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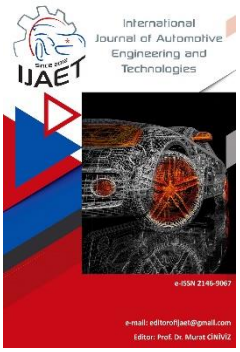

Original Research Article

Investigation of the under-vehicle plastic protection parts manufactured by core-back injection process in terms of strength and weight

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ABSTRACT

Material type, chemical foaming agent, NOx level, core-back distance, and cavity temperature, being the influential parameters in an injection process, significantly affect the weight-based issues and mechanical properties of the resulting product. When the product under inspection is an automotive part, in terms of both the weight and the mechanics are considered to be of high importance. This work is carried out due to a recent task, assigned to NOVARES Engineering and R&D Departments, about the weight reduction of the vehicle underbody plastic protection part (VUPPP), which is located in the rear-lower section of the vehicles. As the core-back process is mostly applied in industry to parts with thickness values of 2.5 mm, the present work involves a challenge due to the fact that before core-back the initial thickness of VUPPP changes between 1.5-1.8 mm. In this study, prototypes are produced with recycled two different polypropylene materials from (PP1 and PP2), two different chemical foaming agents (CFA-X and CFA-Y), six different core-back distances, and two different NOx levels. Finally, laboratory tests are performed on the prototypes to evaluate the weight-based and mechanical features. Experimental data are debated in particular to outline the individual and combined effects of the influential parameters.

Keywords: Core-back process, mold injection, weight reduction, mechanical properties, chemical foaming

1. Introduction

Vehicle parts are designed and manufactured by considering different aspects and targets. The current expectations are lighter components, but having still robust quality and durability; which is mostly recognized in the automotive industry as weight-reduction [1]. As a vehicle body with lower weight results in fewer carbon emissions and lower fuel consumption; mechanical strength is inevitably a primary must. VUPPP is located between the rear wheels and it covers the rear axle of the vehicles. Its visual and CAD data presentation is given in Figure 1, and it has been manufactured by NOVARES since 2015. Recently the task of weight-reduction is assigned for VUPPP; thus, the NOVARES Engineering and R&D Departments focused on this objective.

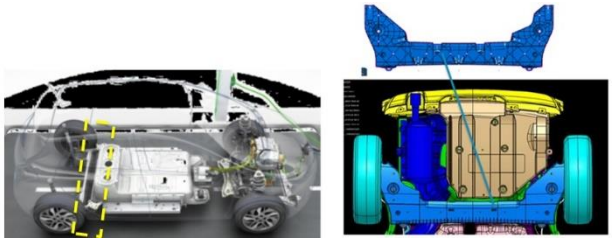


Figure 1. Visual and CAD Data Presentation of the VUPPP.

VUPPP is produced with foam injection molding (FIM) technology. This process is among the most widely used in automotive plastic parts manufacturing processes. In the production of VUPPP, the core-back method is applied to create voids in the internal structure of the sprayed foam. These gaps provide lightening of the product.

Considerable scientific and industrial efforts have been carried out on the core-back FIM process. Liu et al. investigated the influences of four nucleation agents on the nucleation effect and occurring morphologies in the polypropylene foaming injection molding process. Experimental investigations were carried out with and without core-back applications. Both the physical and mixture parameters of the nucleation agents are defined in tabulated form. Results are given in terms of SEM nucleation photos, cell size & cell density, volume expansion ratio, the void fraction of foams, and foaming efficiency. The primary evaluations are (i) the existence of cavities on the boundaries of nucleation agent and polymer, (ii) foaming is observed with the core-back application, (iii) cavities result in higher bubble density and lower bubble diameter, (iv) micro-structures depend on the selection and volume fraction of nucleation agents [2]. In another research, Wang et al., prepared and blended the composition with cellulose nanofibers (CNF) to augment the mechanical features of polypropylene. The composites are prepared with 2 different levels of CNF addition, namely 0.2 and 0.4. Nitrogen (N_2) is applied, by 0.2 wt%, as the physical blowing agent. As the cell density is increased by the addition of CNF, the cell diameters are observed to decrease. Besides the mechanical properties such as tensile modulus and yield stress are recorded to promote by the inclusion of CNF. Moreover, the effects of core-back application are also investigated for different distances which were in the range of 1-9 mm, resulting in expansion ratios of foams with 2-10 fold. Core-back application is determined to weaken the mechanical durability of foam by decreasing the elastic modulus and collapse stress [3]]. Bai et al. investigated the effects of time and compression pressure on the cell built of polystyrene foam during the foaming operation. The investigations were performed with core-back speed and distance of 2 mm/s and 1 mm respectively; moreover, the compression pressure range was 0-300 bar. The main evaluation is the drop in cell diameter and the growth of cell density with compression pressure. Besides, the results indicated that die compression caused high pressure, while the core-back technique provided a rapid pressure reduction. Rapid pressure decrease and higher cavity pressure caused the formation of thin cell builds [4]. A new method with a unique secondary filling stage right after the core-back operation is proposed by Wu et al. It is stated that by combining core-back and secondary filling, a closed shell composed of dense polymer skins can be created right before melt filling. This closed shell is declared to prevent the gas loss from the melt flow front, and act as the gas counter pressure to reduce cell coalescence and collapse, thus leading to significant improvement of cell structure. Tests indicated that plastic foams provide notch impact strength, elastic modulus, and improved tensile strength with the new technology. Azodicarbonamide (AC) was used as the chemical blowing agent; core-back speed and distance of 7 mm/s and 3.5 mm respectively [5]. Pascual et al. foamed a mixture of a polyolefin elastomer (POE), a long-chain branched polypropylene (LCB-PP), and a linear polypropylene (L-PP) with the help of core-back injection molding. The chemical blowing agent Hydrocerol CF 40 E, which is a composition of sodium bicarbonate and sodium citrate, was applied 2 wt%. With the addition of POE, it was observed that the impact response was improved in solids and cellular polymers, while the stiffness decreased. Furthermore, replacing L-PP with LCB-PP in blends including POE has revealed in solids and cellular materials with superior stiffness and impact characteristics[6]. Polyamide 6 (PA6) injection microcellular foams were produced by Jiang et al. via short-

