Optimization and dimensional stabilization of thin-walled modified polypropylene moldings through shrinkage inhibition on cooling fixtures

Optymalizacja i stabilizacja wymiarowa cienkościennych wyprasek z modyfikowanego polipropylenu poprzez ograniczenie skurczu na przyrządach chłodzących

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The article discusses dimensional stabilization of thin-walled passenger seat back covers injection-molded from modified polypropylene as a replacement for PC/ABS. Two PP-based composites were tested, with attention to post-molding cooling fixtures. The results show that fixtures reduce transverse shrinkage, but their effectiveness depends on material anisotropy and filler type.

KEYWORDS: polypropylene, processing shrinkage, cooling fixture, thin-walled molding, glass fiber, talc, shrinkage anisotropy, passenger seats

Artykuł omawia stabilizację wymiarową cienkościennych osłon oparć foteli pasażerskich formowanych wtryskowo ze zmodyfikowanego polipropylenu jako zamiennika PC/ABS. Przebadano dwa kompozyty PP, zwracając szczególną uwagę na uchwyty chłodzące po wyjęciu z formy. Wyniki wskazują, że ograniczają one skurcz poprzeczny, lecz skuteczność zależy od anizotropii i rodzaju napełniacza.

SŁOWA KLUCZOWE: polipropylen, skurcz przetwórczy, uchwyt chłodzący, cienkościenna wypraska, włókno szklane, talk, anizotropia skurczu, siedzenie pasażerskie

Introduction

Thermoplastic injection molding is a process in which the dimensional accuracy of the product depends not only on the shape of the mold cavity, but on the combined effect of holding pressure, melt and mold temperatures, cooling rate, crystallization, and post-molding stress relaxation [1], [2], [4]. In the case of thin-walled components, such as passenger seat back covers, a minor dimensional deviation can disrupt snap-fit assembly, the connection with the steel frame, and the visual appearance of the part [15], [16]. For this reason, material substitution from PC/ABS to PP is not a simple replacement of plastic in the process sheet but simultaneously requires the optimization of both the material and the post-process cooling conditions [2], [4].

The technological objective of the analysed project was to replace the reference PC/ABS-based material as directly as possible with a polyolefin polypropylene-based plastic using the existing tooling. This means that a mold designed for a low-shrinkage material was to be used for a semi-crystalline material, which under typical conditions exhibits a greater change in specific volume during cooling [5] [8]. This requirement particularly tightens the tolerances in the cover width, as the cross-flow direction proved to be critical for fitting the part to the seat frame [4], [9].

The problem is interdisciplinary in nature. On one hand, it was necessary to maintain the impact strength and operational safety of the seat component [12]; on the other hand, the PP material had to meet the dimensional stability and fire resistance requirements specific to the interiors of public transport vehicles [3], [13]. In practice, this required the use of fillers, impact modifiers, and flame-retardant additives, which improve selected properties but simultaneously alter melt rheology, crystallization kinetics, and the shrinkage balance [9], [14].

The aim of this article is to describe the mechanism of dimensional optimization of PP moldings through mechanical shrinkage inhibition on cooling fixtures directly after the injection molding process. The physical fundamentals of shrinkage in semi-crystalline polymers, the role of fillers in shaping anisotropy, the principles of the stabilization process on fixtures, and the interpretation of measurement results for Scolefin and Inspire materials are presented. Of particular importance is the comparison between the glass-fibre-reinforced material, in which shrinkage along the flow axis is strongly suppressed by oriented fibres, and the talc-filled material, where the nucleation and stiffening effect does not provide a similar inhibition in the X-axis.

Physical Fundamentals of PP Molding Shrinkage

Molding shrinkage is the macroscopic result of the reduction in the polymer's specific volume during the transition from the molten to the solid state [1], [15].

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In engineering descriptions, p-v-T relationships are utilized, which correlate pressure, specific volume, and temperature during the injection molding cycle [16]. During the holding phase, the increase in pressure limits the free volume and partially compensates for future shrinkage; however, after gate freeze-off and the completion of mass transfer, further cooling leads to irreversible dimensional changes [4]. This phenomenon is described by the Tait equation [6]. For semi-crystalline PP, this phenomenon is particularly intense as it encompasses not only the thermal contraction of the melt but also the ordering of polymer chains into a crystalline phase [5].

