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Volumetric shrinkage estimation of benchmark parts developed by rapid tooling mold insert

SAGAR KUMAR* and AMIT KUMAR SINGH

Department of Mechanical Engineering, Malaviya National Institute of Technology, Jaipur 302017, India
e-mail: sagar800k@gmail.com; 2013rme9049@mnit.ac.in

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Abstract. This paper estimates the volumetric shrinkage for thermoplastic Polypropylene (PP) injection molded components made using digital Acrylonitrile butadiene styrene (ABS) mold. The parameters affecting volumetric shrinkage for the digital ABS mold are mold temperature and injection temperature, cooling time, hold pressure and injecting speed. Therefore, twelve standard benchmark CAD model were selected with different geometric attributes. Subsequently, simulation analysis was performed on all CAD model using Moldflow® (MFA) simulation software. Additionally, regression analysis is applied to identify the effect of injection molding parameters on the volumetric shrinkage of part made using rapid tooling mold insert of digital ABS material. It is found that maximum volumetric shrinkage (18.75%) is observed for square pyramid frustum, conical frustum, and solid torus. On the contrary, hollow rectangular prism shows minimum shrinkage effect having 12.61% of volumetric shrinkage. This study predicted that shrinkage is the main concern for these three geometric features (i.e., square pyramid frustum, conical frustum, and solid torus) and must be looked for its minimization. The results are experimentally validated, with 3D scanner integrated with COMET plus and Inspect plus softwares. Since shrinkage estimation for digital ABS mold using Rapid Tooling technique has not been attempted before, therefore, this study provides guidance for the optimum parameter selection and assigning suitable shrinkage compensation values for digital ABS mold made using direct rapid tooling.

Keywords. Benchmark parts; injection molding; volumetric shrinkage; regression technique.

1. Introduction

Additive manufacturing is being accepted globally by industries for its potential in saving on process time and cost. Potential of rapid prototyping for normal production run is still not being contextualized [1]. In that situation Rapid Tooling (RT) becomes a viable alternative that deals with the rapid manufacturing of parts that work as a tool in contrast to being a model or a functional part. Generally, RT is categorized as soft or hard and direct or indirect tooling.

The common materials used in tooling include wax, wood, polymers, metals, ceramics and composites. In soft tooling, the molds produced directly or indirectly are broken after a single cast or are used for a small batch production. In hard tooling, molds are generally made of metals, ceramics, or composites and can be utilized for mass volume production. By development of RT, RP performs excellent tooling and manufacturing capabilities. RT significantly reduces the time required for mold-forming process hence increases the speed of production [2]. The greatest opportunity for rapid tooling implementation is the use of Additive Manufacturing (AM) technology. Further, polymer based direct rapid tooling provide substantial cost reduction and is also be readily accessible by industries. With the advances in materials along with the new access and low cost plastic-based AM equipment, direct use Polymer Rapid Tools (PRTs) would be a far more advantageous option in creating injection molds for small and highly flexible production. The use of polymer based direct rapid tooling by industries is curtailed due to the issues with the dimensional stability [3, 4]. This work explores the application of the Digital ABS material in RT, paying attention on dimensional stability i.e., volumetric shrinkage during the injection process. Digital ABS is depleted in the present study to make mold inserts, and the resulting volumetric shrinkage is investigated.

Plastic injection molding is one of the most adaptable operations for automatically mass-producing intricate plastics parts. Nevertheless, one of its inherent limitations being the part volumetric shrinkage changing with the process parameters which is due to the divergence of the filling, packing and cooling processes [5, 6]. Shrinkage is among the most significant phenomena that occur in the plastic injection molding process, as it affects the final outcome of a product, such as warpage, weld line and sink

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*For correspondence

marks on the surface. Injection molding process usually produces intricate shaped plastic parts with distinctive internal and external features. It becomes an important task to evaluate maximum shrinkage among different geometric features for plastic parts. Currently, the plastic injection molding industry is always facing challenges to improve the quality and worth of their parts, along with minimizing the production costs, thus demanding a greater knowledge of shrinkage control.

