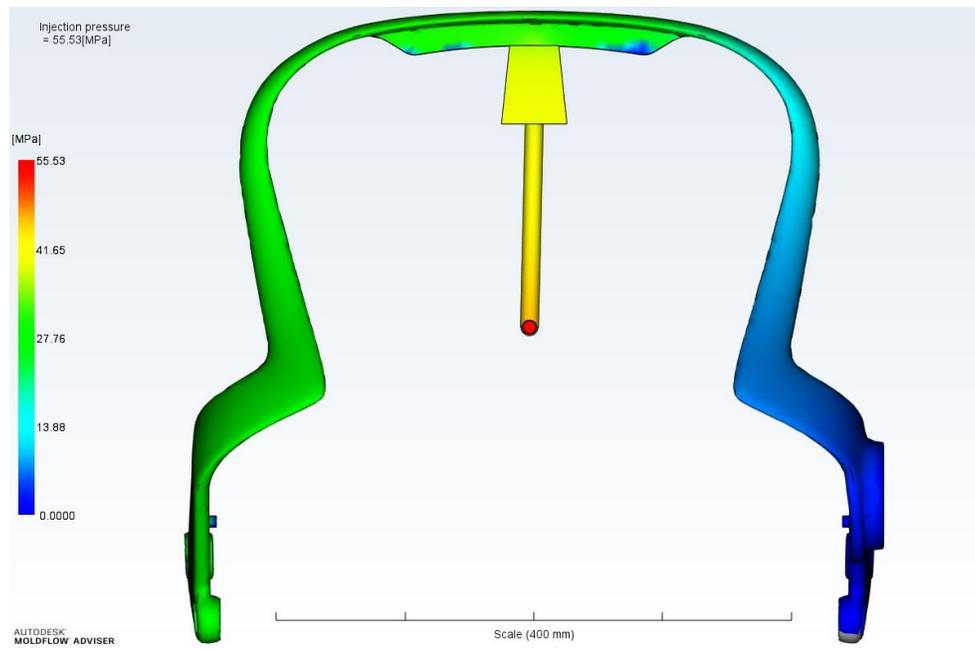
Sample #65 Fill time
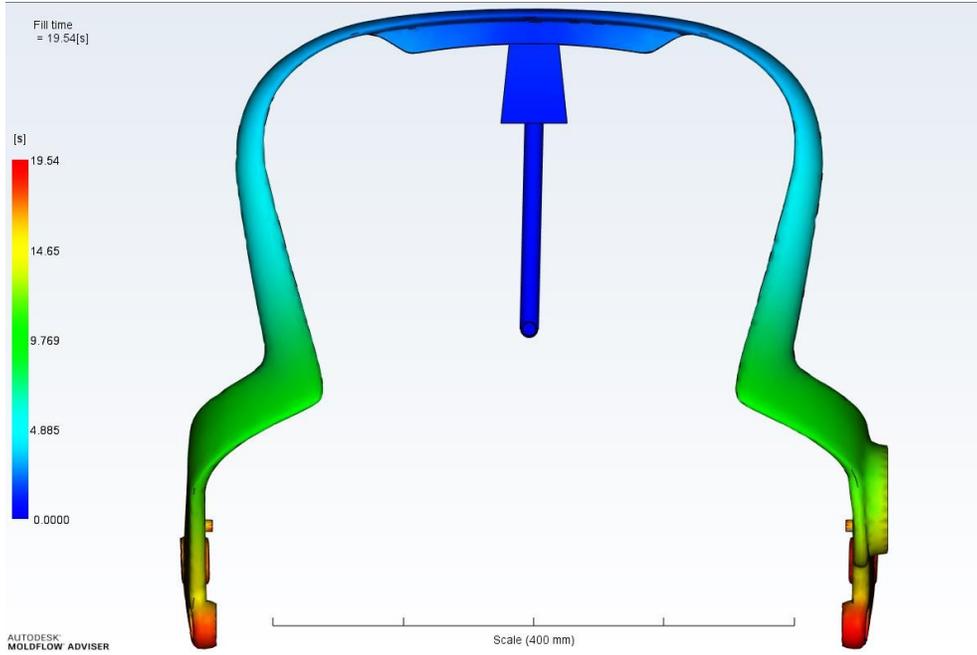
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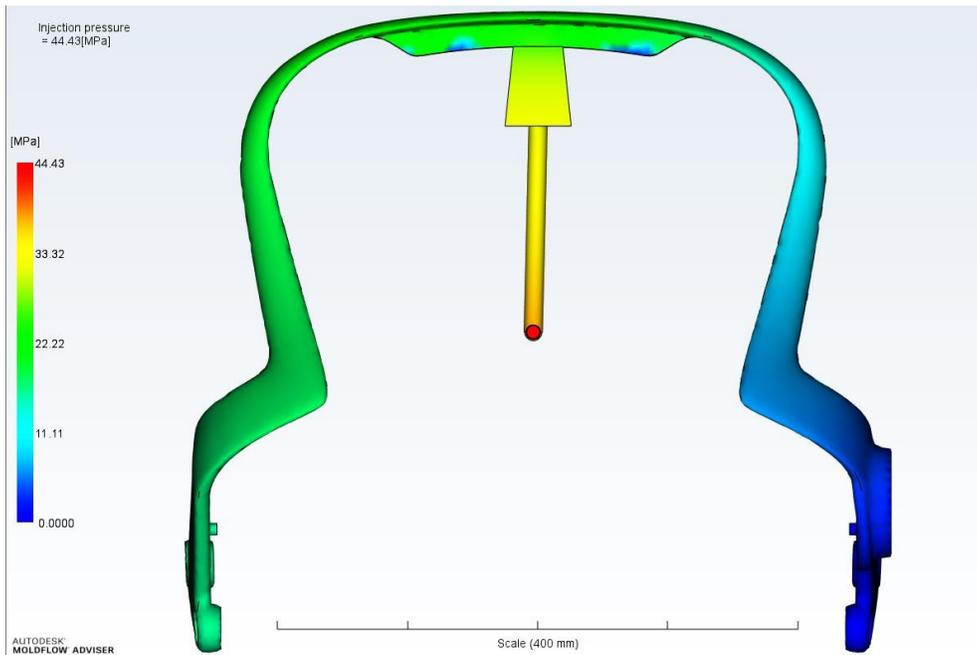