The difference between PC/ABS and PP stems primarily from their morphology [3]. As an amorphous material, PC/ABS undergo a glass transition during cooling, and the polymer chains become immobilized in a disordered state. The absence of crystallization limits step-like changes in density and promotes more isotropic behaviour [5]. Polypropylene, especially isotactic PP, is a semi-crystalline polymer: during cooling, nucleation and growth of lamellae and spherulites occur, and the crystalline phase is characterized by a higher density than the amorphous phase [7]. Consequently, the shrinkage potential of PP remains significantly higher than that of PC/ABS, even after the introduction of fillers [6], [8].

Crystallization kinetics depend heavily on the cooling rate [7]. In an actual thin-walled molding, the skin layer near the mold wall cools rapidly, while the core cools more slowly and retains the capacity for structural reorganization over a longer period [16]. This gradient results in variations in the degree of crystallinity and orientation across the wall cross-section, thus inducing residual stresses [7], [16]. Here, p-v-T models for semi-crystalline materials are more accurate when they better account for the cooling history, as rapid cooling can shift crystallization temperatures and restrict the time available for chain ordering [5], [6].

The process of dimensional changes does not cease after the part is ejected from the mold. In polypropylene, post-molding shrinkage occurs, which is associated with secondary crystallization, stress relaxation, and the further refinement of the lamellar structure. Literature regarding injection-molded PP indicates that a significant portion of these changes can take place within the first few hours post-process, and long-term measurements demonstrate a dependence of both dimensions and mechanical properties on conditioning. This is critical for the covers under consideration, as the fixture operates precisely during this period, when the material has not yet achieved full thermal and structural stability.

Materials Used in the Study

Two main directions of polypropylene modification were analysed in this study. The first was Scolefin 62G 22-0 FR (40), a PP composite containing glass fibre and mineral fillers, designed to reduce shrinkage and increase the stiffness of the cover [9], [14]. The second was Inspire TF1305, a talc-filled material modified with a 3% addition of Engage 8150 elastomer [11], [12], and in one variant, an additional 3% flame-retardant additive [13]. This selection of materials represents a typical trade-off in the design of plastics for vehicle interiors: reinforcement and dimensional stabilization must be balanced against impact strength, flammability, processability, and warpage risk [9], [13], [14].

Scolefin represents a composite in which glass fibres act as a reinforcing phase [9], [14]. During flow within the mold cavity, short fibres orient predominantly along the flow direction, particularly in regions of high shear stress [14]. After the matrix solidifies, they restrict shrinkage along their own axis; thus, shrinkage in the flow direction is significantly lower than transverse shrinkage [9], [15]. While this mechanism is beneficial for the X dimension, it introduces strong anisotropy, which can cause warpage when directional deformations are not balanced by the part geometry or the cooling method [10], [15].

Inspire TF1305 represents a different stabilization mechanism. Talc has a platy morphology and can restrict shrinkage more uniformly than fibres under certain orientation conditions, but its primary role in PP is also to act as a heterogeneous nucleating agent [11]. The surface of the talc facilitates the formation of numerous crystallization nuclei, promoting a finer morphology and increased stiffness, but it does not create mechanical reinforcement along the flow axis comparable to glass fibre [9], [11]. For this reason, in the discussed part, the talc-filled material may require additional shrinkage inhibition in the X-axis, especially when the fixture primarily stabilizes the width in the Y-axis [15].

The addition of Engage 8150 served as an impact modifier. Polyolefin elastomers based on ethylene-octene copolymers can improve the impact energy absorption capacity of PP by initiating local plastic deformation mechanisms and mitigating brittle fracture [12]. In the analysed case, however, the improvement in impact performance was accompanied by a deterioration in dimensional stability, as the elastomer phase features a low modulus, high compliance, and its own thermal contraction during cooling [12], [14]. Consequently, the Inspire + 3% Engage variant required the most aggressive dimensional correction on the cooling fixture [14].

The flame-retardant additive used in the Inspire + Engage + flame retardant variant introduces another material trade-off. Ammonium polyphosphate-based systems belong to halogen-free intumescent systems that form a carbonaceous char layer during thermal decomposition, restricting heat and oxygen access to the polymer [13]. While such additives are justified in public transport interior components, as a solid phase they modify melt viscosity, crystallization behaviour, and stress transfer within the composite [13]. In the measurement data, the variant with the flame retardant still exhibited large dimensional deviations, confirming that fire resistance does not resolve the shrinkage problem.

