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BEHAVIOR OF 3D-PRINTED FILAFLEX FOAMY TPU FOR DIFFERENT EXTRUSION TEMPERATURE, FLOW RATE AND NOZZLE DIAMETER CONFIGURATIONS

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Abstract: *This paper investigated the processing behavior of Filaflex Foamy, an expandable thermoplastic polyurethane (TPU) filament with a thermally activated foaming agent, processed by Material Extrusion (MEX) process. The study analyzed the influence of extrusion temperature, flow rate factor and nozzle diameter on the dimensional accuracy, apparent density and Shore A hardness of 3D-printed cuboid samples. Filaflex Foamy was investigated in two experimental stages. In the first stage, samples were printed with a 0.4 mm nozzle at extrusion temperatures of 230 °C, 240 °C and 250 °C and flow rate factors of 0.8, 0.9 and 1.0. In the second stage, the influence of nozzle diameter was analyzed at 240 °C using 0.4 mm, 0.6 mm and 0.8 mm nozzles. The results showed that Shore A hardness was strongly associated with the apparent density and flow rate factor, while the extrusion temperature had a secondary effect within the investigated range. The dimensional deviation along the build direction showed a dependence on both extrusion temperature and flow rate factor. At low flow rate factors, the samples' height remained below the nominal value, and at a flow rate factor of 1.0, positive values were obtained, especially at higher extrusion temperature. The nozzle diameter also influenced the dimensional response, but the effect showed no clear trend. varioShore TPU data were used as a reference. The comparison showed that the two expandable TPU materials presented different density-hardness responses, with varioShore TPU reaching higher Shore A hardness values at lower apparent density levels. The results also indicated that expandable TPU filaments require material-specific calibration as the processing window cannot be directly transferred from one filament system to another.*

Key words: *foaming agent filaments, Filaflex Foamy, varioShore, apparent density, Shore A, extrusion temperature, flow rate, nozzle diameter.*

1. INTRODUCTION [1]

The continuous development of 3D printing-based applications is supported not just by improvements in the equipment performance and cost reduction [1], but also by the advent of new filament materials with properties that extend the capabilities of the Material Extrusion (MEX) process [2]. Commonly used materials for MEX process include thermoplastics such as PLA (polylactic acid), PETG (polyethylene terephthalate glycol-modified), ABS (acrylonitrile butadiene styrene), etc., used for prototyping, functional parts and general purpose applications [3]. There are also the flexible thermoplastic elastomers such as TPU (thermoplastic polyurethane) and TPE (thermoplastic elastomers), which can enable the production of parts requiring deformability or compliance [4, 5], while in recent years, functional and modified filaments were developed with the purpose of further extending the range of applications [6, 7]. Composite filaments reinforced with fibers or particles improve the stiffness, strength, dimensional stability or thermal behavior [8]. Conductive filaments allow the fabrication of electrically functional parts, sensors or simple circuit elements [9-10]. Metal-filled and ceramic-filled filaments offer higher density, specific surface appearance or post-processing possibilities, while multi-material or blended systems [11], such as PLA-TPU based combinations, are used to obtain intermediate mechanical behavior between rigidity and flexibility [12]. Research conducted on these materials showed that the performance of MEX parts is controlled not only by the geometry and process parameters, but also by the functional design of the filament itself.

A more recent development is represented by filaments with thermally activated foaming agents [13, 14] that allow the modification of density, hardness and mechanical response of 3D-printed parts by settings of process parameters such as extrusion temperature, flow rate factor, printing speed or cooling conditions [13, 15]. In the case of expandable/foamed TPU filaments, this capability is especially relevant for applications that require lightweight structures, softness tuning, cushioning and comfort-oriented performance [16].

In a recent review, Nofar et al. [17] noted the studies performed to generate cellular structures by 3D printing for such applications using solutions like in-situ foaming of filaments containing blowing agents or post-foaming

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of printed parts. Among these, the use of filaments containing blowing agents is one of the most practical solutions, which is however insufficiently studied considering the complexity given by the material and the adjustment process based on 3D printing parameters, and the interaction between them. Thus, before such filaments can be reliably used in application-oriented products, their process-response behavior should be understood under controlled printing conditions. This is particularly important as changes in extrusion temperature, flow rate factor or nozzle diameter may simultaneously affect material deposition, expansion-related dimensional response, apparent density and local hardness. Therefore, a calibration based approach is required in order to identify processing windows that provide predictable density and hardness levels while maintaining acceptable dimensional accuracy.

In this context, the present study investigated the processing behavior of Filaflex Foamy, an expandable TPU filament containing a thermally activated foaming agent. The influence of extrusion temperature, flow rate factor and nozzle diameter on dimensional response, apparent density and Shore A hardness were evaluated. In addition, varioShore TPU data were used as a comparative reference in order to position the behavior of Filaflex Foamy within the broader category of expandable TPU materials processed by MEX.

2. MATERIALS AND METHOD

In this study, the research methodology included conducting tests on Filaflex Foamy (Recreus, [18]), followed by a comparative results analysis using varioShore TPU (ColorFabb, [19]) data, also experimentally determined. Filaflex Foamy was investigated in two stages: a temperature-flow study, and a nozzle diameter study. For all analyzed parameters' configurations, the dimensional accuracy, apparent density and Shore A hardness were evaluated.

2.1. Materials

As mentioned, two materials were used in this research, both in the category of TPU filaments with thermally activated foaming agents, namely Filaflex Foamy and varioShore. According to producers' data, Filaflex Foamy has a nominal density of approximately 1.12 g/cm³ in its non-expanded state [18], while varioShore TPU has a nominal density of approximately 1.2 g/cm³ in the base, non-foamed state [19]. Prior to 3D printing, both filaments were dried for 4 h (Sunlu S2 filament dryer) in order to reduce moisture-related variability. The focus of the research was the study of the process parameters influence over Filaflex Foamy samples characteristics, while varioShore, previously investigated [14, 20], was used for comparison.

2.2. Filaflex Foamy sample preparation and 3D printing

All samples had a cuboid shape (30 mm x 30 mm x 10 mm), and were 3D printed with the base in the xy plane and the height along the z direction, on Original Prusa MK3.5S 3D printer equipped with E3D Revo extruder. Based on prior works [20, 21], the flexibility of TPU required the adjustment of the extruder gear tension to ensure stable and consistent material feeding.