shot and core-back foaming processes to examine the foaming process's effect on cell and surface quality. Experiments were carried out with core-back speed and distance weight reduction values of 20 mm/s, 0.2-10 mm, and 5-25 % respectively; moreover, the chemical foaming masterbatch (F-70) was applied 2 %. Results show that the core-back foaming microcellular foams possess lower deformation of cells, smaller cell size, and narrower cell size distributions with the same weight reduction, compared to the samples prepared using the short-shot foaming process. PA6 microcellular foams that were manufactured via core-back foaming had higher surface glossiness with different weight reductions [7]. Ishikawa and Ohshima foamed copolymer polypropylene with carbon dioxide in a core-back injection-molding investigation. Experiments were carried out with core-back speed and CO2 injection period ranges of 1-10 mm/s and 2-4 s. When the cavity is completely filled, the bubbles disappear; The cavity pressure drops and die plate actuation were confirmed by experiments to induce bubble nucleation. According to the results, it was observed that faster return rates and higher gas concentrations caused an increase in the number of bubbles but reduced the size of the bubbles [8]. The effects of chemical blowing agent content, shot size, mold temperature, holding time, injection speed, holding pressure, and core-back rate [mm/s] on the core-back foam injection molding process was studied by Wu et al. As azodicarbonamide (AC) was used as the chemical blowing agent, the core-back velocity and AC content were in the ranges of 1-9 mm/s and 3-9 %. The cell density is recorded to increase with AC content. The filling rate is determined to increase with the first stage holding pressure time; besides there exist specific time instants for maximum/optimum mechanical properties [9]. Ruiz et al. used polyethylene-based compounds, containing citric acid and sodium bicarbonate, as chemical blowing agents in a core-back foam injection molding investigation. The specific information in this article is the variation of pressure in the mold cavity during filling, packing, and core-back periods [10]. The sequential molding process, with one die for manufacturing multi-component products, was investigated by Park and Anh for different core-back distances. It was observed that the geometric quality/precision of the product can be satisfied with different core-back distances; however, optimization is necessary from the point of material usage amount as well. On the mechanical side, filling time and injection pressure cross-correlate to cause higher residual stress on the skin part of the product [11].

In this study, it has aimed to reduce the weight of the VUPPP structure without weakening it mechanically. Prototypes were produced using recycled two different polypropylene materials and two different chemical foaming agents to observe the effect of different NOx levels and core-back distances on the product. The core-back process is mostly associated with products with thickness values around 2.5 mm. The research's original contribution is applying the core-back process to VUPPP with thickness values in the range of 1.5-1.8 mm. The positive results demonstrated by this innovative side of the research revealed the potential in the lightening of all products that can be produced, although very thin, in the injection process using the core-back method. Within the scope of the research, geometric, weight-based, and mechanical tests were applied to the prototypes. The evaluations were presented in tabular form and discussed in detail, identifying the individual and combined roles of the effective parameters on the results.

2. Material and Method

2.1. Materials

Polypropylene is a thermoplastic polymer with a wide range of uses, from textile and food packaging to parts used in the automotive industry [12, 13]. Products created using this polymer are generally used in automotive interior parts, as this material is light, durable, and easily shaped [14 - 16].