Cooling Fixtures as a Post-Process Stabilization Tool

In the analysed process, the cooling fixture is not part of the mold, but rather a separate stabilizing station where the part is transferred immediately after the completion of the injection molding cycle [1], [16]. Its function is to mechanically enforce the target geometry before post-molding shrinkage and stress relaxation can occur freely [8]. The molding is mounted on the fixture in such a way as to restrict the reduction in width along the Y-axis. As a result, the material's natural tendency to contract is partially converted into a state of tensile and compressive stresses within the still warm, viscoelastic structure [2], [15].

The operating mechanism of the fixture can be interpreted as controlled dimensional retention within a window where the material already has the shape of the molding, but the core and amorphous regions retain the capacity for relaxation [7]. If the part is left unsupported, post-molding shrinkage leads to unconstrained dimensional reduction and the formation of warpage resulting from a non-uniform cooling history [15], [17]. If it is locked onto the fixture, the polymer chains and the crystalline-amorphous system reorganize under the imposed geometric constraint, which allows a smaller deviation to be fixed along the critical axis [8], [15].

In the studied process organization, the injection cycle time was 70 s, and the number of stabilizing stations was 15 [16]. The retention time of the part on the fixture can therefore be calculated as the product of the number of stations and the cycle time:

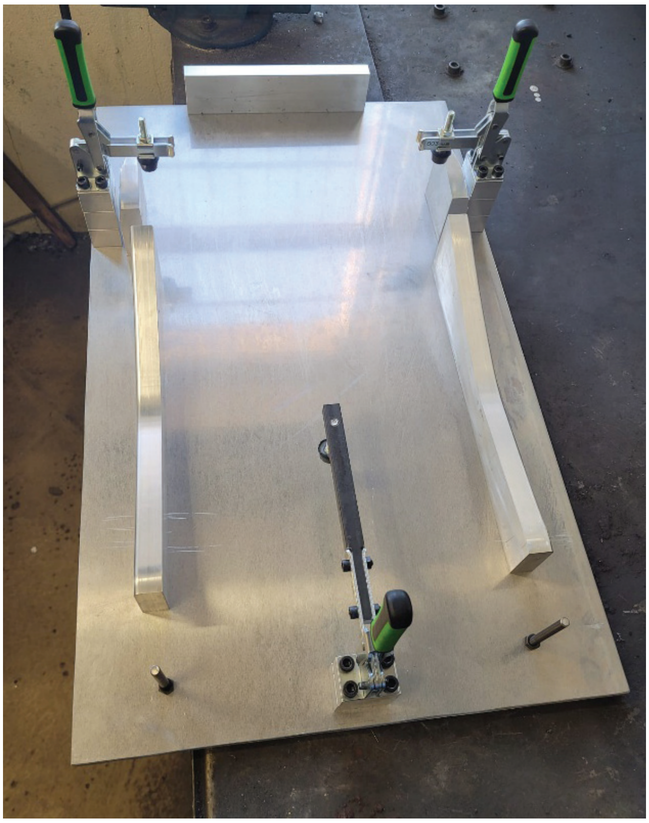


Fig. 1 General view of the stabilizing fixture for the seat back cover post-injection molding (source: own work)

$$15 \times 70s = 1050s = 17{,}5 \ min$$

This is a technologically significant duration because it encompasses the initial phase of cooling outside the mold, during which the post-molding shrinkage of PP occurs most intensively [8]. At the same time, the arrangement of 15 fixtures allows stabilization to be synchronized with mass production without stopping the injection molding machine [1], [15].

Dimensional Evaluation Methodology

The evaluation of the fixtures' effectiveness was based on comparing molding deviations against the nominal reference geometry for which the mold and part assembly were designed [15]. The source outline indicates the use of overall dimensional measurements and 3D scan analysis with reference to the CAD model [4], [15]. The moldings selected for dimensional measurements were chosen randomly. For each material variant, the state after standard cooling was compared with the state after retention on the fixture

Fig. 2 Method of mounting the molding on the fixture and orientation of the X/Y axes relative to the melt flow direction (source: own work)

Fig. 3 Support and locking points for the part width along the Y-axis (source: own work

[10]. Significance was assigned to two directions: The X-axis, parallel to the dominant melt flow direction and the Y-axis, transverse to this direction [9], [10].