Till date, most of the studies suggest that the output of plastic injection molding process is largely dependent upon operator's skills and optimum process parameters. Mirigul suggested optimal injection molding conditions for minimum shrinkage using the Taguchi experimental design and the analysis of variance (ANOVA) [7]. Chiang and Chang presented the optimal initial process parameter settings for an injection molded plastic part with a thin shell feature [8]. Chang and Faison predicted the shrinkage behavior and process optimization of polystyrene, high-density polyethylene and ABS parts by employing the Taguchi and ANOVA methods. They found that the mold and melt temperatures along with the holding pressure and the holding time were the most important factors affecting the shrinkage [9].

Leo and Cuvelliez [10] examined the effect of the packing parameters and gate geometry on the final dimensions of a molded part by experiment. The result suggests that a thinner gate attains a more equable shrinkage in the process of the same applied packing pressure. One of the studies reported the optimum process parameters value in injection molding component in order to achieve least warpage using the finite element software MoldFlow, design of experiments, artificial neural network and genetic algorithm. Shrinkage and warpage were regarded as the lower-the-better performance characteristics in an injection-molded part with a thin-shell feature [11]. The above literatures confirm the effect of optimum process parameters as one of the key factors affecting shrinkage of injection mold. Very few authors, for instance, Hamdy *et al* [12] studied the effect of location of the cooling channels on the shrinkage and temperature throughout the product by utilizing a compressible fluid mode for the physical system. This study suggests that appropriate cooling channel position in a component is also an important factor for the shrinkage minimization along with optimum process parameter. Afterwards, no literature is available exploring the appropriate location of cooling channel in part defect improvement using rapid tooling digital ABS mold material.

This paper proposes effective shrinkage estimation of twelve benchmark part geometries generally used in an injection molded plastic component. The reference feature includes cylinder, rectangle, square, triangle, sphere, prism, pyramid and cone. In this study, a systematic methodology based on the Moldflow® (MFA) software is applied to identify the effect of shape and geometry parameters on the performance of volumetric shrinkage. Further, statistical regression technique used for determining the percentage contribution of geometric attributes on volumetric shrinkage. The basic purpose of the proposed methodology is to estimate volumetric shrinkage according to geometric attributes employed with RP-based rapid tooling design injection molding process.

2. Methodology

In this study, polypropylene material is selected for simulation of the plastic injection molding process using digital ABS rapid tool mold insert. Properties of the selected polymer material are listed in table 1. The selected twelve benchmark parts (figure 1) consists of standard geometric features which are generally used in any industrial component.

Figure 2 shows the process flow diagram describing a sequence of steps for modeling and simulation of twelve benchmark parts using Autodesk Inventor and Moldflow® (MFA) software, respectively. Tooling design requires (1) orientation of the parting plane, (2) scaling the model to accommodate for shrinkage allowance according to molten material selection, (3) generating draft angle and (4) splitting the part geometry at parting line to create die and cavity shapes.

The value of shrinkage ratio is different for different material and depends upon type of molten plastic material. One of the significant steps for modeling the benchmark part is to apply shrinkage ratio actually for particular material. Standard benchmark CAD model in .stl file format is used as an input for simulation study.

3. Material selection and properties

Tables 2 and 3 show the mold material (Digital ABS) properties and default simulation setting parameter is considered for PP material, respectively. The Moldflow® (MFA) analysis is performed after assigning a molten

Table 1. Input parameter of thermoplastic polypropylene (PP) material [13]

Parameter	Range value	
Elastic modulus (MPa)	1574.77	1530.86
Coefficient of thermal expansion (1/°C)	0.00010	0.00015
Poisson ratio	0.35	0.44

Parameter	Value
Melt density liquid (g/cm^3)	0.73
Melt density solid (g/cm^3)	0.89
Shear modulus (Mpa)	523.90
Specific heat (J/kg °C)	2740
Thermal conductivity (W/m °C)	0.16


1. Cylinder
2. Rectangular Prism


3. Hollow Cylinder
4.HollowRectangular Prism


5.Square Pyramid
6.Square Pyramid Frustum


7.Hollow Square Pyramid Frustum
8.Conical Frustum


9.Hollow Conical Frustum
10.Rectangular Prism Hollow with Cylinder


11.Solid Torus
12.Hollow Torus

Figure 1. 3D Model of benchmark parts using Autodesk Inventor software [16, 19]

material with similar analysis for all benchmark parts during the injection molding process. The material used in this experiment is commercially available for injection molding for the product and is listed in table 2.