Researchers aim to reduce the amount of waste to some extent by recycling this polymer [17, 18]. The properties of the recycled polypropylene used in this study and purchased from 2 different suppliers are shown in Table 1. Two different chemical blowing agents were used in the production of VUPPP prototypes. The reason for this is to examine the impact of diverse blowing agents on the features of the part. The properties of 2 different chemical foaming agents are shown in Table 2.

Table 1. Properties of used polypropylenes

	PP 1	PP 2
Density (g/cm^3)	0.90-0.95	0.95
Melt flow rate (230^{o}C; 2,16 kg) (g/10min)	9-14	15
Tensile stress (50 mm/min) (MPa)	≥16	20
Tensile strain at break (50 mm/min) (%)	≥40	-
Tensile modulus (1mm/min) (MPa)	≥750	900-1200
Flexural modulus (2mm/min) (MPa)	≥700	1000
Notched impact strength (Izod) (23^{o}C) kJ/m^2	≥8	10
Hardness (D-shore)	56-60	-

Table 2. Characteristics of chemical foaming agents

	CFA-X	CFA-Y
Characteristic	Endothermic composition	Endothermic composition
Types of chemical foaming	Bicarbonate	Bicarbonate
Start of activation/decomposition	160°C	140-150°C
Active content	65%	40%
Processing temperature	160-180°C	170-190°C
Dosage for injection molding	0.5-2.0%	1.0-3.0%

2.2. Methods

Conventional FIM technology is applied by short-shot injection of a mixture of polymer melt and supercritical fluid into a closed mold cavity, and the expandable melt/gas mixture forms a foam structure under reduced pressure. Meanwhile, polymer foams are widely used in various fields due to their superior properties such as lightweight, and high specific strength. Injection-compression molding is a process in which the mold is filled through controlled compression, after which the cavity pressure increases rapidly. In general, the core-back operation is a process in which the filling operation is completed, after which the cavity expands at a certain opening rate, in the direction perpendicular to the flow at a certain distance. For core-back technology, a fast pressure drop in a cavity can be acquired easily. Core-back FIM process is an advanced technology to further increase the plastic foam's weight reduction. In the core-back FIM process, When the filling phase is complete, the core side of the mold is retracted to a certain extent, creating an extra area for foaming and thus the weight reduction of the final molded foam can be particularly augmented [19 - 21]. A schematic presentation of the chemical foaming agent-assisted core-back injection process is given in Figure 2.

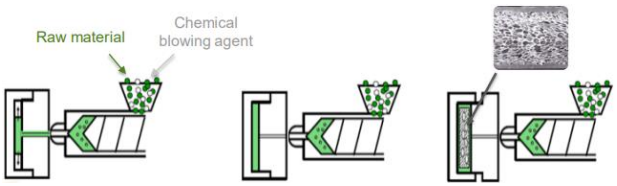
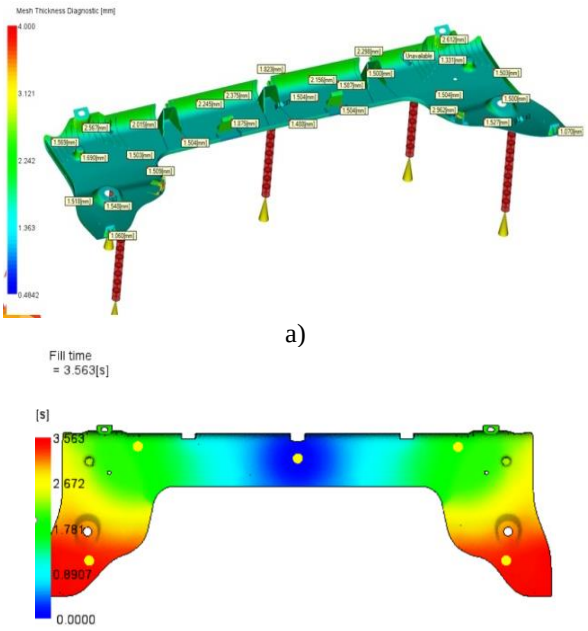


Figure 2. Schematic Presentation of Chemical Foaming Agent Assisted Core-Back Injection Process.

Although the objective of the present research is to produce some prototypes and perform weight-based and mechanical tests on them, MoldFlow simulations are also carried out to inspect the process. Figure 3 displays the result of the MoldFlow simulation executed on the part, with a thickness of 1.5 mm, to evaluate the filling behavior. As Figure 3(a) displays the thickness distribution of the part, the elapsed time for the melt to fill different sections of the mold is shown in Figure 3(b). Moldflow simulation shows that there is no problem in filling with a 1.5mm thick part with current gate numbers.



a)

b)

Figure 3. a) The thickness distribution of the part, b) the elapsed time for the melt to fill different sections of the mold

Prototypes are produced with thickness values of 1.5, 1.8, 2.0, and 2.5 mm. The prototype plaque mold, with different thicknesses, available in the NOVARES production area is shown in Figure 4.