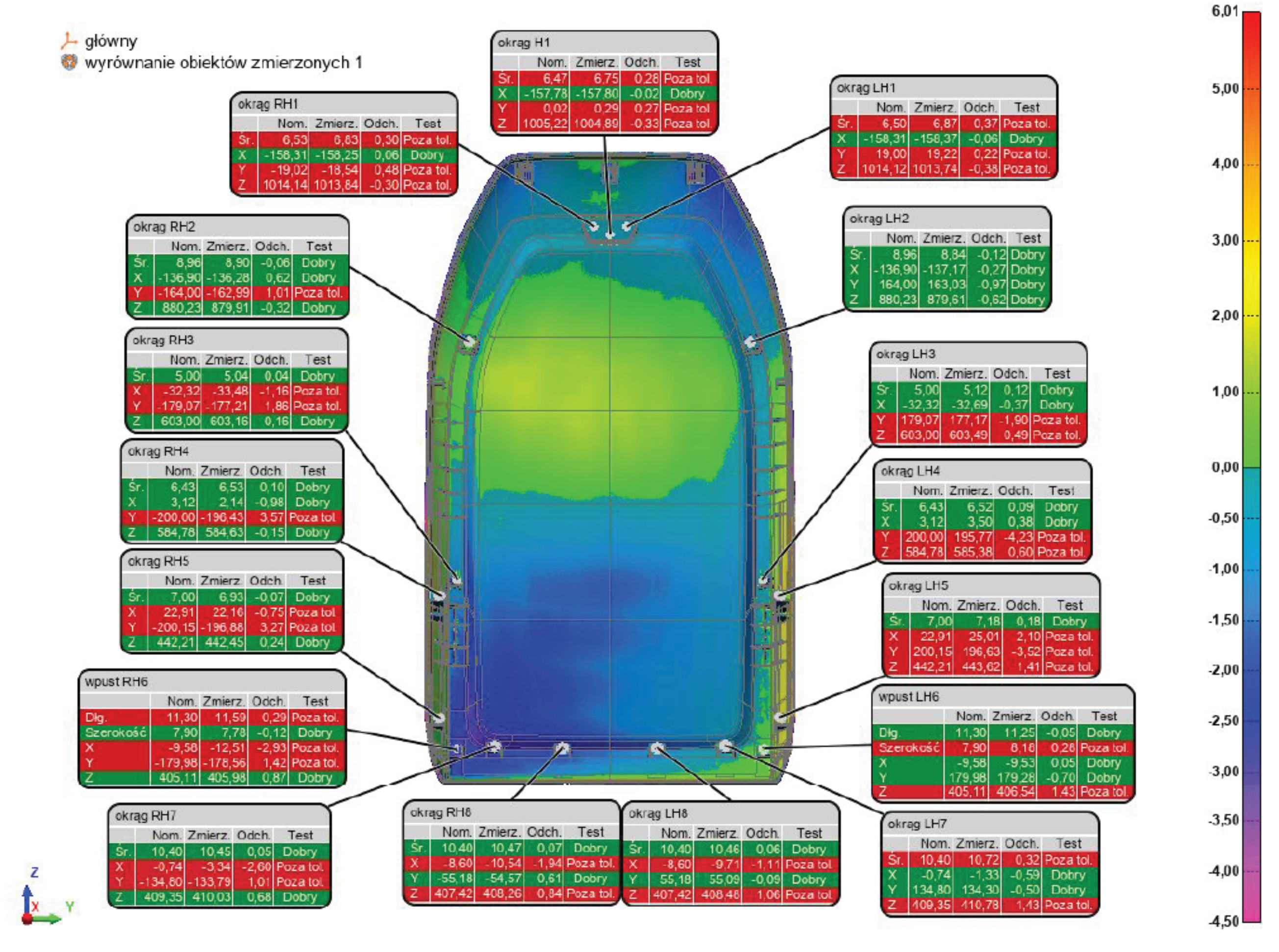
The reported results represent averaged dimensional deviations obtained from 3D scans of two PP covers. The measurements were carried out after one week of conditioning, during which the covers were stored in cardboard boxes under room conditions. Therefore, the results should be interpreted as dimensions after post-molding stabilization rather than as immediate post-ejection values. The results were interpreted not only as numerical shrinkage values but also as the response of the material–process–fixture system [15]. A reduction of the deviation in the Y-axis demonstrates the direct effectiveness of the fixture, whereas the persistent shrinkage in the X-axis indicates the design limitations of the fixture and the necessity to leverage the properties of the material itself [10], [14]. Such an approach is particularly important when comparing Scolefin and Inspire, as both materials feature different filler morphologies and distinct shrinkage anisotropy [9], [11].