Table 1 presents the values of the process parameters used in 3D printing the Filaflex Foamy samples, both the parameters kept constant during the tests, and the varied parameters: nozzle diameter, extrusion temperature and flow rate. The reference configuration of nozzle diameter was 0.4 mm. However, for further assessing the influence of deposition geometry, additional samples were produced with larger nozzle diameters, respectively 0.6 mm and 0.8 mm diameter. The research was conducted in two experimental stages: I. temperature-flow study in which the parameters values were: nozzle diameter: 0.4 mm; temperature: 230 °C, 240 °C, 250 °C; flow rate: 0.8, 0.9, 1.0, and II. nozzle diameter study, in which the parameters were: temperature: 240 °C; nozzle diameter: 0.4, 0.6, 0.8 mm; flow rate: 0.8, 0.9, 1.0.

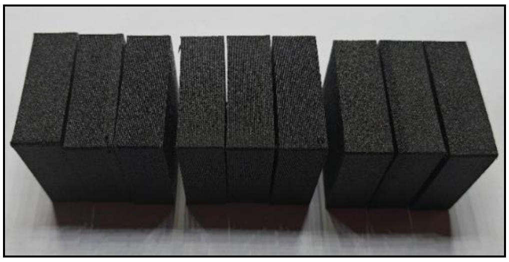
Figure 1 shows representative Filaflex Foamy samples obtained using the investigated configurations.

Table 1

Experimental parameters used in the study

<table>
<tr><th>Fixed parameters</th><th>Experimental stages</th></tr>
<tr><td rowspan="4">Bed temperature: 40 °C
Printing speed: 35 mm/s
Fan speed: 0%
Layer height: 0.2 mm
Infill: 100%
Perimeters: 3
Extrusion width: 0.45 mm for 0.4 mm nozzle; 0.65 mm for 0.6 mm nozzle; 0.85 mm for 0.8 mm nozzle</td><td>Stage I: temperature-flow study</td></tr>
<tr><td>Nozzle diameter: 0.4 mm
Extrusion temperature: 230 °C, 240 °C, 250 °C
Flow rate factor: 0.8, 0.9, 1.0</td></tr>
<tr><td>Stage II: nozzle diameter study</td></tr>
<tr><td>Extrusion temperature: 240 °C
Nozzle diameter: 0.4 mm, 0.6 mm, 0.8 mm
Flow rate factor: 0.8, 0.9, 1.0</td></tr>
</table>

a



b

Fig. 1. Foamy TPU samples printed in different processing conditions.

Figure 1a presents the samples 3D-printed with the reference 0.4 mm nozzle during the temperature-flow study, while in Fig. 1b, the side surface morphology and the layered structure of the 3D-printed specimens are shown. The visual inspection of the samples indicated the existence of differences in the surface appearance associated with the selected processing conditions.

2.3. VarioShore TPU comparative data set

As mentioned, varioShore TPU was included in this study as a comparative reference in order to position the behavior of Filaflex Foamy within the category of expandable TPU filaments. The comparison was not based on similar flow rate factor values for the two materials, but on the processing windows and calibration conditions set for each material.

The comparative data set included previously obtained results for varioShore TPU specimens produced at 240 °C using a 0.6 mm nozzle [21]. These data were selected because they allowed a direct comparison with Filaflex Foamy processed under the same extrusion temperature and nozzle diameter. Another subset of data was used to analyze the influence of nozzle diameter on the dimensional and hardness response of varioShore TPU. Thus, varioShore specimens were 3D-printed at 240 °C using 0.4 mm, 0.6 mm and 0.8 mm nozzle diameters (Fig. 2). For each nozzle diameter, flow rate factor values of 0.60, 0.65 and 0.70 were tested based on the dimensional calibration range previously determined [21].

varioShore resulting specimens were evaluated in terms of dimensional response, apparent density and Shore A hardness, in a similar manner as for Filaflex Foamy specimens.

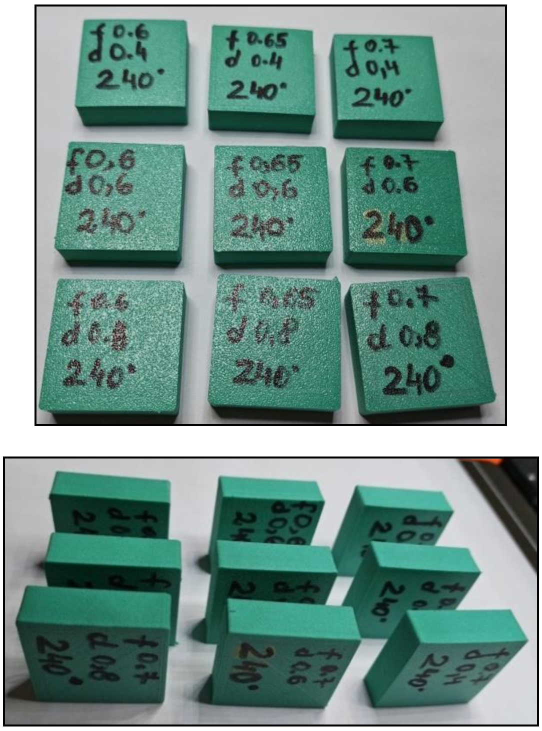


Fig.2. varioShore samples, 3D-printed in different parameters' configurations.

2.4. 3D-printed samples characterization

The dimensions of the Filaflex Foamy samples were measured to determine their actual volume. Samples' length and width were measured with a digital caliper (resolution of 0.01 mm), as shown in Fig. 3a, while the height was measured with a micrometer (resolution of 0.01 mm) by applying minimum contact pressure, as shown in Fig. 3b, in order to avoid the local compression of the foamed TPU structure, and to improve the measurement accuracy along the build direction where dimensional variations caused by foaming were expected to be more pronounced. For each sample, the length and width were measured at five positions, while height was measured at seven positions distributed over the top surface. All measurements were performed after the samples had cooled to the room temperature.

The dimensional deviation along z direction, ΔH, was calculated as the difference between the mean measured height and the nominal height defined in the CAD model (Eq. 1).

$$\Delta H = \frac{H_{measured} - H_{nominal}}{H_{nominal}} * 100, \qquad (1)$$

For each sample, repeated measurements were performed for the relevant dimensions, and the mean values were used to calculate the actual volume. The apparent density (ρ_{app}) was then calculated as the ratio between the measured mass (m) and the actual sample volume (V_{actual}), Eq. 2.

$$\rho_{app} = \frac{m}{V_{actual}}. \qquad (2)$$

a

b

Fig. 3. Measurement process: (a) sample dimensions (length and width) using a digital caliper (230 °C, 0.8 flow material); (b) along the build direction (230 °C, 0.8 flow rate factor).