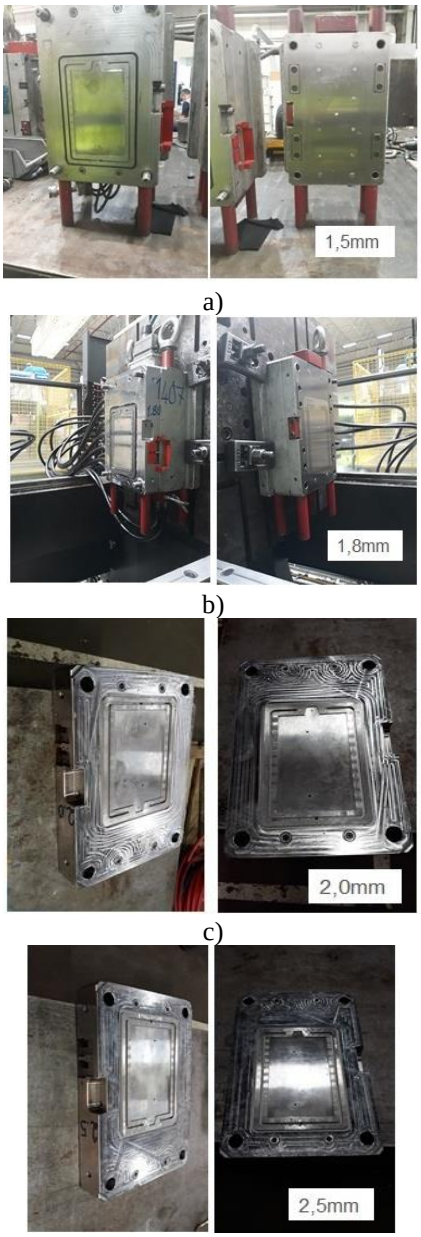


Figure 4. Prototype Plaque Mold with Different Thickness a) 1.5 mm b)1.8 mm c) 2.0 mm d)2.5 mm

Both of the used CFA types contain bi-carbonate type sort active material with 40 and 60% portions. Besides the CFA types react in the endothermic way, where reaction formulations are given in Eq. (1-5).

$$CFA(endo) \xrightarrow{+\Delta E} CO_2 + H_2O + inorganic\ subprod. \quad (1)$$

$$2NaHCO_3 \rightarrow Na_2CO_3 + H_2O + CO_2 \quad (2)$$

$$C_6H_8O_7 \rightarrow C_6H_6O_6 + H_2O \quad (3)$$

$$C_6H_6O_6 \rightarrow C_5H_6O_4 + CO_2 \quad (4)$$

$$C_6H_8O_7 + 3NaHCO_3 \rightarrow Na_3C_6H_5O_7 + 3H_2O + 3CO_2 \quad (5)$$

Tensile and impact tests were applied to the produced prototypes. The prototypes were cut according to the TS EN ISO 527 standard for the water jet tensile test and the TS EN ISO 180/A1 standard for the impact tests and tested in accordance with these standards.

3. Results and Discussion

Laboratory tests are performed on the prototypes which are produced with different recycled polypropylene materials, chemical foaming agents, NOx levels, and core-back distances. Evaluations and discussions are based on geometrical, interior structure of plaques, weight-based and mechanical results.

3.1. Effects of CFA

The variants in this data set are the CFA (CFA-X, CFA-Y) and the thickness of the mold (1.5, 1.8, 2.0 mm). Moreover, the CFA adding ratio is 1.5% and the cavity temperature is 37oC stable, the main target of this injection trial is CFA types effect in different thicknesses. For the CFA types CFA-X and CFA-Y, according to the results, the CFA-X weight reduction ratio seems more than CFA-Y for each thickness value. The corresponding tensile strength at yield was 19.69 and 20.99 MPa, the tensile strength at break was 17.40 and 16.29 MPa, and the tensile modulus values were 1201 and 1221 MPa respectively. From the point of strains, the related data for tensile strain at yield were 6.05 and 5.18%, and tensile strain at break was 31.23 and 28.32% respectively. These data as a whole indicate that CFA-X causes higher weight reduction, which can be associated with the excess content ratio of CFA-X with respect to CFA-Y. As a result, the higher weight reduction can be attributed to more bubbles with bigger cell diameters in the VUPPP volume. In return, the mechanical properties are comparably poorer when compared to those of the CFA-Y case, with lower tensile strength values and higher strain data. Table 3 presents the results of the experiments that were carried out on the prototypes which were produced by PP1.