Results

Figure 4 presents the dimensional deviations of the moldings in millimetres. The largest transverse shrinkage without the fixture was recorded for Inspire TF1305 + 3% Engage, where the value along the Y-axis was −9.70 mm. After applying the fixture, the deviation decreased to −2.80 mm, which represents a significant improvement and a drop below the specified 3 mm threshold. Simultaneously, the shrinkage of the same material along the X-axis remained high, shifting only from −5.80 mm to −5.00 mm. This result demonstrates that the fixture operated effectively on the width but did not resolve the problem of length or the direction parallel to the flow.

A different distribution of changes is observed for Scolefin. The variant with the fixture achieved a transverse deviation of approximately −0.90 mm, which is a highly favourable result regarding the part width. Simultaneously, the deviation along the X-axis was +0.50 mm, which from an assembly standpoint is significantly less problematic than the multi-millimetre longitudinal shrinkage observed for Inspire. This behaviour is consistent with the operating mechanism of oriented glass fibres: the fixture assumes control over the Y-axis, while the fibres restrict shrinkage along the X-axis.

Figure 5 presents analogous data in the form of percentage shrinkage. The percentage values clearly illustrate the difference between the materials: the Inspire + 3% Engage variant without the fixture reached 2.26% transverse shrinkage, and 0.65% with the fixture, whereas along the longitudinal axis, the values



okrąg H1

	Nom.	Zmierz.	Odch.	Test
Śr.	6,47	6,75	0,28	Poza tol.
X	-157,78	-157,80	-0,02	Dobry
Y	0,02	0,29	0,27	Poza tol.
Z	1005,22	1004,89	-0,33	Poza tol.

okrąg RH1

	Nom.	Zmierz.	Odch.	Test
Śr.	6,53	6,83	0,30	Poza tol.
X	-158,31	-158,25	0,06	Dobry
Y	-19,02	-18,54	0,48	Poza tol.
Z	1014,14	1013,84	-0,30	Poza tol.

okrąg LH1

	Nom.	Zmierz.	Odch.	Test
Śr.	6,50	6,87	0,37	Poza tol.
X	-158,31	-158,37	-0,06	Dobry
Y	19,00	19,22	0,22	Poza tol.
Z	1014,12	1013,74	-0,38	Poza tol.

okrąg RH2

	Nom.	Zmierz.	Odch.	Test
Śr.	8,96	8,90	-0,06	Dobry
X	-136,90	-136,28	0,62	Dobry
Y	-164,00	-162,99	1,01	Poza tol.
Z	880,23	879,91	-0,32	Dobry

okrąg LH2

	Nom.	Zmierz.	Odch.	Test
Śr.	8,96	8,84	-0,12	Dobry
X	-136,90	-137,17	-0,27	Dobry
Y	164,00	163,03	-0,97	Dobry
Z	880,23	879,61	-0,62	Dobry

okrąg RH3

	Nom.	Zmierz.	Odch.	Test
Śr.	5,00	5,04	0,04	Dobry
X	-32,32	-33,48	-1,16	Poza tol.
Y	-179,07	-177,21	1,86	Poza tol.
Z	603,00	603,16	0,16	Dobry

okrąg LH3

	Nom.	Zmierz.	Odch.	Test
Śr.	5,00	5,12	0,12	Dobry
X	-32,32	-32,69	-0,37	Dobry
Y	179,07	177,17	-1,90	Poza tol.
Z	603,00	603,49	0,49	Poza tol.

okrąg RH4

	Nom.	Zmierz.	Odch.	Test
Śr.	6,43	6,53	0,10	Dobry
X	3,12	2,14	-0,98	Dobry
Y	-200,00	-196,43	3,57	Poza tol.
Z	584,78	584,63	-0,15	Dobry

okrąg LH4

	Nom.	Zmierz.	Odch.	Test
Śr.	6,43	6,52	0,09	Dobry
X	3,12	3,50	0,38	Dobry
Y	200,00	195,77	-4,23	Poza tol.
Z	584,78	585,38	0,60	Poza tol.