Sample #66 Fill time
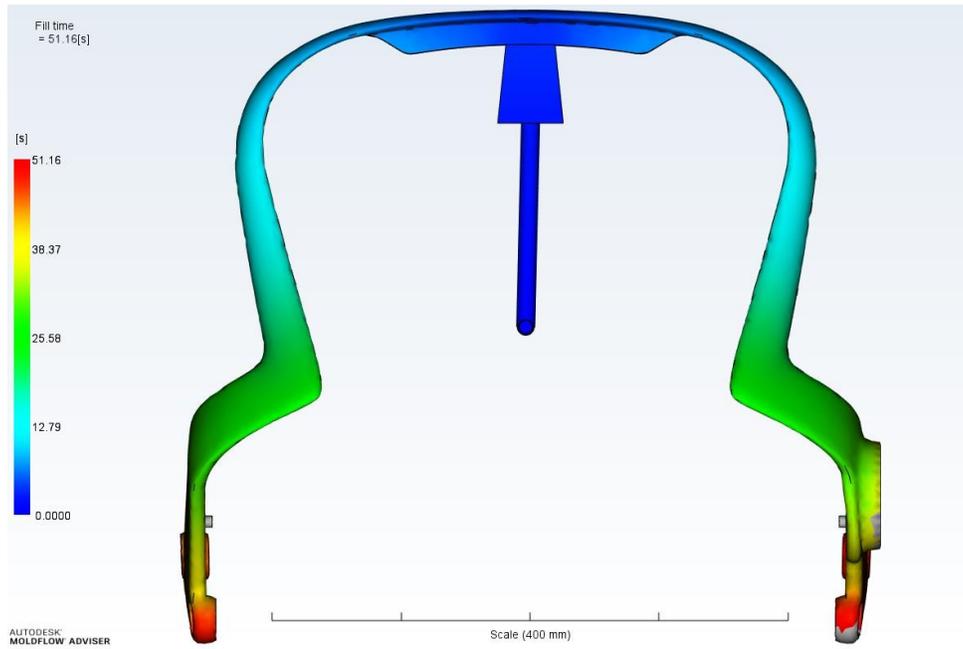
Sample #66 Injection pressure
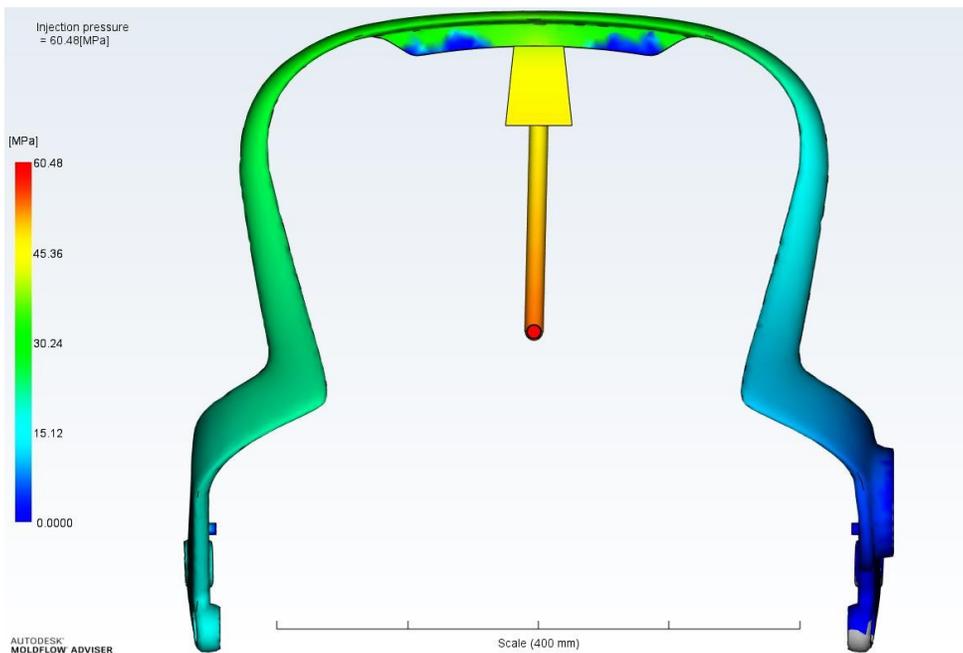
Sample #67 Fill time