As the weight reduction is less with CFA-X, the mechanical properties are recorded to be superior to those of CFA-Y. Such that tensile strength at yield was 23.63 and 22.4 MPa, tensile strength at break was 21.31 and 17.86 MPa, and the tensile modulus values were 1312 and 1296 MPa for CFA-X and CFA-Y respectively. From the point of strains, the related data for tensile strain at yield were 6.22 and 5.21%, and tensile strain at break was 19.47 and 22.65% respectively.

Table 3. Effects of CFA Type on the Weight and Mechanical Properties of Prototypes.

Material Descriptions	**Values According to Scenarios**					
Started Thickness (mm)	2.0	2.0	1.8	1.8	1.5	1.5
Final Thickness (mm)	2.0	2.0	1.85	1.85	1.54	1.53
Core-Back (mm)	0	0	0.05	0.05	0	0.03
Theoretical Mass (acc to final thick.) (g)	50.64	50.64	46.84	46.84	38.99	38.74
Measured Mass (g)	46.74	46.21	43.00	43.50	38.10	38.29
Weight Reduction (%)	7.7	8.7	8.2	7.1	2.3	1.2
CFA	CFA-X	CFA- Y	CFA-X	CFA- Y	CFA-X	CFA- Y
CFA adding % (w/w)	1.5	1.5	1.5	1.5	1.5	1.5
Mechanical Test Result						
Tensile Strength at Yield / Tensile stress (50mm/min) (MPa)	17.75	19.58	19.69	20.99	23.63	22.4
Tensile Strain at Yield (50 mm/min) (%)	5.88	5.15	6.05	5.18	6.22	5.21
Tensile Strength at Break / (50 mm/min) (MPa)	16.49	17.72	17.40	16.29	21.31	17.86
Tensile Strain at Break (50 mm/min) (%)	42.99	33.99	31.23	28.32	19.47	22.65
Tensile Modulus (1 mm/min) (MPa)	1090	1146	1201	1221	1312	1296
Charpy Impact no notched (23°C)						
1J hammer (kJ/m^2)	No break	No break	No break	No break	No break	No break
5J hammer (kJ/m^2)	No break	No break	No break	No break	No break	No break

Table 4. Effects of NOx usage on the weight and mechanical properties of prototypes.

Material Descriptions	**Values According to Scenarios**			
Started Thickness (mm)	1.8	1.8	1.8	1.8
Final Thickness (mm)	1.85	1.8	1.88	189
Core Back (mm)	0.05	0	0.08	0.09
Theoretical Mass (acc to final thick.) (g)	46.8373	45.5715	47.5969	47.8500
Measured Mass (g)	43	43.8	42.24	43.3
Weight Reduction (%)	8.2	3.9	11.3	9.5
CFA ID	CFA- X	CFA-X	CFA- X	CFA- X
CFA % Adding	1.50%	1.50%	1.50%	1.50%
NO_X %	No	1%	No	1%
Mechanical Test Result				
Tensile Strength at Yield / Tensile stress (50 mm/min) (MPa)	19.69	21.60	24.21	23.66
Tensile Strain at Yield (50 mm/min) (%)	6.05	5.28	7.62	7.86
Tensile Strength at Break/(50 mm/min) (MPa)	17.40	14.51	21.14	21.52
Tensile Strain at Break (50 mm/min) (%)	31.23	31.26	34.84	32.05
Tensile Modulus (1 mm/min) (MPa)	1201	1078	1071	991
Charpy Impact no notched (23°C)				
1J hammer (kJ/m2)	No break	No break	25.5	No break
5J hammer (kJ/m2)	No break	No break	-	No break

3.2. Effect of NOx addition

Effects of NOx addition are also investigated and the evaluated results are given in the tabulated form in Table 4. The expectation in NOx addition is to optimize the variation of mechanic property variations of the recycled material in every individual product. The material and CFA types used in these scenario sets were selected to be PP1 and CFA-X respectively. The starting thicknesses were always 1.8 mm, core-back distances were in the range of 0-0.09 mm and the cavity temperatures were around 36-38 ºC. In the case with the core-back distance of 0.09 mm, NOx was applied by 1%; the weight reduction attained here was 9.5%. However, in the comparably lower core-back distance of 0.08 mm, without NOx addition (0%) the weight reduction was higher with the specific value of 11.3%. These results indicate the suppressive effect of NOx on weight reduction. From the mechanical testing

perspective, NOx addition does not seem to have an inspectable role in mechanical properties. Such that tensile strength at yield was 23.66 and 24.21 MPa, tensile strength at break was 21.52 and 21.14 MPa, the tensile modulus values were 991 and 1071 MPa for with (1.5%), and without NOx addition (0%) respectively. From the point of strains, the related data for tensile strain at yield were 7.86 and 7.66%, and tensile strain at break was 32.05 and 34.84% respectively.