4. Geometric attributes consideration

Geometric attributes are used to estimate the dimensional accuracy of the part features developed by a particular machine. The geometric features (shape and size) like volume of part, height, thickness and draft angle considered in this study. The weight of benchmark part model and the total weight (included sprue) of a same part model measured from the CAD software (considering the density value of PP molten material = 0.000738 g/mm^3), the volume is obtained of all twelve benchmarks parts with using mass property function in Autodesk Inventor software.

Volume Ratio (V_R): It is the ratio of the benchmark parts volume as obtained using the 1+S formulas for shrinkage factor calculation, Here 'S' denote shrinkage ratio to the bounding box volume. The bounding box volume assumes the maximum length, width, and height of the part geometry. The volume of all the reference parts considered is the same and is nearly about to 20,000 mm^3, where S = Shrinkage ratio (0.01–0.025).

$$V_R = \frac{V}{V_B} \tag{1}$$

Thickness ratio (T_R): this is the ratio of the minimum thickness of benchmark part to the maximum height of the same part.

$$T_R = \frac{T_{min}}{H_{max}} \tag{2}$$

Draft angle ratio (D_R): it is the ratio of draft angle in parts to the standard draft angle consideration which is maximum up to 3° depending on the height of parts. In this study, the height constraint of all twelve benchmarks parts is same (20 mm).

$$D_R = \frac{D_A}{S_{DA}} \tag{3}$$

Part weight ratio (W_R): it is the ratio of part weight to the total weight of the part.

$$W_R = \frac{W}{W_T} \tag{4}$$

Quality prediction ratio (Q_R): this is the ratio of quality prediction percentage to the desired quality (say 100%) of all benchmarks parts.

$$Q_R = \frac{QP\%}{QP_{100\%}} \tag{5}$$

Cycle time ratio (CT_R): this is the ratio of cooling time to the total cycle time.

$$CT_R = \frac{C_T}{TC_T} \tag{6}$$

The above steps were involved in design criteria framework for Rapid Tooling injection molding process; it includes tooling design (die and cavity), simulation and the statistical technique. Finally, these results are validated by using regression method (table 4).

5. Moldflow simulation results and analysis for the benchmark parts

Simulation is performed on Moldflow® (MFA) FEM software. Simulation study was done to evaluate and advise the injecting location, observed defects (air trap, weld lines,