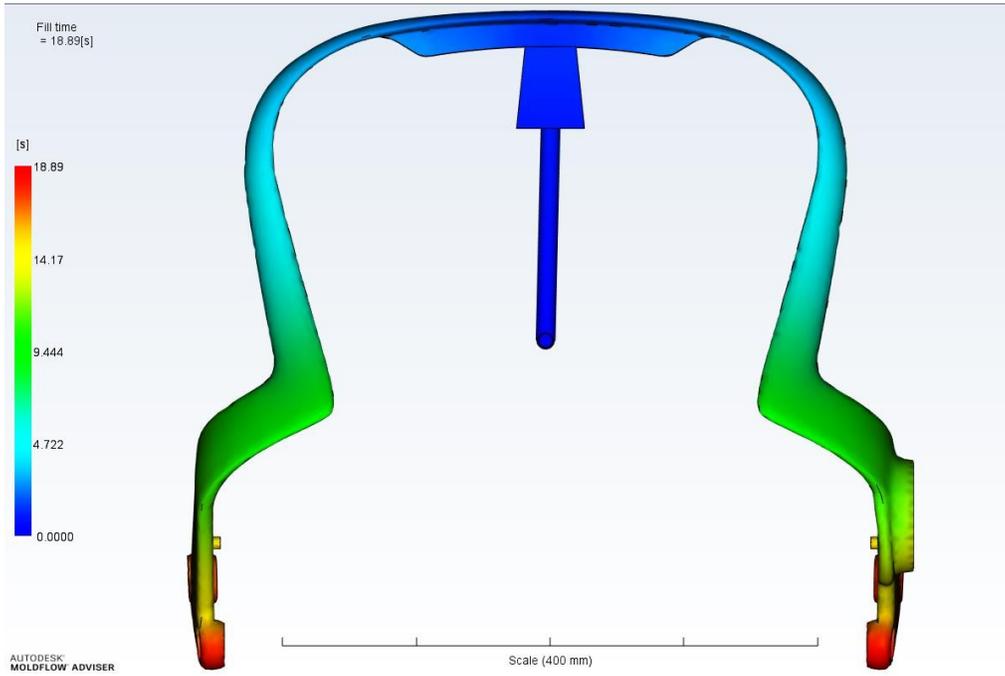
Sample #67 Injection pressure
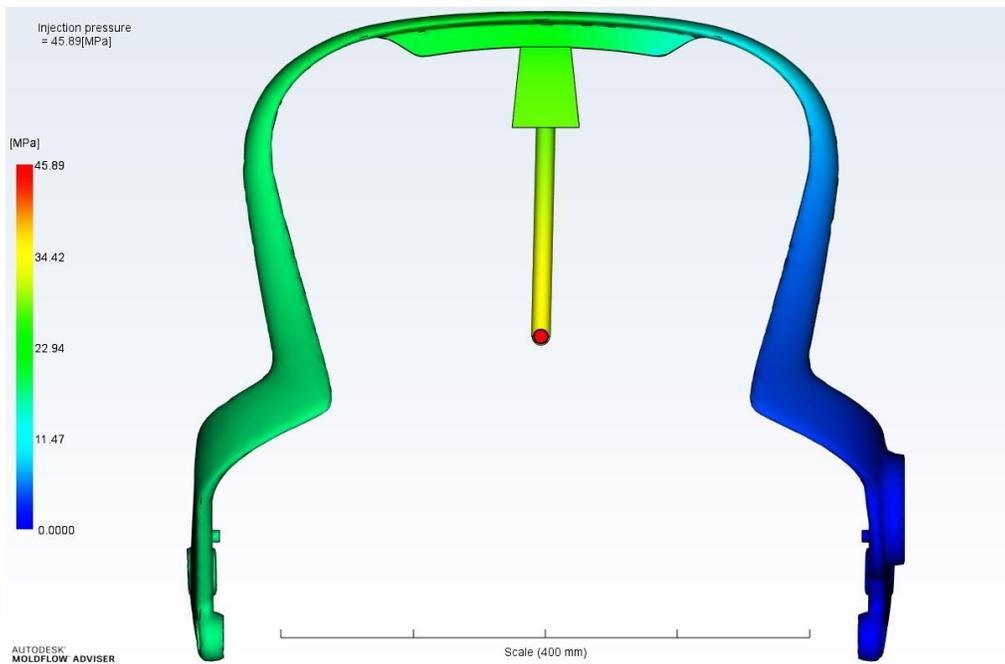
Sample #68 Fill time
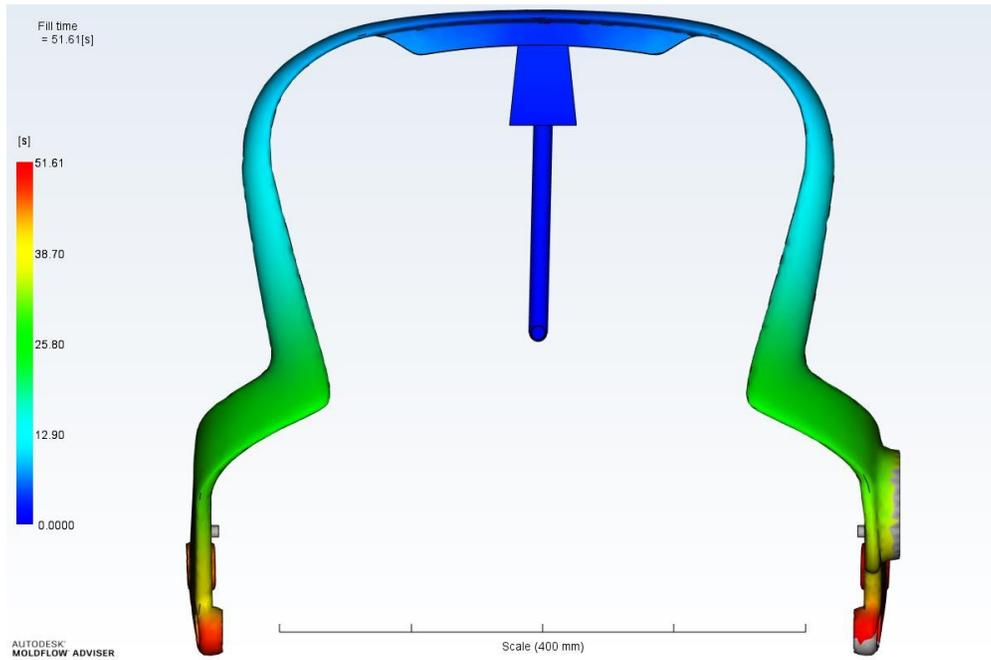
Sample #68 Injection pressure