okrąg RH5

	Nom.	Zmierz.	Odch.	Test
Śr.	7,00	6,93	-0,07	Dobry
X	22,91	22,16	-0,75	Poza tol.
Y	-200,15	-196,88	3,27	Poza tol.
Z	442,21	442,45	0,24	Dobry

okrąg LH5

	Nom.	Zmierz.	Odch.	Test
Śr.	7,00	7,18	0,18	Dobry
X	22,91	25,01	2,10	Poza tol.
Y	200,15	196,63	-3,52	Poza tol.
Z	442,21	443,62	1,41	Poza tol.

wpust RH6

	Nom.	Zmierz.	Odch.	Test
Dłg.	11,30	11,59	0,29	Poza tol.
Szerokość	7,90	7,78	-0,12	Dobry
X	-9,58	-12,51	-2,93	Poza tol.
Y	-179,98	-178,56	1,42	Poza tol.
Z	405,11	405,98	0,87	Dobry

wpust LH6

	Nom.	Zmierz.	Odch.	Test
Dłg.	11,30	11,25	-0,05	Dobry
Szerokość	7,90	8,18	0,28	Poza tol.
X	-9,58	-9,53	0,05	Dobry
Y	179,98	179,28	-0,70	Dobry
Z	405,11	406,54	1,43	Poza tol.

okrąg RH7

	Nom.	Zmierz.	Odch.	Test
Śr.	10,40	10,45	0,05	Dobry
X	-0,74	-3,34	-2,60	Poza tol.
Y	-134,80	-133,79	1,01	Poza tol.
Z	409,35	410,03	0,68	Dobry

okrąg RH8

	Nom.	Zmierz.	Odch.	Test
Śr.	10,40	10,47	0,07	Dobry
X	-8,60	-10,54	-1,94	Poza tol.
Y	-55,18	-54,57	0,61	Dobry
Z	407,42	408,26	0,84	Poza tol.

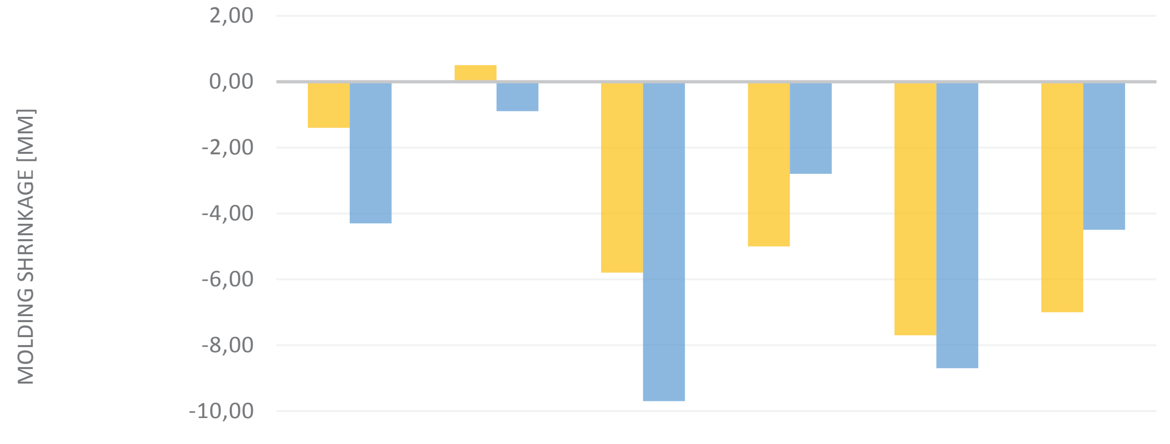
okrąg LH8

	Nom.	Zmierz.	Odch.	Test
Śr.	10,40	10,46	0,06	Dobry
X	-8,60	-9,71	-1,11	Poza tol.
Y	55,18	55,09	-0,09	Dobry
Z	407,42	408,48	1,06	Poza tol.

okrąg LH7

	Nom.	Zmierz.	Odch.	Test
Śr.	10,40	10,72	0,32	Poza tol.
X	-0,74	-1,33	-0,59	Dobry
Y	134,80	134,30	-0,50	Dobry
Z	409,35	410,78	1,43	Poza tol.