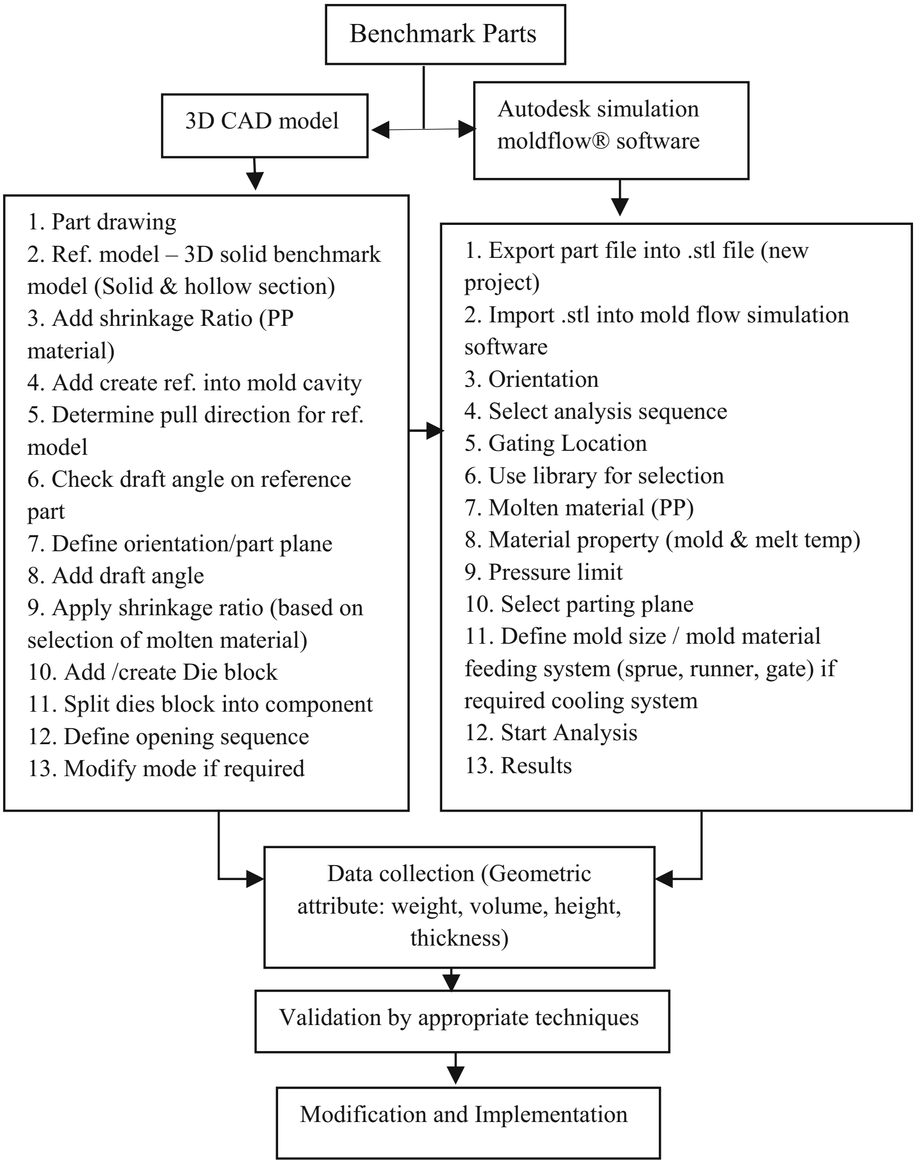


Figure 2. Process flow diagram for design, simulation and analysis [18]

Table 2. Input parameter of mold material (Digital ABS) [14]

Thermal properties		Mold mechanical properties	
Parameter	Value	Parameter	Value
Mold density (g/cm^3)	1.2	Elastic modulus (MPa)	3000
Mold specific heat (J/kg °C)	1900	Poisson ratio	0.23
Mold thermal conductivity (W/m °C)	0.27	Mold coefficient of thermal expansion (1/°C)	75×10^{-5}

shrinkage, warpage), cycle time (fill time, packing time, cooling time, mold-open time) in order to be able to improve the accuracy in the injection molded parts made using Digital ABS Rapid Tooling Mold Inserts. The result of the simulation study for a single benchmark part is shown in figure 3 as an example; similarly it is preceded for the rest of the benchmark parts.

The geometric features were related to the die and cavity, and the injection molding process consists of melting of the polymer and then it is injected into the mold cavity [15].

Table 3. Simulation process setting parameter for Digital ABS mold

Melt temperature (°C)	240
Mold temperature (°C)	40
Packing pressure (MPa)	80
Packing time (s)	10
Maximum machine injection pressure (MPa)	180

After the determination of the number of input parameters and the range of their changeability, the design of experiments performed by statistical software [13, 14].

6. Simulation results and analysis for the complex part with different benchmark part features

A complex shape geometry (figure 4) integrated with standard benchmark part feature was then considered for estimating the overall combined volumetric shrinkage for different features in a single part. The investigation of the results for benchmark parts was extended for a complex part.

Simulation results using Moldflow® (MFA) simulation software are shown in tables 5 (B1) and 5 (B2).

7. Result and discussion

The mathematical model is developed in term of the polynomial equation that is established to show the influence of geometric attribute and processing parameters on the volumetric shrinkage percentage Eq. (7). In this section, the software Minitab® was used to analyze and obtain different coefficients of the polynomial Eq. (7).

$$\begin{aligned} VS_{\%} &= 2.97 - 0.78V_R + 2.19T_R - 0.10DA_R - 3.66\,W_R \\ &\quad + 0.80QP_R + 17.43CT_R \\ S &= 0.562051,\ R - sq = 96.37\%,\ R - sq\,(adj) = 92.01\% \end{aligned} \tag{7}$$

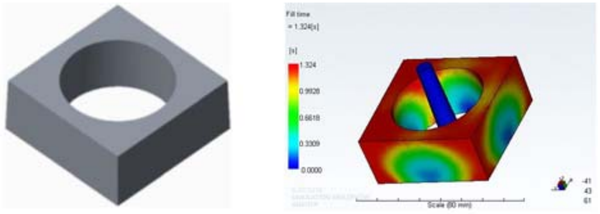
The regression equation for estimating volumetric shrinkage percentage for all twelve benchmark parts designs using geometric attributes and the Moldflow® (MFA) simulation results obtained in table 6 and Regression graph shown in figure 5.