Sample #69 Fill time

Sample #69 Injection pressure

Sample #70 Fill time

Sample #69 Injection pressure

Sample #71 Fill time

Sample #71 Injection pressure

Sample #72 Fill time

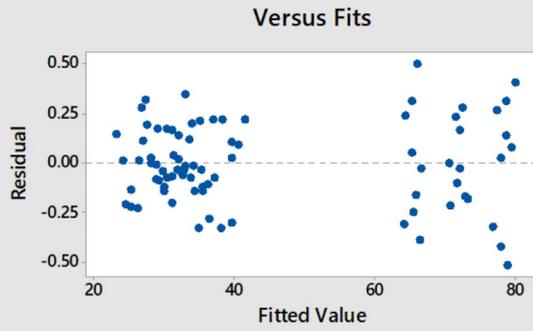Sample #72 Injection pressure

Sample #73 Fill time

Sample #73 Injection pressure

Sample #74 Fill time

Sample #74 Injection pressure

Sample #75 Fill time

Sample #75 Injection pressure

Sample #76 Fill time

Sample #76 Injection pressure

Sample #77 Fill time

Sample #77 Injection pressure

Sample #78 Fill time

Sample #78 Injection pressure

Sample #79 Fill time

Sample #79 Injection pressure

Sample #80 Fill time
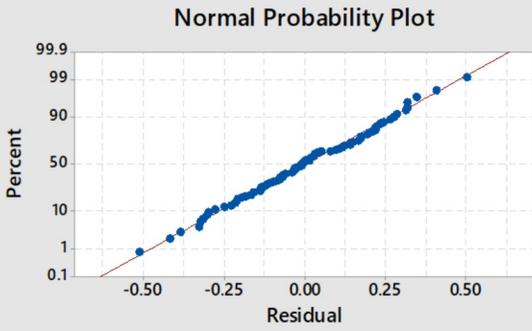

Sample #80 Injection pressure

Sample #81 Fill time


## Sample #81 Injection pressure
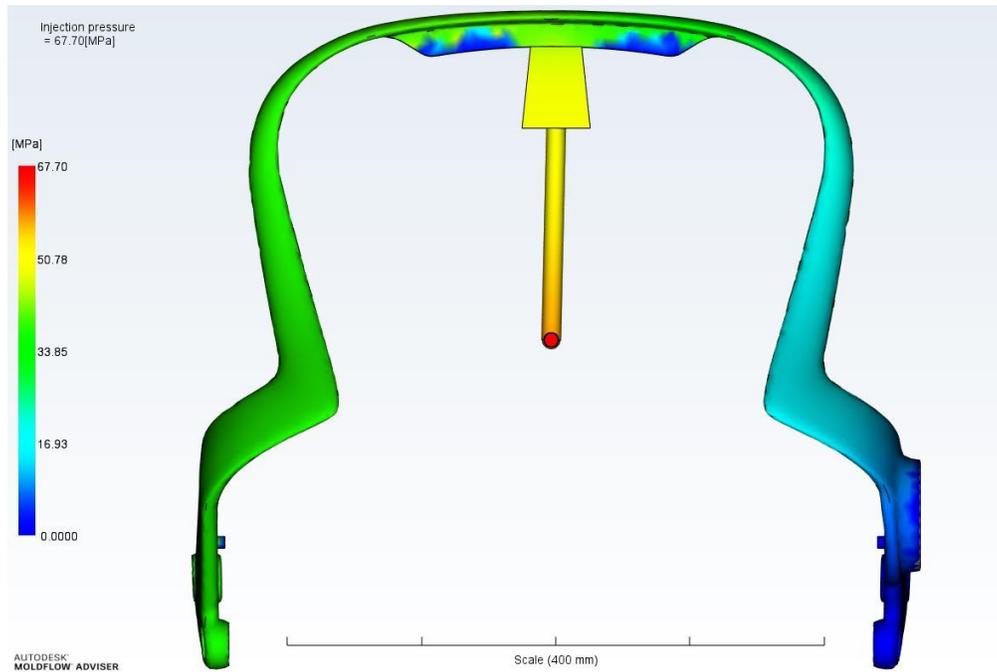
APPENDIX C

APPENDIX C

Residual Plots for time
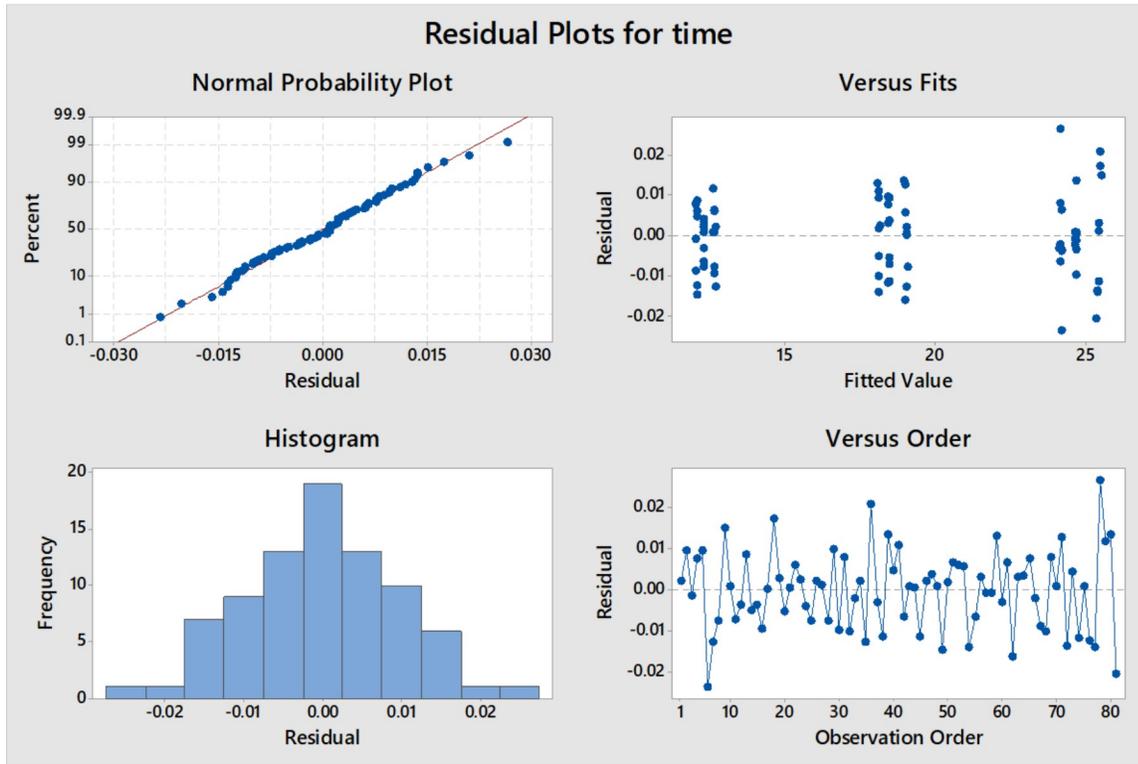
Residual Plots for pressure

Residuals Versus mold temp
(response is time)

Residuals Versus melt temp
(response is time)

Residuals Versus viscosity
(response is time)

Residuals Versus injection speed
(response is time)

Residuals Versus mold temp
(response is pressure)

Residuals Versus melt temp
(response is pressure)