Fig. 4. Shore A hardness measurement of the printed samples (230 °C, 0.8 flow rate factor).

The hardness of the specimens was evaluated using a Shore A durometer (Digital Shore Durometer Sclerometer, China), applied to the printed samples as shown in Fig. 4. According to ISO 7619-1:2004 [22], the hardness value was recorded after 3 s to ensure consistent measurements, as it is known that the initial response decrease during the first seconds after indentation.

For each sample, five Shore A measurements were performed at different positions on the top surface, the sample edges being avoided. The mean value was used for analysis. The same characterization procedure was applied to the Filaflex Foamy and varioShore TPU samples.

3. RESULTS AND DISCUSSION

3.1. Density-hardness relationship and foaming behavior

For Filaflex Foamy, the relationship between the Shore A hardness and the apparent density was approximately linear for all tested extrusion temperature (Fig. 5). Thus the apparent density can be strongly associated with the hardness variation of the 3D-printed samples. However, there are different slopes obtained for the three extrusion temperatures, which shows that the density-hardness relationship is not identical for all processing conditions. This indicates that the apparent density is a useful descriptor of the hardness response, but it does not fully describe the effect of extrusion temperature.

The highest slope was obtained at 240 °C (yellow line in Fig. 5), suggesting that, within the investigated range, Shore A hardness was more sensitive to changes in apparent density at this temperature. At 230 °C (blue line in Fig. 5) and 250 °C (orange line in Fig. 5), the lower slopes indicate a weaker hardness variation for comparable changes in apparent density. Therefore, the hardness response of Filaflex Foamy should be interpreted as the result of the apparent density and the extrusion temperature, rather than the density alone.

To further analyze the influence of process parameters, Fig. 6 presents the variation of Shore A hardness as a function of extrusion temperature and flow rate factor for Filaflex Foamy samples 3D-printed with the 0.4 mm nozzle. The results showed a clear raise in hardness with increasing flow rate factor, from 0.8 to 1.0, for all tested extrusion temperatures. This trend was consistent with the corresponding increase in apparent density observed for the same samples, indicating that the flow rate factor strongly affects the hardness response through its influence on material deposition and apparent density.

In comparison, the effect of extrusion temperature was less pronounced for the investigated values. For the same flow rate factor, the hardness values varied only slightly between 230 °C, 240°C and 250 °C extrusion temperatures, without a strictly monotonic trend. Therefore, in the tested conditions, Shore A hardness was mainly associated with flow rate factor and apparent

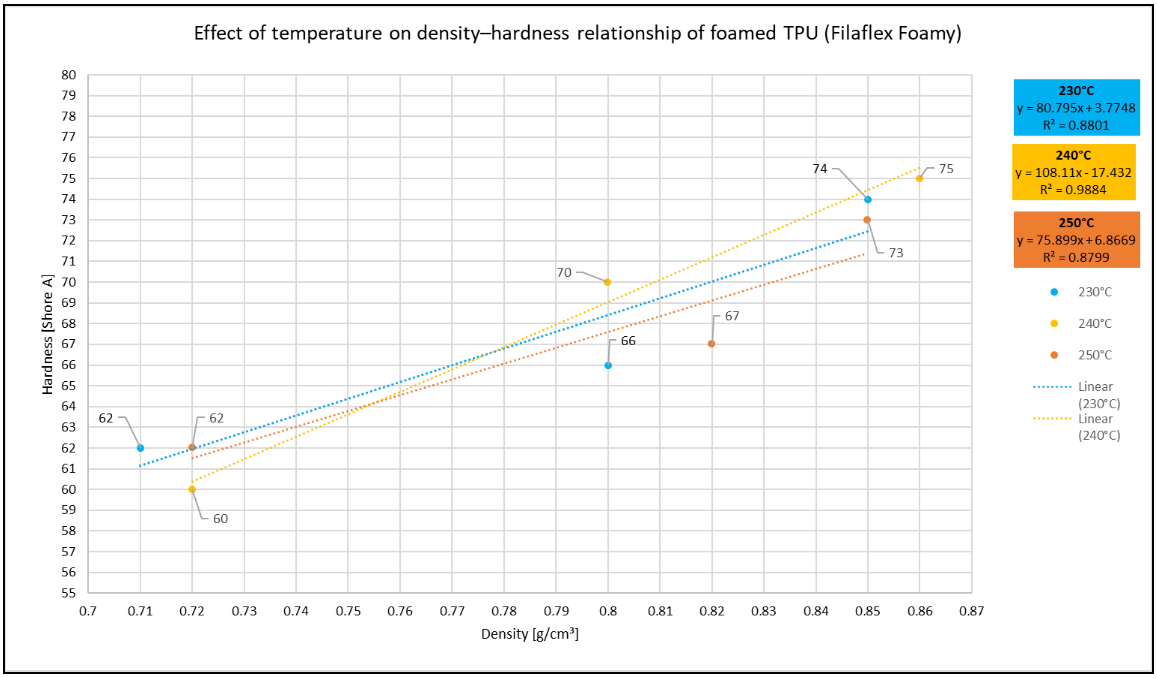


Fig. 5. Apparent density-hardness relationship of Filaflex Foamy at different extrusion temperatures.