Linear regression models are most powerful statistical techniques for solving optimization problems and can affluence complicated relationships among several variables. They help in explaining the relationship between dependent variable (volumetric shrinkage), with observed values of one or more independent variables (V_R, T_R, D_{AR}, W_R, Q_{PR}, C_{TR}). For modeling the process mathematical

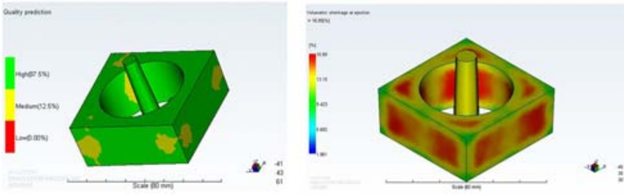
Table 4. Geometric attribute data compiled for regression analysis

Part sl. no.	V (mm)	V_B (mm)	V_R (mm)	T_{Min} (s)	H_{Max} (mm)	T_R (mm)
1	20,424.5	24,500	0.785	20	20	1
2	20,479	19,220	1.066	20	20	1
3	21,454.9	84,500	0.223	10	20	0.5
4	22,764.4	60,500	0.330	10	20	0.5
5	20,029.1	58,320	0.333	20	20	1
6	18,717.1	24,500	0.741	20	20	1
7	20,978.7	32,000	0.636	10	20	0.5
8	19,960.2	32,000	0.605	20	20	1
9	22,657.5	50,000	0.439	10	20	0.5
10	23,468.1	40,500	0.524	10	20	0.5
11	20,958	32,000	0.635	20	20	1
12	20,337.3	50,000	0.394	10	20	0.5

Part sr. no.	D_A (deg)	S_{DA} (deg)	D_R (deg)	W(g)	W_T (g)	W_R (g)
1	1.5	3	0.5	14.19	15.606	0.909
2	1.5	3	0.5	14.18	15.694	0.903
3	1.5	3	0.5	13.90	18.593	0.747
4	1.5	3	0.5	14.75	19.855	0.742
5	0	3	0	14.35	15.464	0.927
6	0	3	0	13.41	14.337	0.935
7	0	3	0	18.20	16.308	1.116
8	0	3	0	14.30	15.256	0.937
9	0	3	0	16.23	17.390	0.933
10	1.5	3	0.5	15.69	18.139	0.864
11	0	3	0	15.46	15.946	0.969
12	0	3	0	14.57	15.543	0.937



Part model Filling time



Quality prediction percentage Volumetric shrinkage percentage

Figure 3. Moldflow® (MFA) simulation results for rectangular prism hollow with cylinder

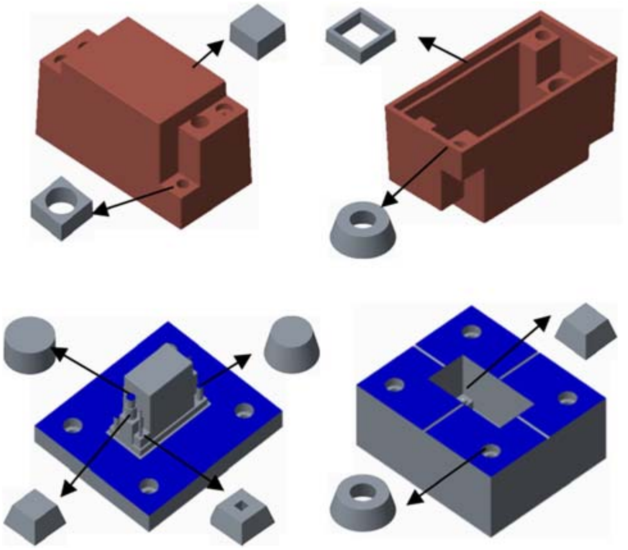


Figure 4. Complex benchmark shapes with the integration of standard features in mold and mold insert

function including linear polynomial curve is used. Therefore, correlation coefficients, R^2 value, of the equations for volumetric shrinkage of 96.37%, calculated which explores the volumetric shrinkage of a linear relationship between the simulation data and the expected values from the regression model. Based on this R^2 test, quadratic polynomial models are best fitted for the output. The normal probability plot of residuals for the shrinkage defects of ABS mold notice that the residuals generally fall on straight line employing that the errors are normally distributed and obviously shows that the quadratic modal obtained is precisely accurate. It can be easily noticed from the table 5, highest volumetric shrinkage percentage (18.75 %) results are obtained for square pyramid frustum, conical frustum, and solid torus, and the lowest volumetric shrinkage percentage of 12.61% is achieved for the hollow rectangular prism, which is investigated through Moldflow® (MFA) simulation software.