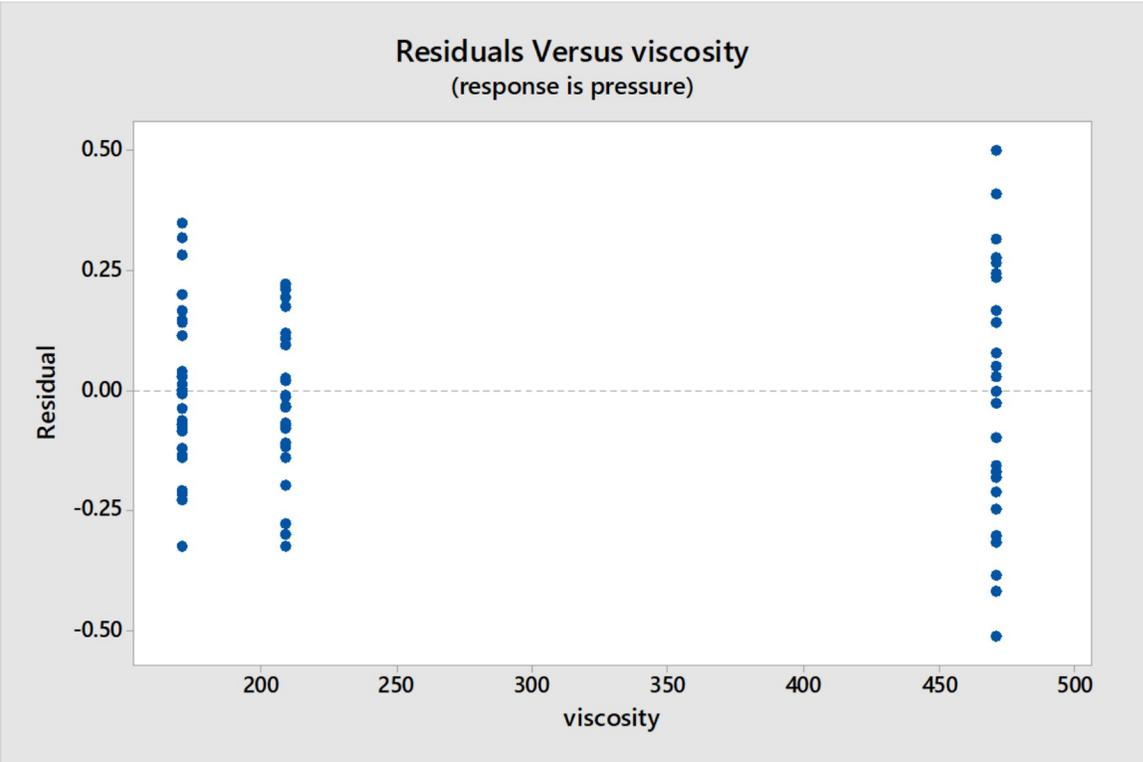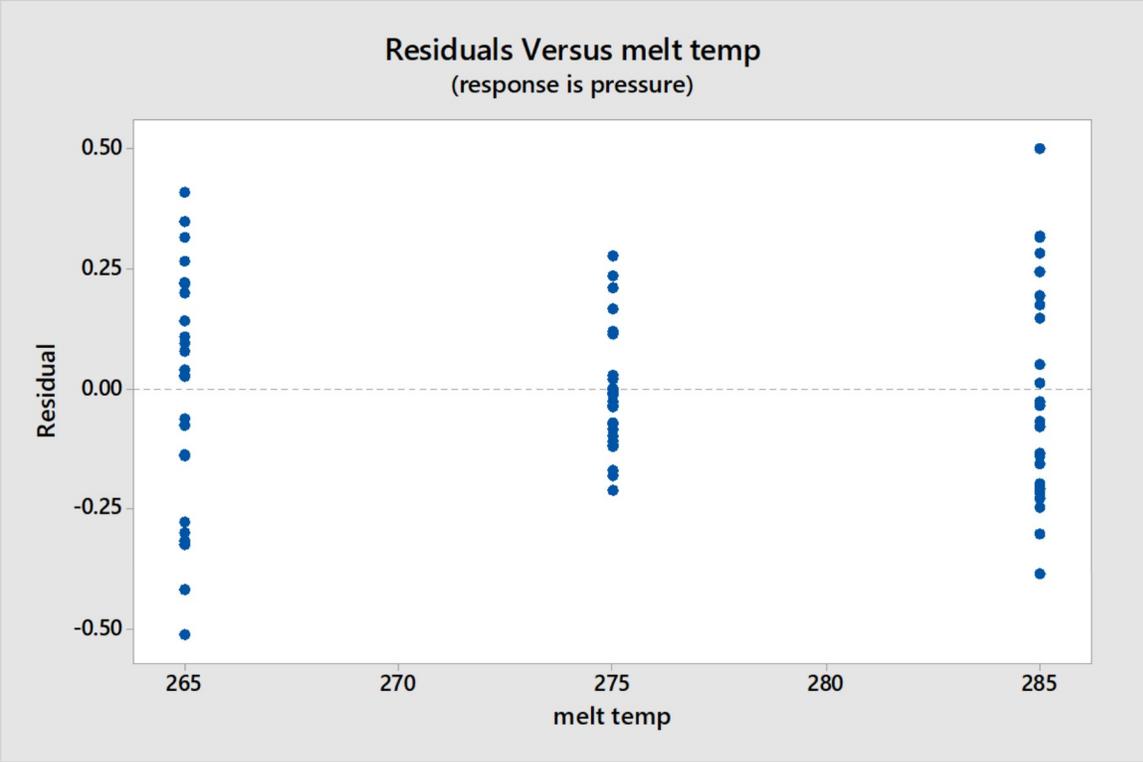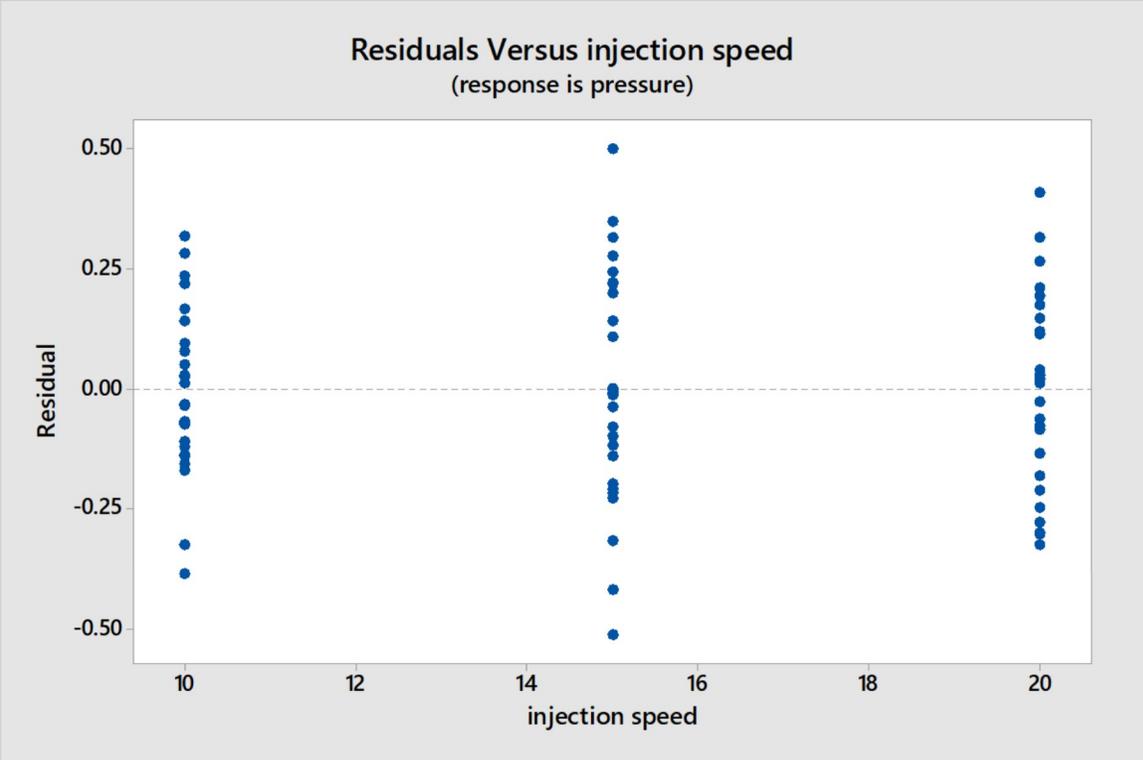**Residuals Versus viscosity**
(response is pressure)
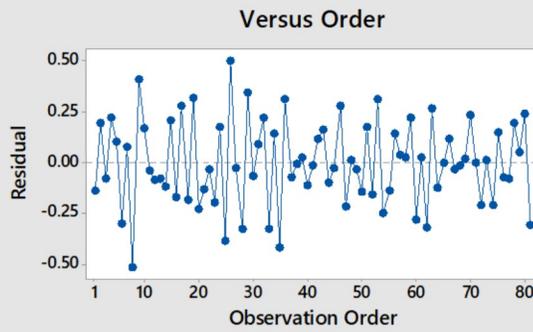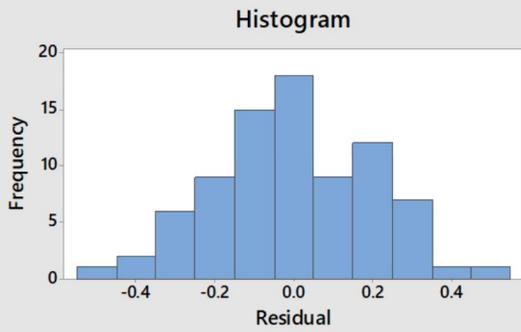
Residuals Versus injection speed
(response is pressure)
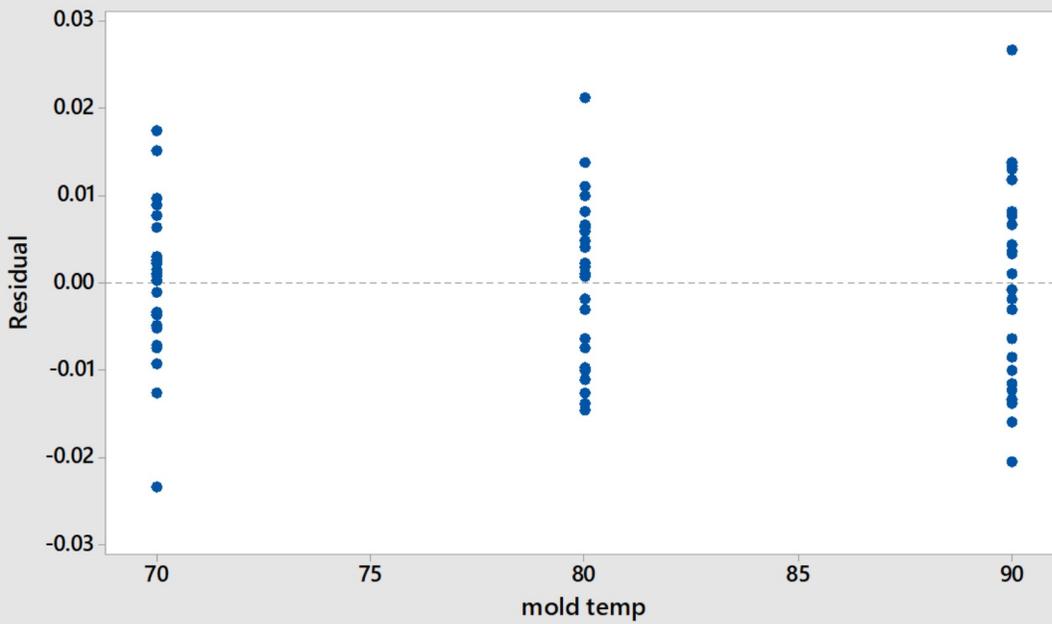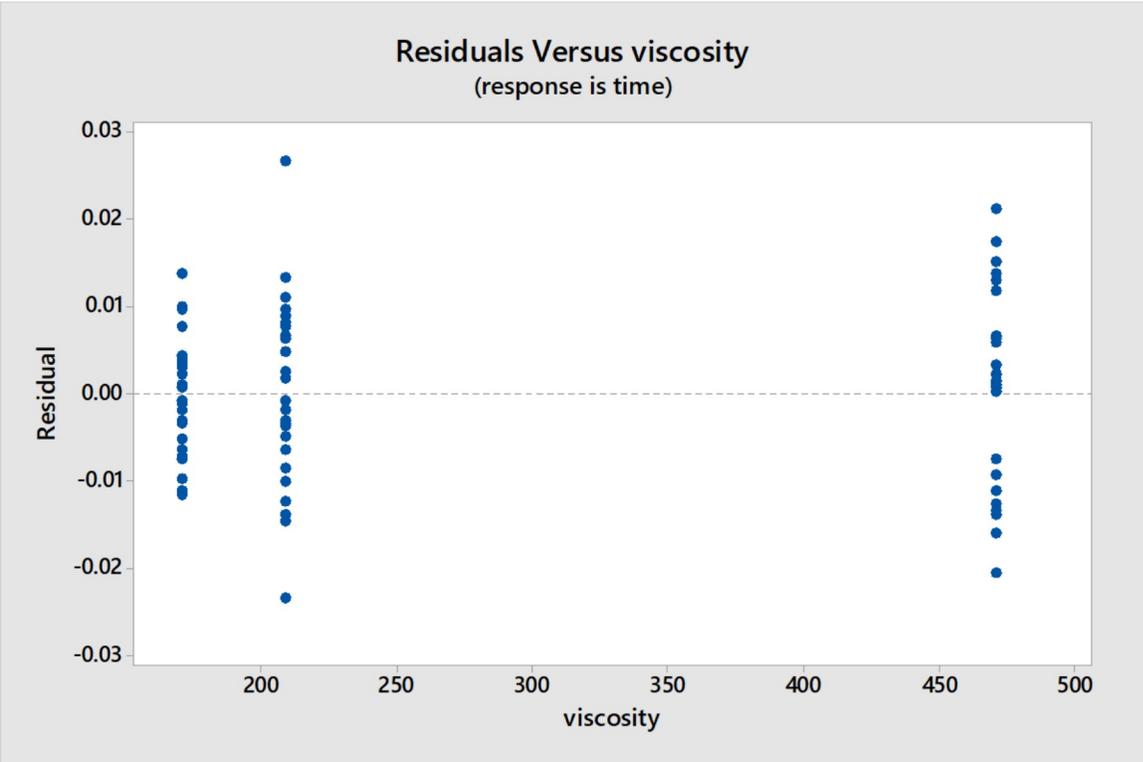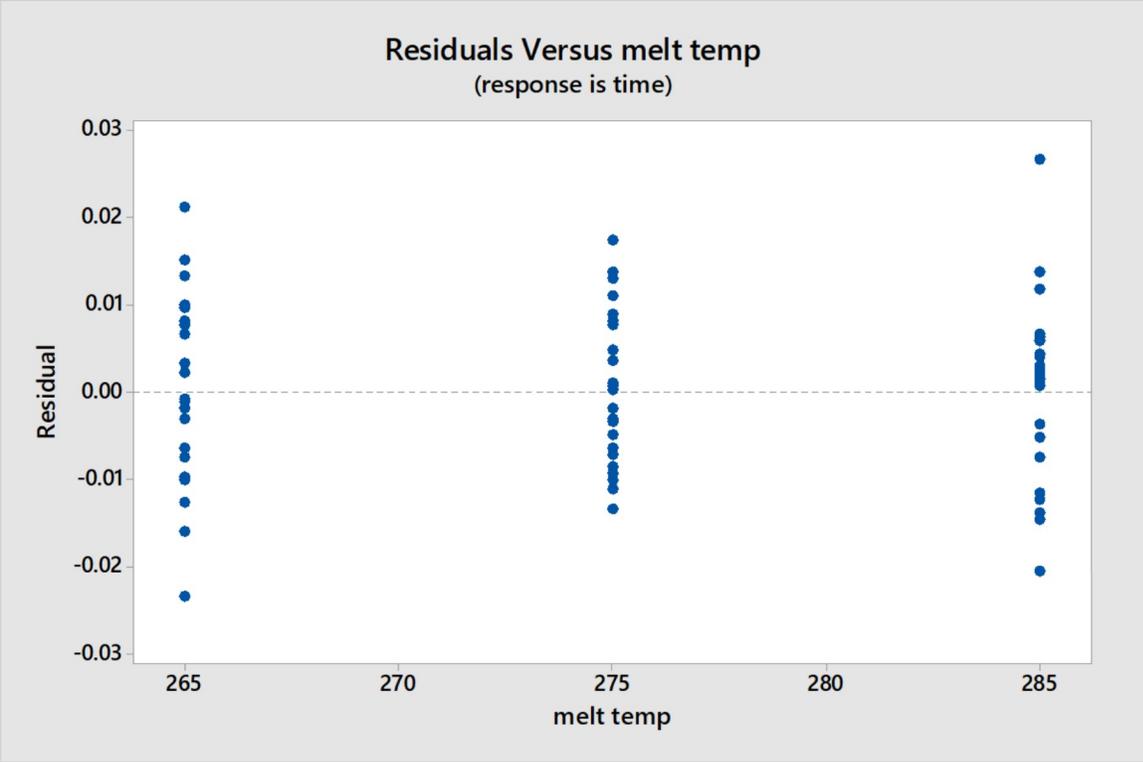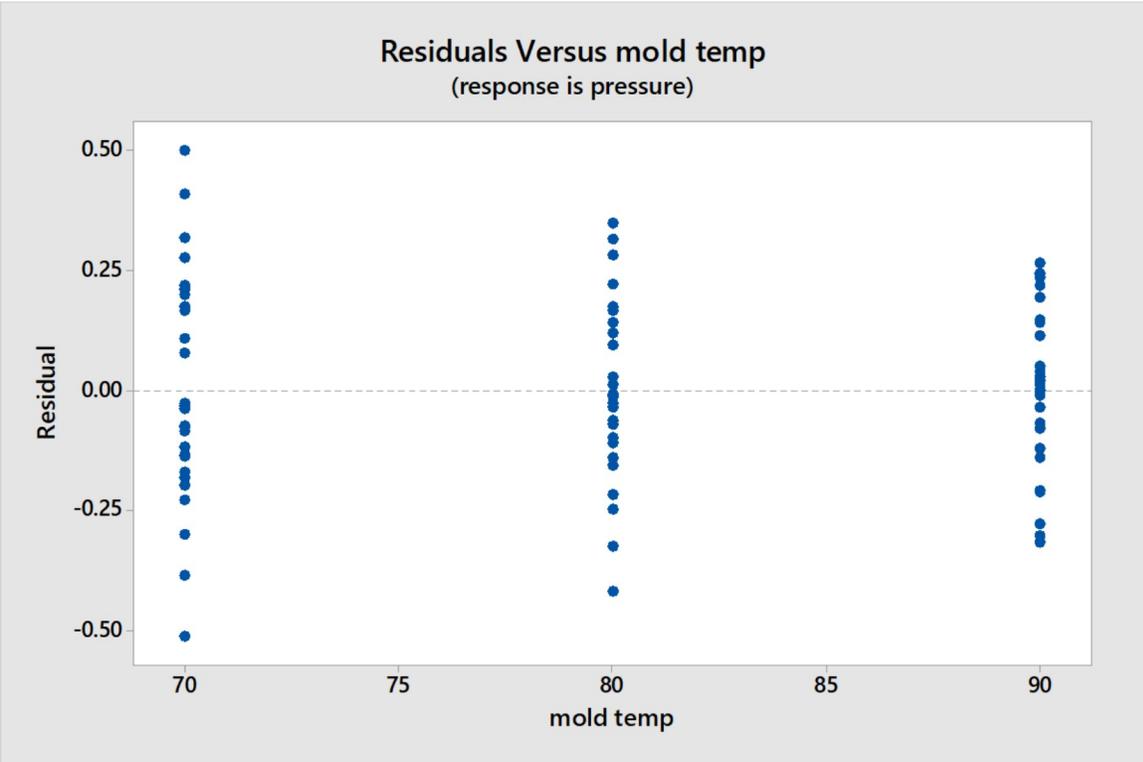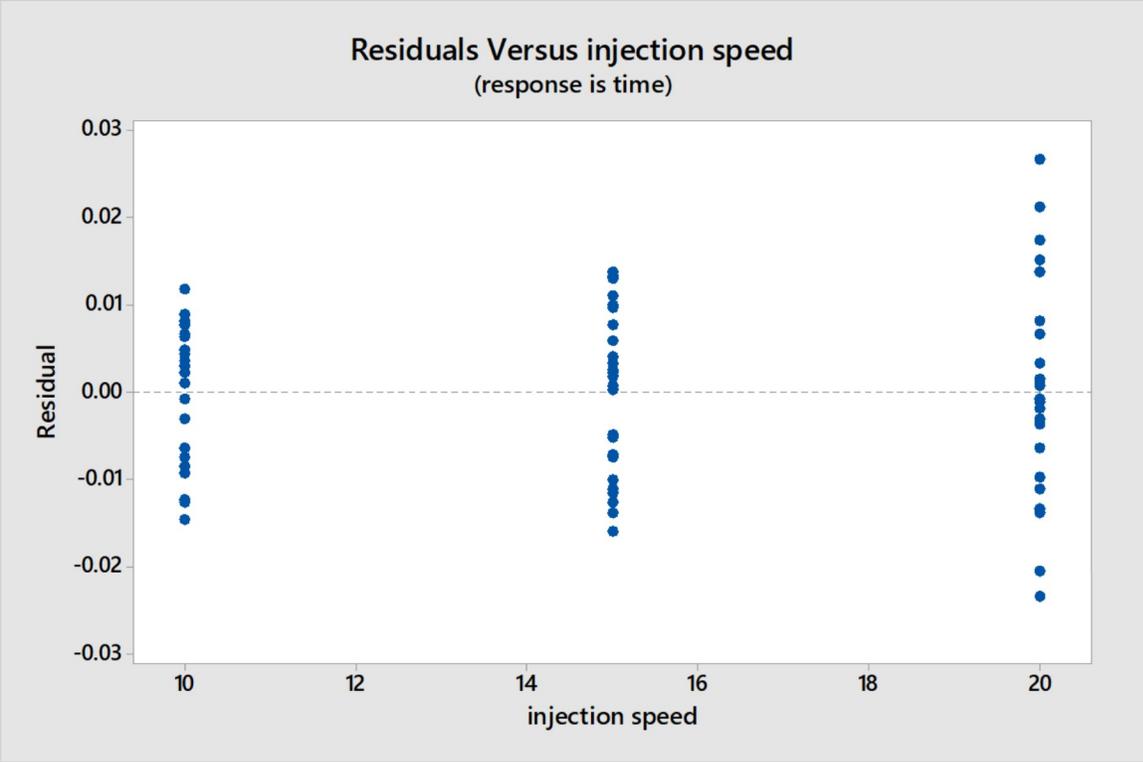
BIOGRAPHICAL SKETCH

Claudia Lizette Lopez is a first-generation college student. Her parents migrated from Mexico seeking for a better education for her and her siblings. She attended high school, were she learned English as her second language (ESL) and decided to attend college after her graduation in 2004. Her father was the one who encourage her to pursuit an engineering degree because of the aptitudes he saw her. After graduation, she enrolled at the University of Texas-Pan American where she was able to attend college full time and complete her bachelor degree in Mechanical Engineering in 2010 while working three jobs at once. On her last semester of her bachelor's degree she decided to enroll in a Master's class just for curiosity and undecided if she was going to keep working on her master's degree. Luckily by September of 2010, she was hired by a Steelcase Inc., a company to which she is still currently working. She was giving the opportunity to work as a welding and finishing engineer and had to put her master's degree on pause for a couple of years because her job asked for her to travel for training and transferences of products. She was able to come back to the masters program in 2012 to continue with her studies while working full time. In 2014, she had to pause her studies once again because of work and because she gave birth to her first-born child. She returned to conclude her master's degree in 2016 and received her Master's degree in Mechanical Engineering in July of 2018 from the University of Texas Rio Grande Valley. Her address is 4706 N. 24th Ln, McAllen, TX and her email address is claudia.lizette.lopez@gmail.com.