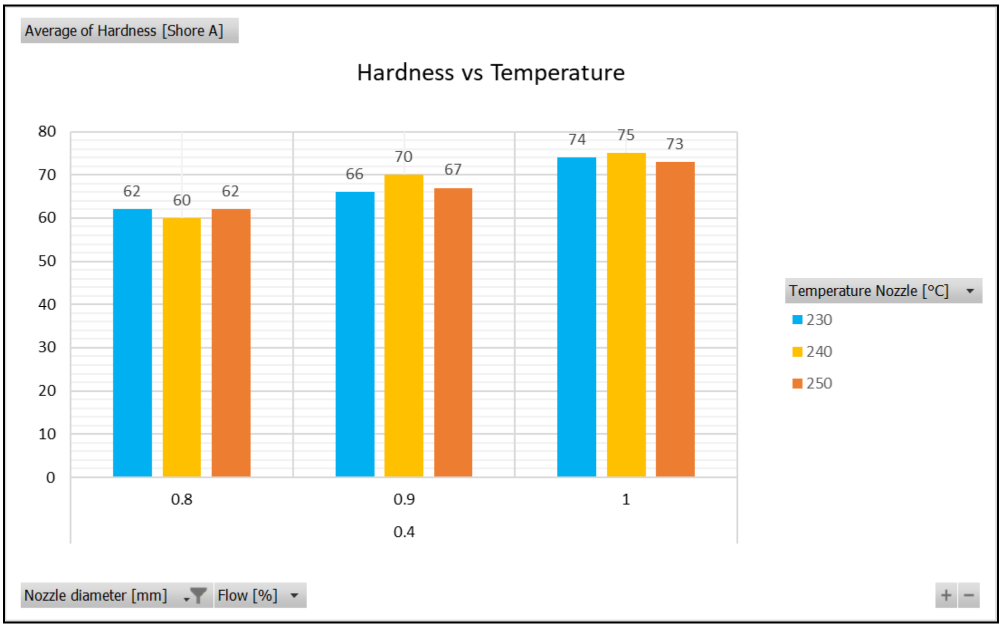


Fig. 6. Effect of extrusion temperature and flow rate factor on Shore A hardness of Filaflex Foamy samples printed with a 0.4.mm nozzle.

density, while extrusion temperature had a secondary effect.

These observations are consistent with the general behavior previously reported for expandable TPU materials processed by MEX [14, 20-21, 23], where process parameters were shown to affect hardness, density-related behavior and mechanical response. However, the present analysis is specific to Filaflex Foamy and it should not be directly extrapolated to other expandable TPU filaments without considering material-specific calibration conditions.

3.2. Dimensional deviation and expansion behavior

Besides the apparent density and hardness, the dimensional deviation along the build direction (ΔH) was evaluated to assess the expansion behavior, using Eq. (1). The measured dimensions of the samples in the *x*, *y*, and *z* directions are presented in Table 2. Variations were noted for all directions, indicating that both material expansion and deposition-related factors influenced the final geometry of the 3D-printed parts. Deviations in the xy plane were affected by extrusion width, bead spreading and deposition path. In comparison, the dimensional deviation along z direction was more directly related to layer-by-layer addition and expansion along the build direction. Therefore, ΔH was used as the representative parameter for evaluating the vertical dimensional response of the material.

To provide an overview of the expansion-related dimensional response, a heat map (Fig. 7) was generated for the 0.4 mm nozzle data set, using extrusion temperature and flow rate factor as input variables and ΔH as the response variable. The heat map was used as a descriptive visualization tool in order to identify the

Table 2

Measured dimensions of Filaflex Foamy samples for different processing conditions and nozzle diameters

Item	Nozzle diameter [mm]	Extrusion temperature [°C]	Flow rate factor	Length [mm]	Width [mm]	Height [mm]	ΔH [%]
1	0.4	230	0.8	29.63	29.64	9.97	–0.3
2	0.4	230	0.9	29.75	29.7	9.99	–0.1
3	0.4	230	1	30.01	29.92	10.01	+0.1
4	0.4	240	0.8	29.58	29.6	9.86	–1.4
5	0.4	240	0.9	29.88	29.82	9.94	–0.6
6	0.4	240	1	30.08	30.1	10.11	+1.1
7	0.4	250	0.8	29.59	29.65	9.81	–1.9
8	0.4	250	0.9	29.65	29.58	9.82	–1.8
9	0.4	250	1	30.07	29.97	10.21	+2.1
10	0.6	240	0.8	29.53	29.64	9.68	–3.2
11	0.6	240	0.9	29.86	29.9	9.95	–0.5
12	0.6	240	1	30.03	30.02	10	0.0
13	0.8	240	0.8	29.63	29.66	9.84	–1.6
14	0.8	240	0.9	29.81	29.88	9.96	–0.4
15	0.8	240	1	30.06	30.01	10.04	+0.4

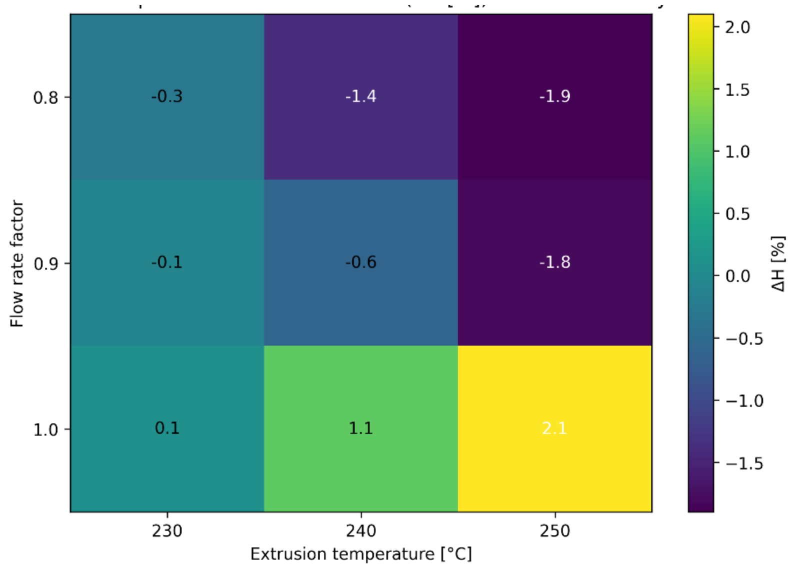


Fig. 7. Heat map of ΔH [%] of Filaflex Foamy as a function of extrusion temperature and flow rate factor.

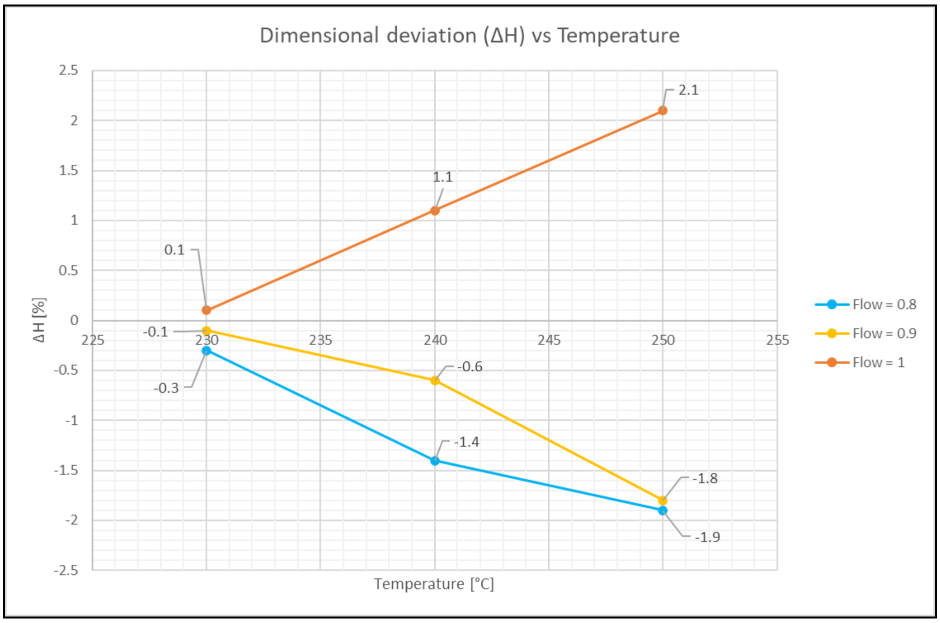


Fig. 8. Effect of extrusion temperature and flow rate factor on ΔH for Filaflex Foamy samples printed with a 0.4 mm nozzle.

processing combinations associated with negative or positive deviation along the build direction.