Table 5. Effects of material type on the weight and mechanical properties of prototypes.

Material Descriptions	**PP1**	**PP2**
Started Thickness (mm)	1.8	1.8
Final Thickness (mm)	1.85	1.85
Core Back (mm)	0.05	0.05
Theoretical Mass (acc to final thick.) (g)	46.8373	46.8373
Measured Mass (g)	43	42.24
Weight Reduction (%)	8.2	9.8
CFA ID	CFA -X	CFA -X
Mechanical test result		
Tensile Strength at Yield/Tensile stress (50 mm/min) (MPa)	19.69	24.21
Tensile Strain at Yield (50 mm/min) (%)	6.05	7.62
Tensile Strength at Break / (50 mm/min) (MPa)	17.40	21.14
Tensile Strain at Break (50 mm/min) (%)	31.23	34.84
Tensile Modulus (1 mm/min) (MPa)	1201	1071
Charpy Impact no notched (23°C)		
1J hammer (kJ/m^2)	No break	25.5
5J hammer (kJ/m^2)	No break	-

Table 6. Effects of core-back application on the weight and mechanical properties of prototypes.

Material Descriptions	**Values According to Scenarios**							
Started Thickness (mm)	1.56	1.5	1.5	1.8	1.8	1.8	1.8	1.8
Final Thickness (mm)	1.56	1.54	2.04	1.8	1.8	1.85	2.03	2.2
Core Back (mm)	0	0	0.54	0	0	0	0.23	0.4
Theoretical Mass (acc to final thick.) (g)	41.26	38.98	51.39	45.57	45.57	46.83	51.39	55.69
Measured Mass (g)	42.51	38.10	47.81	45.57	43.8	43	44	43.2
Weight Reduction (%)	0.0	2.3	6.97	0.0	3.9	8.2	14.4	22.4
CFA adding% (w/w)	0	1.5	1.5	0	1.5	1.5	1.5	1.5
Mechanical test result								
Tensile Strength at Yield / Tensile stress (50 mm/min) (MPa)	25.43	23.63	22.98	24.3	21,60	19.69	19.53	18.84
Tensile Strain at Yield (50 mm/min) (%)	5.91	6.22	8.09	5.7	5.28	6.05	6.41	6.98
Tensile Strength at Break (50 mm/min) (MPa)	14.61	21.31	19.59	10.05	14.51	17.40	17.51	16.98
Tensile Strain at Break (50 mm/min) (%)	28.77	19.47	20.32	31.5	31.26	31.23	30.87	33.52
Tensile Modulus (1 mm/min) (MPa)	1340	1312	1251	1219.9	1078	1201	892	842
Charpy Impact no notched (23°C)								
1J hammer (kJ/m^2)	N/A	N/A	N/A	No break	No break	No break	18,86	16,77
5J hammer (kJ/m^2)	N/A	N/A	16,9	No break	No break	No break	No break	No break

3.4. Effect of Core-back Application

The starting thicknesses were in the range of 1.5-1,8 mm and the core-back distances were applied within the limits of 0.5 mm. The increase of air voids formed after this process in Figure 5 can be seen clearly.

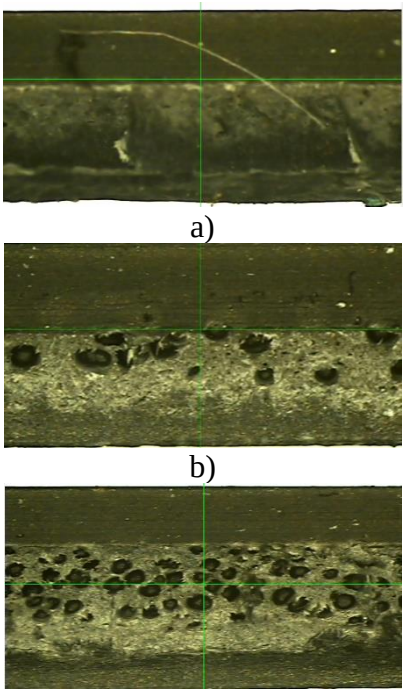


Figure 5. Prototype cross-section images of different thicknesses a) 1.5 mm thickness without CFA b) 1.8 mm thickness with CFA c) 2.2 mm thickness with CFA + 0.5mm core-back