Fig. 4 3D scan of plastic cover made from Inspire TF 1305+ 3% Engage (source: own work)



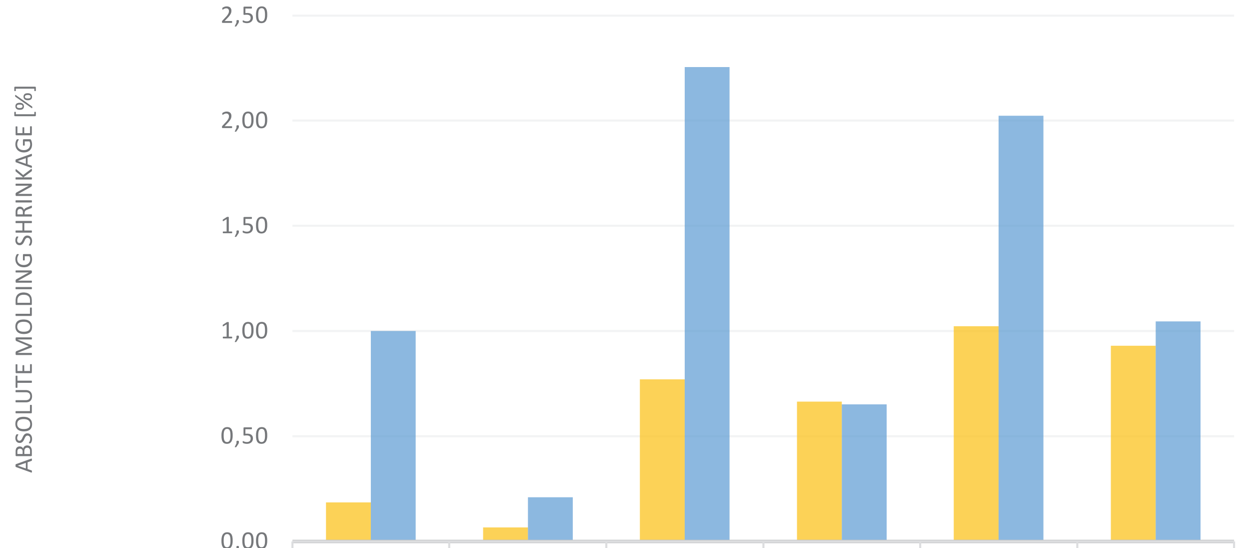
	Scolefin 62G 22-0 FR (40)	Scolefin 62G 22-0 FR (40) + cooling jig	Inspire TF1305 + 3% Engage	Inspire TF1305 + 3% Engage + cooling jig	Inspire TF1305 + 3& Engage +3% fireblocker	Inspire TF1305 + 3& Engage +3% fireblocker + cooling jig
🟨 Longitudinal shrinkage	-1,40	0,50	-5,80	-5,00	-7,70	-7,00
🟦 Transverse shrinkage	-4,30	-0,90	-9,70	-2,80	-8,70	-4,50

Fig. 5 Dimensional change along X and Y axes for PP materials under different conditioning methods

remained 0.77% and 0.66%, respectively. The Inspire variant with the flame retardant also improved along the Y-axis after using the fixture, but the result of 1.05% remains higher than for the variant without the flame retardant and distinctly higher than for the modified Scolefin with the fixture.

Discussion

The most important conclusion from the measurements is the directionality of the fixture's operation. Post-injection stabilization primarily restricted shrinkage along the Y-axis, i.e., transverse to the material



	Scolefin 62G 22-0 FR (40)	Scolefin 62G 22-0 FR (40) + cooling jig	Inspire TF1305 + 3% Engage	Inspire TF1305 + 3% Engage + cooling jig	Inspire TF1305 + 3& Engage +3% fireblocker	Inspire TF1305 + 3& Engage +3% fireblocker + cooling jig
🟨 Longitudinal shrinkage	0,19	0,07	0,77	0,66	1,02	0,93
🟦 Transverse shrinkage	1,00	0,21	2,26	0,65	2,02	1,05

Fig. 6 Percentage shrinkage along the X and Y axes for PP materials under different conditioning methods

flow direction [10], [15]. For both material families, a significant improvement in width was achieved, yet the final effect differed. Thanks to the glass fiber, Scolefin already possessed an internal blocking mechanism for the X-axis, and the fixture supplemented it along the Y-axis [9], [14]. Inspire, owing to the talc, achieved improvement along the Y-axis but lacked a similar mechanical constraint along the X-axis; hence, longitudinal shrinkage remained significant [9], [11].