As shown in Fig. 7, ΔH depended on the combined effect of extrusion temperature and flow rate factor. At flow rate factors of 0.8 and 0.9, all ΔH values remained negative, indicating that the measured height was lower than the nominal height over the investigated temperature range. By comparison, at a flow rate factor of 1.0, ΔH became positive and increased with extrusion temperature, from +0.1% at 230 °C to +2.1% at 250 °C. The heat map also shows that the strongest contrast between negative and positive ΔH values occurred at 250 °C, where the dimensional response became more sensitive to the selected flow rate factor.

The same trend is also represented in Fig. 8, where ΔH is represented as a function of extrusion temperature for the samples printed with the 0.4 mm nozzle. This representation confirmed that the transition from negative to positive ΔH cannot be attributed to extrusion temperature alone, but it should be interpreted as the result of the combined effect of extrusion temperature and flow rate factor.

From Fig. 8 it could be also noted that at 250 °C, the difference between flow rate factors is more pronounced. At flow rate factors of 0.8 and 0.9, ΔH was negative for the investigated temperatures, showing that the measured height was lower than the nominal height. At a flow rate factor of 1.0, ΔH became positive and increased with extrusion temperature, from +0.1% at 230 °C to +2.1% at 250 °C. This indicated that the dimensional response along the build direction depends on the combined effect of extrusion temperature and flow rate factor.

For evaluating the influence of the deposition geometry, additional samples were 3D-printed at 240 °C using nozzle diameters of 0.4 mm, 0.6 mm and 0.8 mm.

The variation of ΔH as a function of flow rate factor is presented in Fig. 9. At 240 °C, ΔH increased with flow rate factor for all tested nozzle diameters. For the 0.4 mm

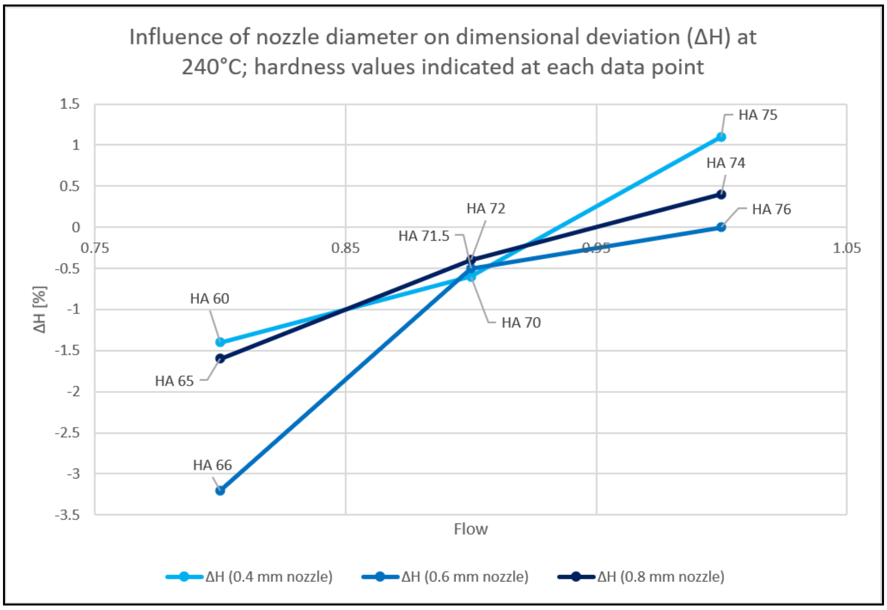


Fig. 9. Influence of nozzle diameter and flow rate factor on ΔH, for Filaflex Foamy samples printed at 240 °C.

nozzle, ΔH increased from −1.4% to +1.1%; for the 0.6 mm nozzle, from -3.2% to 0.0%; and for the 0.8 mm nozzle, from −1.6% to +0.4%. This shows that the flow rate factor had a clear influence on the vertical dimensional response of Filaflex Foamy.

The effect of nozzle diameter was also visible, but it was not monotonic as the 0.6 mm nozzle produced the largest negative deviation at the lowest flow rate factor, while the 0.4 mm nozzle produced the highest positive deviation at the highest flow rate factor. This indicated that deposition geometry affects ΔH through the combined influence of bead width, layer formation and material accumulation.The Shore A hardness values in Fig. 9 generally increased with flow rate factor. However, the differences between nozzle diameters were smaller than the differences produced by increasing flow rate factor. Therefore, under the tested conditions, hardness was more strongly associated with flow rate factor and apparent density than with nozzle diameter alone.

3.3. VarioShore TPU reference data set

To provide a comparative reference for Filaflex Foamy, varioShore TPU samples were produced at 240 °C using nozzle diameters of 0.4 mm, 0.6 mm and 0.8 mm. The extrusion temperature of 240 °C was selected because it was common to both material data sets and allowed the influence of nozzle diameter and flow rate factor to be evaluated under a fixed thermal condition. For each nozzle diameter, flow rate factor values of 0.60, 0.65 and 0.70 were selected based on the dimensional calibration procedure previously established for this material [21].

The measured dimensions of the varioShore TPU specimens are presented in Table 3. The results show that the dimensional response varied with both flow rate factor and nozzle diameter. At the lowest flow rate factor, the 0.4 mm nozzle produced the largest negative deviation along the Z direction, while the 0.8 mm nozzle produced dimensions closer to the nominal height. With increasing flow rate factor, ΔH increased for all nozzle diameters, reaching positive values at a flow rate factor of 0.70.