Table 5. (B1). Moldflow® (MFA) simulation results in data compiled for regression analysis

Part sl. no.	QP%	$QP_{100\%}$	$QP_R\%$
1	88.5	100	0.885
2	79.8	100	0.798
3	100	100	1
4	100	100	1
5	72.4	100	0.724
6	73.7	100	0.737
7	99.4	100	0.994
8	81.4	100	0.814
9	100	100	1
10	87.5	100	0.875
11	97.4	100	0.974
12	100	100	1

Table 5. (B2) Moldflow® (MFA) simulation results in data compiled for regression analysis

Part sl. no.	C_T (s)	TC_T (s)	CT_R (s)	VS %
1	495.85	511.07	0.970	18.73
2	483.33	498.54	0.969	18.73
3	32.75	49.05	0.667	14.38
4	32.75	49.04	0.667	12.61
5	329.62	344.84	0.955	18.59
6	459.3	474.41	0.968	18.75
7	296.2	311.66	0.950	16.78
8	485.66	500.88	0.969	18.75
9	141.48	157.51	0.898	16.76
10	165.8	182.17	0.910	16.89
11	512.39	527.61	0.971	18.75
12	131.14	147.38	0.889	16.8

Hence, from the above literature it can be concluded that the process of rapid tooling plays an important role in injection molding and simultaneously this process is an important issue also. The exact numerical simulation of this process is a challenging task. In this work, the polyjet technology was used to manufacture the component by injection mold inserts.

8. Experimental verification

The volumetric shrinkage of test part generated and experimentally validated step-wise.

Table 6. Input parameter of simulation of PP injection molding—simulation result

Benchmark parts	V_R	T_R	DA_R	QP_R	W_R	CT_R	VS%	FITS	RESI	SRES	COEF
1	0.785	1	0.5	0.885	0.909	0.970	18.73	18.780	−0.050	−0.136	2.969
2	1	1	0.5	0.798	0.903	0.969	18.73	18.554	0.175	0.485	
											−0.780
3	0.223	0.5	0.5	1	0.747	0.667	14.38	13.535	0.844	2.181	2.188
4	0.330	0.5	0.5	1	0.742	0.667	12.61	13.471	−0.861	−2.222	
											−0.096
5	0.333	1	0	0.724	0.927	0.955	18.59	18.736	−0.146	−0.616	0.795
6	0.741	1	0	0.737	0.935	0.968	18.75	18.615	0.134	0.388	
											−3.663
7	0.636	0.5	0	0.994	1.116	0.950	16.78	16.834	−0.054	−0.835	17.430
8	0.605	1	0	0.814	0.937	0.969	18.75	18.800	−−0.050	−0.102	
9	0.439	0.5	0	1	0.933	0.898	16.76	16.753	0.006	0.015	
10	0.524	0.5	0.5	0.875	0.864	0.910	16.89	16.997	−0.107	−0.372	
11	0.635	1	0	0.974	0.969	0.971	18.75	18.813	−0.063	−0.183	
12	0.394	0.5	0	1	0.937	0.889	16.8	16.627	0.172	0.380	

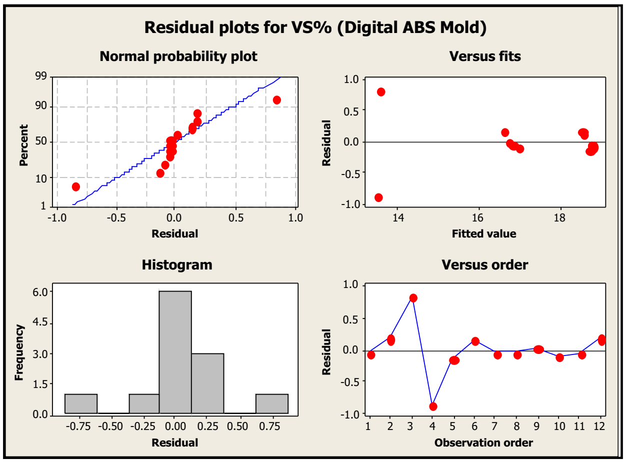


Figure 5. Regression graph for volumetric shrinkage percentage

8.1 *The evaluation of rapid tooling by developing the test mold*

A special geometry part was designed to depict the effect of rapid tool mold properties. The effect of mold design; mold materials, various technological parameters, and geometrical attributes can be easily estimated by developed parts.