The difference between Scolefin and Inspire should not be interpreted solely as a difference in total shrinkage values, but rather as a difference in anisotropy. Once oriented in the flow, glass fibre possesses very high longitudinal stiffness and transfers matrix stresses, thereby inhibiting dimensional change along the flow axis [14], [15]. Talc, as a platy and nucleating filler, improves stiffness and influences crystalline morphology, but it does not form continuous reinforcement along the X-axis [11]. Consequently, the talc-filled material may exhibit a lower tendency toward certain types of anisotropy than the fibrous composite, but in the analysed geometry, it did not provide sufficient compensation for longitudinal shrinkage [9].

The Inspire + Engage variant further confirms that improving impact strength can work against dimensional stability [12]. The elastomer increases the material's capacity for deformation and energy absorption, but it lowers the effective modulus of the composite and increases the system's susceptibility to dimensional changes during cooling [12], [14]. Therefore, despite a highly effective reduction in transverse shrinkage after using the fixture, shrinkage along the X-axis remained at a level of approximately −5 mm [8]. From the standpoint of assembling snap-fits into the seat frame slots, this implies a potential risk of misalignment in the direction that the current version of the fixture did not control [14].

The variant with the flame retardant indicates that additional functional modifications can impair shrinkage predictability. After the fixture, the Inspire + Engage + 3% flame retardant variant reached −4.50 mm along the Y-axis, which is a worse result than the variant without the flame retardant [13]. Possible causes include changes in the viscosity and thermal conductivity of the compound, additional centres of heterogeneity, and a different stress distribution within the matrix [13]. This does not imply a lack of effectiveness of the flame retardant in its fire-retarding function, but rather demonstrates that its introduction requires re-optimization of the cooling process and geometric retention [15], [16].

The warpage observed after applying the fixture is a logical consequence of blocking unconstrained shrinkage. While the fixture improves the critical dimension, it simultaneously generates local stresses, the relaxation of which can manifest as lateral deflection or saddle-like deformation [10], [15]. In the case of thin-walled geometry, even a minor difference in wall thickness, local temperature, or filler orientation can cause the gain in one dimension to be partially offset by a shape deviation in another area [4], [16]. Therefore, the fixture should not be treated as a universal „freezing" of geometry, but rather as a tool for selective deformation control [15].

From the perspective of further optimization, the most justified approach is to separate the strategies for fibrous and talc-filled materials. For Scolefin, the primary task is to refine the support points along the Y-axis and limit local warpage, as the X-axis is naturally stabilized by the oriented fibres [9], [15]. For Inspire, however, it is necessary to consider a biaxially operating fixture: one that not only locks the width but also gently stretches or positions the part along the flow axis [11], [15]. Such a modification, however, could increase the risk of warpage, and would therefore require an iterative selection of mounting points and retention times [10], [15].

Conclusions

Replacing amorphous PC/ABS with a semi-crystalline PP-based plastic without reconstructing the injection mold is only possible through the simultaneous control of the material, process, and post-process conditioning. Modifying PP with fillers alone reduces shrinkage but does not eliminate the problem of anisotropy or post-molding shrinkage. The cooling fixture exploits the fact that immediately after ejection from the mold, the molding remains susceptible to viscoelastic relaxation and secondary crystallization, allowing the imposed geometry to be partially fixed.

The best synergy with the fixture was achieved by the glass-fibre-reinforced Scolefin composite. The fibre orientation along the flow direction restricted shrinkage along the X-axis, while the fixture reduced shrinkage along the Y-axis. As a result, the modified variant with the fixture achieved a very small transverse deviation of approximately −0.90 mm and a favourable longitudinal outcome. This is the material-process system best suited for a fixture operating primarily transverse to the flow.

The talc-filled Inspire TF1305 material with the addition of Engage requires a different approach. The fixture lowered the transverse shrinkage from −9.70 mm to −2.80 mm, thus fulfilling the primary goal of stabilization along the Y-axis, but the longitudinal shrinkage remained high at approximately −5.00 mm. The reason for this is the lack of mechanical reinforcement along the flow axis comparable to glass fibre. Talc acts as a platy filler and a nucleating agent, but it does not sufficiently compensate for shrinkage parallel to the flow within the analysed geometry.

In subsequent steps, it is recommended to develop a biaxial fixture for talc-filled materials and to conduct a controlled design of experiments encompassing retention time, part temperature during mounting on the fixture, the number and location of support points, and the effect of flame-retardant additives. Simultaneously, not only linear shrinkage should be monitored, but also the warpage of lateral surfaces and the position of mounting points. The ultimate optimization should combine 3D scanning, stress or deformation measurements after conditioning, and an evaluation of assembly capability onto the steel seat frame.

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