The variation of Shore A hardness as a function of flow rate factor for different nozzle diameters is presented in Fig. 10. For all investigated nozzle diameters, hardness increased with flow rate factor. At a flow rate factor of 0.70, the hardness values were comparable for all nozzle configurations. At lower flow rate factors, the influence of nozzle diameter was more visible: 0.4 mm nozzle produced the lowest hardness, while the 0.6 mm and 0.8 mm nozzles produced higher hardness values. This suggested that nozzle diameter affected hardness responses mainly at reduced flow rate.

To evaluate further the vertical dimensional response, the variation of dimensional deviation, ΔH, as a function

Table.3

Measured dimensions of varioShore TPU samples for different nozzle diameters and flow rate factors

Item	Nozzle diameter [mm]	Extrusion temperature [°C]	Flow rate	Extrusion width [mm]	Length [mm]	Width [mm]		Height [mm]	ΔH [%]
1	0.4	240	0.6	0.45	29.8	29.85		9.75	−2.5
2	0.4	240	0.65	0.45	30.01	30.09		9.94	−0.6
3	0.4	240	0.7	0.45	30.2	30.19		10.07	+0.7
4	0.6	240	0.6	0.65	29.99	30.01		9.85	−1.5
5	0.6	240	0.65	0.65	30.23	30.32		9.98	−0.2
6	0.6	240	0.7	0.65	30.35	30.3		10.04	+0.4
7	0.8	240	0.6	0.85	30.02	30.04		9.98	−0.2
8	0.8	240	0.65	0.85	30.21	30.28		9.99	−0.1
9	0.8	240	0.7	0.85	30.39	30.26		10.09	+0.9

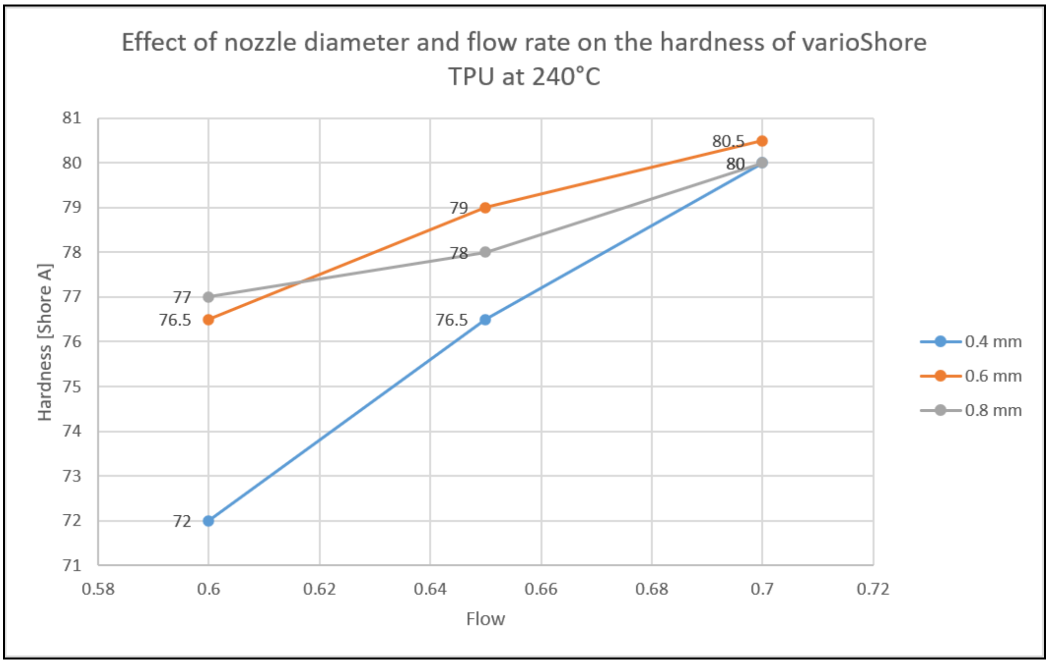


Fig. 10. Effect of nozzle diameter and flow rate on the hardness of varioShore TPU at 240 °C.

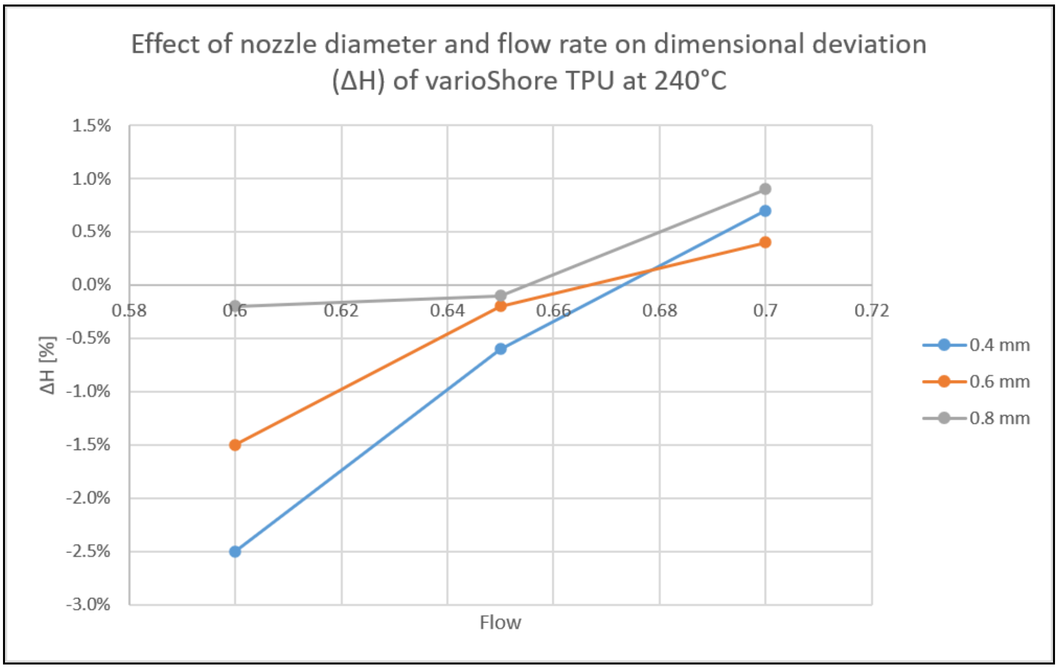


Fig. 11. Effect of nozzle diameter and flow rate on dimensional deviation (ΔH) of varioShore TPU at 240 °C.

of flow rate factor for different nozzle diameters is presented in Fig. 11.