8.2 *Manufacturing of the rapid tooling mold by polyjet technology*

To produce the rapid tooling mold inserts, an Object Alaris 30 rapid prototyping machine is used. Thin 28 μm layers having resolution of 600 × 600 × 900 dpi is used in Alaris 30 printers. The mold inserts were printed using Full Cure 705 as support material and Fullcure720 as building material which was removed by NaOH (5%) solution.

8.3 *Process parameter and material selection for injection molding experiments*

For the test, an advance injection molding machine Arburg 370S 700-290 having screw diameter of 30 mm was used. The operating parameters like Injection volume (44 $cm^{3)}$, the injection rate (50 cm^3/s), the switch-over point (12 $cm^{3)}$, clamping force (50 t), the pressure limit (400 bar) and melt temperature (20°C) was used. Coolant temperature was 20°C in the case of polyjet mold (figure 6).

9. A comparison of the outcome of simulation results with experimental data using 3D scanners

The Steinbichler Comet L3D allows non- contact optical scanning. The version used for the comparison is with resolutions of 2MPX and 1600 × 1200 pixels (table 7).

Figure 6. Part developed by rapid tooling mold [17]

Table 7. Steinbichler Comet L3D parameters [18]

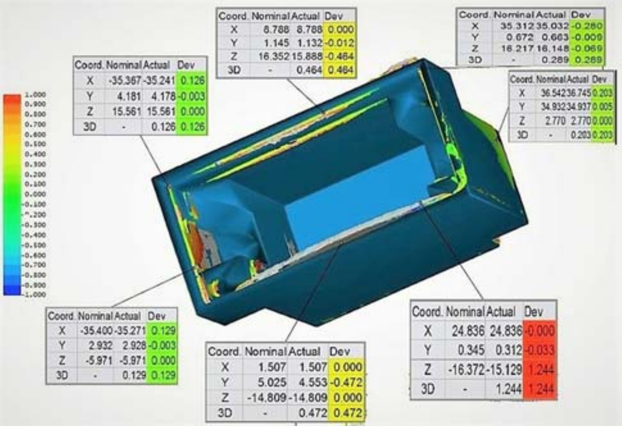
Camera resolution (dpi)	1600 × 1200
Measuring field (mm)	400
Measuring volume (mm^3)	400 × 300 × 250
Point to point distance (μm)	250

9.1 *Scanning methodology*

In this portable scanner, a scanning head is placed on a tripod during scanning. For positioning (rotation) of measured data, a rotating table can be used. The basic modification of scanned data, their comparison with a model and export in the STEP, IGES and STL formats (figure 7) have to be done by using software (COMET PLUS, INSPECT PLUS).

9.1a *Environmental conditions* During scanning it was essential to maintain the basic parameters of surroundings like temperature, humidity and lightning unchanged. In order to stabilize thermal property, it was essential to leave the scanned object in the room where the scanning took place. If the object is with shiny surface then it is essential to modify it with spraying powdered chalk on it. Consequently, the positional markers are put onto the object and/or its surrounding (figure 8).

Figure 7. Steinbichler Comet L3D during scanning



Coord.	Nominal	Actual	Dev
X	8.788	8.788	0.000
Y	1.145	1.132	-0.012
Z	16.352	15.888	-0.464
3D	-	0.464	0.464

Coord.	Nominal	Actual	Dev
X	-35.367	-35.241	0.126
Y	4.181	4.178	-0.003
Z	15.561	15.561	0.000
3D	-	0.126	0.126

Coord.	Nominal	Actual	Dev
X	35.312	35.032	-0.280
Y	0.672	0.663	-0.009
Z	16.217	16.148	-0.069
3D	-	0.289	0.289