The CFA was CFA-X; its adding quantity was 1.5%. Besides, the cavity temperature is set at 25 ºC. The complete set of results indicated a rise in weight reduction with the core-back application. Similarly, CFA-X addition also promoted weight reduction. Cavity temperature appears to limit weight reduction. An increase in weight reduction can be said to be an indicator for loss of mechanical durability with lower property data. Table 6 displays the variation of weight reduction and mechanical property data of 8 scenarios where the primary material was selected as PP1. In addition, tensile test data and graphs of the 5 samples produced for each scenario are also given in Figure 6. The tensile test strength values given in Table 6 are the average values of the data taken from 5 samples. Table 6 and Figure 5 shows that the core-back has a significant effect on increasing the number of air voids and thus the weight reduction ratio. The important issue to be considered is the mechanical properties of polypropylene. After core-back, the tensile stress and strain modulus values decreased for each sample, but this was a negligible decrease. The highest weight reduction rate (22.4%) was observed in the 2.2 mm thick sample with a core back distance of 0.4 mm. While the tensile strength at the yield value of this sample was 18.84 MPa, the tensile strain at the yield value was 6.98%. As the initial thickness increases, the core back distance may increase, and weight reduction can be achieved without affecting the mechanical strength much.

4. Conclusion

An experimental investigation of geometric and mechanical results of the chemical foaming agent-assisted core-back injection process is reported for different suppliers' recycled polypropylene material, chemical foaming agents, NOx levels, core-back distances, and cavity temperatures. The main outcomes of the computations can be summarized as follows;

- The core-back process is successfully applied to VUPPP with thickness values down to 1.5 mm.
- CFA-X, when compared to CFA-Y, causes higher weight reduction, which is return can be attributed to more bubbles with bigger cell diameters in the VUPPP volume. In return, the mechanical properties are comparably poorer, with lower tensile strength values and higher strain data.
- NOx addition does not seem to have an inspectable role in mechanical properties.
- The weight reduction in the PP2 material came up to be superior to that of PP1. On the mechanical side, PP2 was also evaluated to be more durable than PP1.
- The complete set of evaluated results indicated a rise in weight reduction with the core-back application.
- An increase in weight reduction can be said to be an indicator for loss of mechanical durability with lower property data.

CRediT authorship contribution statement

Yasemin Gültekin: Methodology, Resources, Visualization, **Mustafa Atakan Akar:** Investigation, Writing - original draft, Supervision, **Anıl Altındağ:** Investigation, Methodology, Conceptualization, **Doğukan Duran:** Investigation, Methodology, Conceptualization, **Umut Kumlu:** Visualization, Writing - original draft, Writing - review& editing.

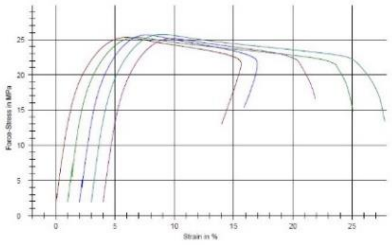
Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Results:

Nr	Et MPa	σ x N/mm²	σM MPa	εM %	σB MPa	εB %	L0 mm
1	1310,00	14,52	25,31	5,92	12,96	32,54	75,18
2	1360,11	14,44	25,30	5,90	14,80	32,68	75,09
3	1395,98	13,75	25,66	5,69	15,36	28,46	75,09
4	1310,30	15,33	26,76	6,15	13,37	29,83	75,13
5	1326,11	14,38	25,16	5,90	16,55	20,32	75,11

Series graphics:

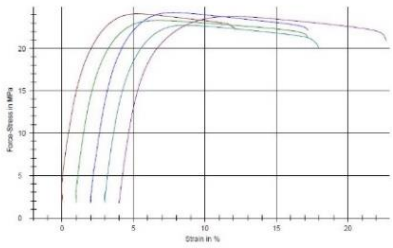


a)

Results:

Nr	Et MPa	σ x N/mm²	σM MPa	εM %	σB MPa	εB %	L0 mm
1	1305,97	15,17	24,09	5,49	22,26	17,37	75,00
2	1318,61	14,67	23,32	5,95	21,26	19,78	75,04
3	1275,63	15,10	24,22	5,93	22,15	19,04	74,98
4	1315,07	14,17	22,73	5,64	19,96	18,48	75,02
5	1345,73	13,46	23,78	6,11	20,88	22,69	75,08

Series graphics:

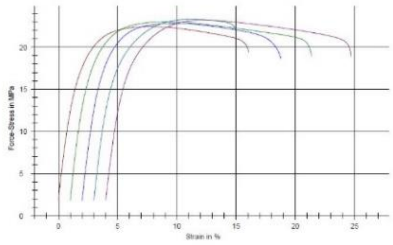


b)

Results:

Nr	Et MPa	σ x N/mm²	σM MPa	εM %	σB MPa	εB %	L0 mm
1	1239,37	13,35	22,45	7,68	19,43	18,65	75,09
2	1327,70	13,22	23,03	8,40	18,04	23,59	75,07
3	1246,86	13,84	22,84	7,64	18,67	19,66	75,09
4	1246,78	13,17	23,33	8,29	22,02	15,78	75,07
5	1194,98	13,38	23,23	8,42	18,87	24,04	75,09

Series graphics:

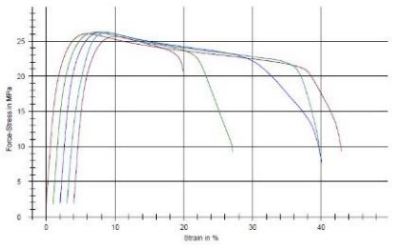


c)

Results:

Nr	Et MPa	σ x N/mm²	σM MPa	εM %	σB MPa	εB %	L0 mm
1	1360,85	17,42	26,85	6,11	9,32	45,46	75,05
2	1326,93	17,29	26,34	6,25	9,25	27,90	75,08
3	1302,51	17,62	26,29	6,10	7,70	39,52	75,06
4	1206,67	15,33	26,17	5,72	9,42	37,76	75,09
5	1341,63	16,86	25,67	6,21	20,75	18,39	75,02

Series graphics:

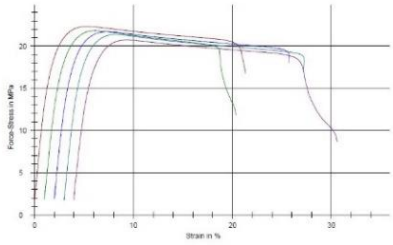


d)

Results:

Nr	Et MPa	σ x N/mm²	σM MPa	εM %	σB MPa	εB %	L0 mm
1	1013,56	17,56	22,34	5,34	16,75	26,05	75,03
2	1046,23	16,16	21,84	5,27	11,81	27,36	75,05
3	1098,52	15,38	21,70	5,22	18,05	36,86	75,02
4	1158,82	14,83	21,37	5,20	17,28	34,22	75,00
5	1073,97	14,32	20,74	5,37	8,69	31,87	74,97

Series graphics:

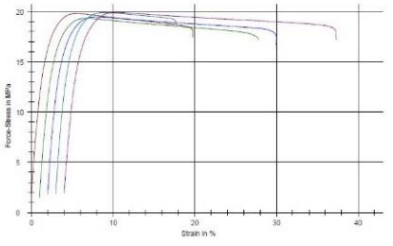


e)

Results:

Nr	Et MPa	σ x N/mm²	σM MPa	εM %	σB MPa	εB %	L0 mm
1	1243,87	11,34	19,82	5,46	17,45	31,23	75,02
2	1227,13	11,29	19,33	5,88	17,17	32,06	75,10
3	1264,59	11,17	19,47	5,84	16,69	36,07	75,11
4	1221,21	11,98	19,92	6,09	18,51	19,79	75,09
5	1048,53	12,26	19,92	7,01	17,18	37,99	75,11

Series graphics:

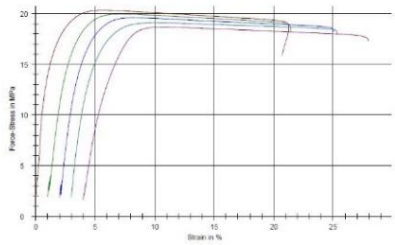


f)

Results:

Nr	Et MPa	σ x N/mm²	σM MPa	εM %	σB MPa	εB %	L0 mm
1	867,64	15,64	20,34	5,92	16,90	37,37	74,98
2	978,10	14,11	19,95	6,12	18,19	28,06	75,10
3	974,58	13,32	19,61	6,09	18,23	30,47	75,09
4	918,78	12,80	19,09	7,18	17,90	29,32	75,13
5	690,89	11,63	18,68	6,77	17,34	29,10	75,14

Series graphics:

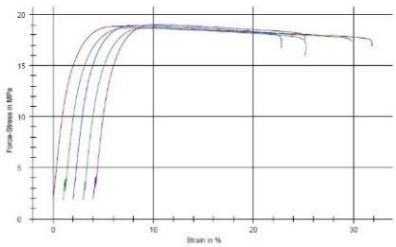


g)

Results:

Nr	Et MPa	σ x N/mm²	σM MPa	εM %	σB MPa	εB %	L0 mm
1	831,04	13,65	18,86	6,83	16,93	40,07	75,13
2	804,58	13,27	18,71	7,96	17,39	34,94	75,13
3	870,96	13,34	18,95	6,61	16,72	30,41	75,13
4	855,26	12,87	18,68	7,00	15,88	32,61	75,12
5	849,80	13,36	19,02	6,50	17,55	29,55	75,13

Series graphics:



h)

Figure 6. Tensile test data and graphics of specimens

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