The results showed that ΔH increased with flow rate factor for all nozzle diameters. However, the magnitude of this variation depended on nozzle diameter. The 0.4 mm nozzle showed the largest change in ΔH, while the 0.8 mm nozzle produced values closer to the nominal height at the lower flow rate factors. The density-hardness relationship of varioShore TPU was also analyzed for all investigated nozzle configurations at 240 °C, as presented in Fig. 12. The results show that Shore A hardness generally increased with relative density.

However, the sensitivity of hardness to relative density variation depended on nozzle diameter. The 0.4 mm nozzle showed the largest hardness variation over the investigated density range, whereas the 0.6 mm and 0.8 mm nozzle configurations maintained comparatively high hardness values even at lower relative density levels.

This indicates that nozzle diameter affects the density-hardness response of varioShore TPU, although the present data do not allow a direct interpretation of the internal cellular morphology.

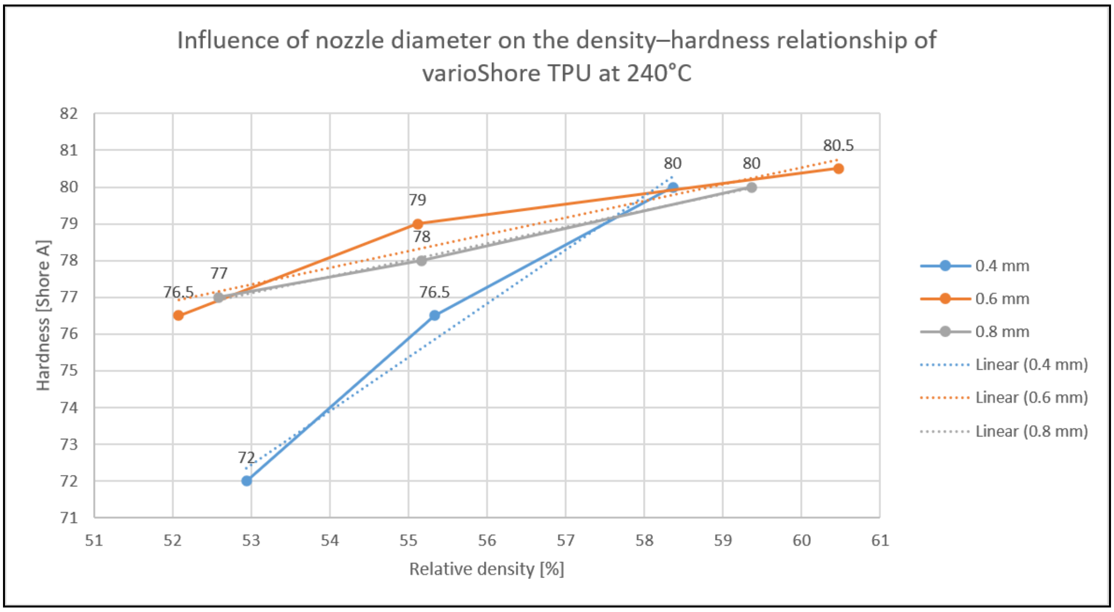


Fig. 12. Influence of nozzle diameter on the density-hardness relationship of varioShore TPU at 240 °C.

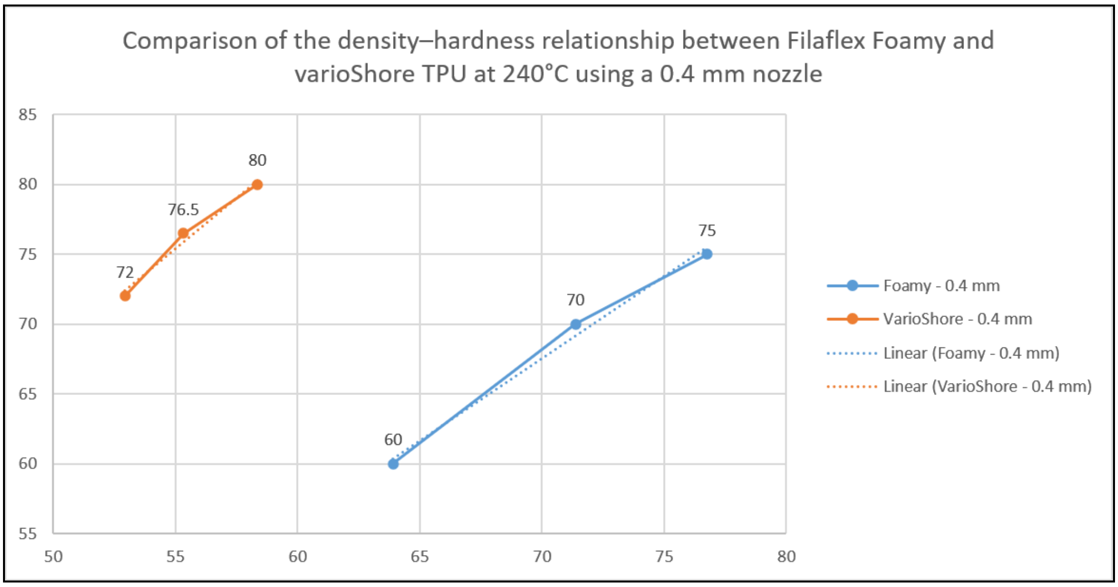


Fig. 13. Density-hardness relationship between Filaflex Foamy and varioShore TPU at 240°C with 0.4 mm nozzle.

3.4. Comparative density-hardness behavior of expandable TPU, Filaflex Foamy and varioShore

Figures 13–15 compare the relationship between relative density and Shore A hardness for Filaflex Foamy and varioShore TPU processed at 240 °C using nozzle diameters of 0.4 mm, 0.6 mm and 0.8 mm. For all investigated nozzle diameters, varioShore TPU reached higher Shore A hardness values at lower relative density levels compared with Filaflex Foamy.

This indicates that the two expandable TPU materials have different density-hardness responses. Filaflex Foamy required higher relative density values to reach hardness levels comparable to those obtained for varioShore TPU. For example, Shore A hardness values close to 76–77 were obtained for varioShore TPU at relative densities around 52–55%, whereas Filaflex Foamy required relative densities close to 77–80% to reach similar hardness values.

The comparison showed that relative density by itself does not fully describe the hardness response when considering different expandable TPU materials. Material formulation, foaming agent behavior and deposition conditions may also influence the measured hardness. Therefore, the calibration ranges identified for one expandable TPU filament should not be directly transferred to another material without experimental verification.

4. CONCLUSIONS

The present study analyzed the processing behavior of Filaflex Foamy TPU under different extrusion temperature, flow rate factor and nozzle diameter configurations. The results showed that the material response is controlled by the combined effect of material deposition, expansion-related dimensional behavior and apparent density.