Coord.	Nominal	Actual	Dev
X	36.542	36.745	0.203
Y	34.932	34.937	0.005
Z	2.770	2.770	0.000
3D	-	0.203	0.203

Coord.	Nominal	Actual	Dev
X	-35.400	-35.271	0.129
Y	2.932	2.928	-0.003
Z	-5.971	-5.971	0.000
3D	-	0.129	0.129

Coord.	Nominal	Actual	Dev
X	1.507	1.507	0.000
Y	5.025	4.553	-0.472
Z	-14.809	-14.809	0.000
3D	-	0.472	0.472

Coord.	Nominal	Actual	Dev
X	24.836	24.836	-0.000
Y	0.345	0.312	-0.033
Z	-16.372	-15.129	1.244
3D	-	1.244	1.244

Fig. 8. Deviation between 3D scan and CAD model

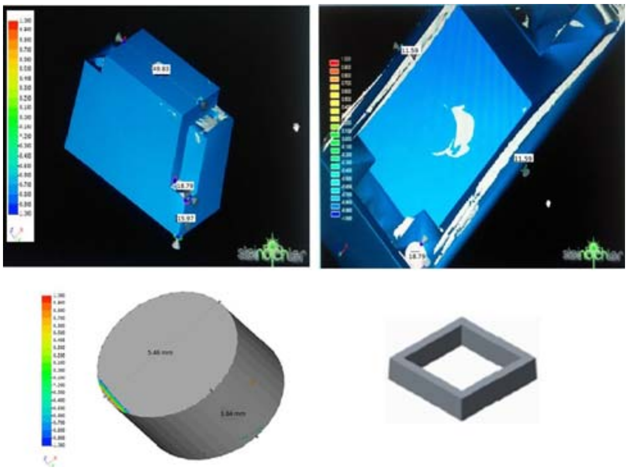


Fig. 9. Highest volumetric shrinkage for cylinder 18.79% and lowest volumetric shrinkage for hollow rectangular prism 11.57%

The independent Evaluation of Deviations between the CAD model of the specimen and the obtained mesh were performed. The BEST-FIT function is used for comparison of a 3 D scan against the model, where the rapid, rough alignment is followed by a precision adjustment [19]. The evaluation distance is set as 1 mm. In the graphic processing the color scale was set to ±0.2 mm; values over and above this boundary are denoted. Volumetric shrinkage estimation of benchmark features using Inspect plus software (figure 9).

10. Conclusion

The aim of this research work is to identify the exact location, where the possibility of shrinkage occurs in injection molded part, provide modification for better part quality. In this present change driven environment, determining the volumetric shrinkage percentage during design stage can help in comparing alternative design solution before the start of plastic part production. In this methodology, geometrical parameter involves such as volume, height, weight, draft angle, thickness, quality prediction percentage, total cycle time. With the help of integrating software package, CAD model is used for analysis with Moldflow® (MFA) simulation. Regression analysis using twelve benchmark parts criteria were determining the coefficient of the geometric parameter equation. The regression equation can be employed in early phases of part lifecycle, significantly in design for manufacturability; the designer can easily estimate the volumetric shrinkage percentage of an injected part (from its CAD model), allowing comparison of alternate designs in term of the influence on die and cavity material. The outcomes were experimentally validated with 3D scanner integrated with inspection softwares.

Nomenclature

PP	polypropylene
ABS	acrylonitrile butadiene styrene
CAD	computer aided design
MFA	moldflow analysis
RT	rapid tooling
PRT	polymer rapid tools
RP	rapid prototyping
AM	additive manufacturing
ANOVA	analysis of variance
STL	stereolithography
VR	volume ratio
V	benchmark parts volume
V_B	bounding box volume
S	shrinkage ratio
T_R	thickness ratio
T_{min}	minimum thickness of benchmark part
H_{max}	maximum height
D_R	draft angle ratio
D_A	draft angle
SD_A	standard draft angle
W_R	part weight ratio
W	part weight
W_T	total part weight
Q_R	quality prediction ratio
Qp%	quality prediction percentage
$Qp_{100}\%$	desired quality
CT_R	cycle time ratio
C_T	cooling time
TC_T	total cycle time
VS%	volumetric shrinkage percentage
R^2	correlation coefficients
STEP	standard for the exchange of product
IGES	initial graphics exchange specification

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