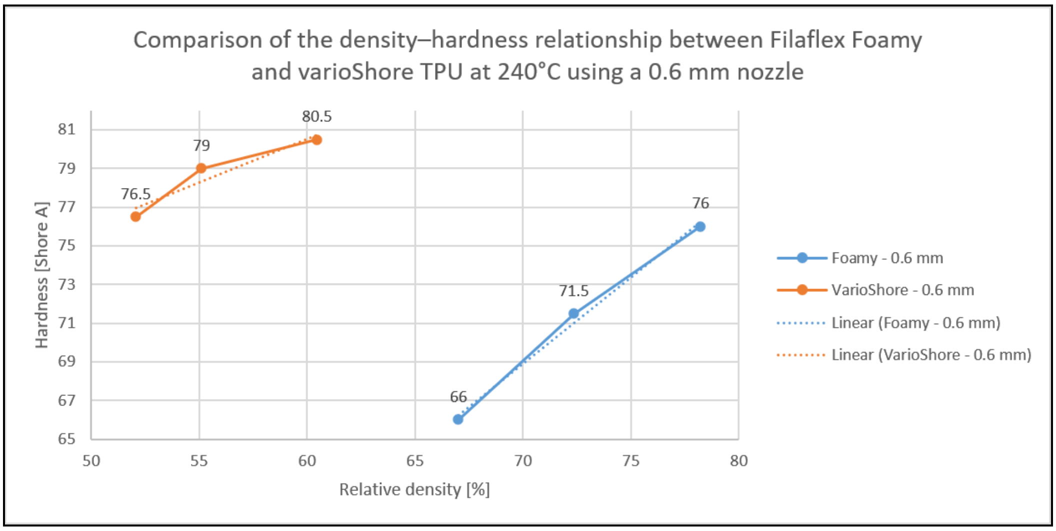


Fig. 14. Density-hardness relationship between Filaflex Foamy and varioShore TPU at 240°C with 0.6 mm nozzle.

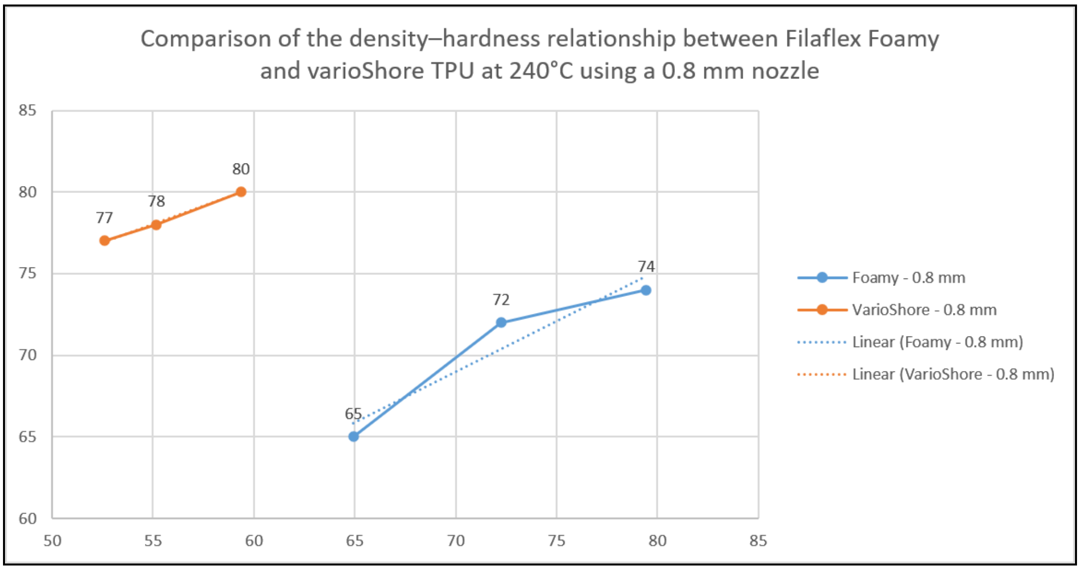


Fig. 15. Density-hardness relationship between Filaflex Foamy and varioShore TPU at 240°C with 0.8 mm nozzle.

For the samples printed with the 0.4 mm nozzle, Shore A hardness increased with flow rate factor for all investigated extrusion temperatures. This behavior was consistent with the increase in apparent density, indicating that flow rate factor had the clearest influence on the hardness response. In comparison, the effect of extrusion temperature on hardness was less pronounced and did not show a strictly monotonic trend within the investigated range.

The relationship between apparent density and Shore A hardness was approximately linear for each extrusion temperature. However, the different slopes obtained for 230 °C, 240 °C and 250 °C showed that apparent density alone does not fully describe the hardness response. Therefore, the hardness of Filaflex Foamy should be interpreted as the result of apparent density together with process-dependent effects associated with extrusion temperature and material deposition.

The dimensional deviation along the build direction, ΔH, was affected by both extrusion temperature and flow rate factor. At flow rate factors of 0.8 and 0.9, ΔH remained negative over the investigated temperature range, indicating that the measured height was lower than the nominal height. At a flow rate factor of 1.0, ΔH became positive and increased with extrusion temperature, reaching +2.1% at 250 °C. This confirms that the vertical dimensional response cannot be attributed to extrusion temperature alone, but depends on its combination with flow rate factor.

The nozzle diameter also influenced the dimensional response at 240 °C. For all tested nozzle diameters, ΔH increased with flow rate factor. However, the effect of nozzle diameter was not monotonic. The 0.6 mm nozzle produced the largest negative deviation at the lowest flow rate factor, while the 0.4 mm nozzle produced the highest positive deviation at the highest flow rate factor. This indicates that deposition geometry affects the dimensional response through bead width, layer formation and material accumulation.

The comparison with varioShore TPU showed that the two expandable TPU materials have different density–hardness behavior. VarioShore TPU reached higher Shore A hardness values at lower relative density levels, while Filaflex Foamy required higher relative density values to reach comparable hardness. This shows that relative density alone is not sufficient for comparing different expandable TPU filaments, and that material formulation and foaming-agent behavior must also be considered.

Overall, the results indicate that Filaflex Foamy requires a material-specific calibration procedure in order to obtain predictable dimensional accuracy, apparent density and Shore A hardness. The processing conditions identified for another expandable TPU filament, such as varioShore TPU, should not be directly transferred to Filaflex Foamy without experimental verification.

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