Abstract

Although fused deposition modeling (FDM) is of great interest for the cost-effective manufacture of polymer parts with complex customized geometries, it currently provides insufficient mechanical integrity for the production of high performance functional structures, and is restricted to too limited a range of materials. The present work is aimed at investigating the suitability of new combinations of hard and soft thermoplastics for FDM. To this end, non-isothermal fusion bonding of polypropylene (iPP) and a thermoplastic elastomer (TPE) with a continuous plasticized iPP matrix was investigated by overinjecting the TPE onto a solid iPP insert. The influence of temperature and pressure was evaluated by tensile testing of butt joint specimens, and optical and electron microscopy. Interface temperatures approaching the iPP melting point gave high bond strengths for hold pressures above 200 bars, resulting in cohesive failure in the TPE as well as adhesive failure at the interface. The pressure was more critical at lower interface temperatures, but bond strengths sufficient to cause cohesive failure in the TPE could still be obtained at interface temperatures well below the iPP melting point if the maximum pressure was high enough. Moreover, too low a hold pressure led to poorer bonding at high interface temperatures than at low interface temperatures, an effect attributed to uncompensated shrinkage during solidification. Similar trends were seen in fusion deposition of TPE onto iPP, where bond strengths comparable with those obtained by overinjection were observed at low bed temperatures, while high bed temperatures resulted in poorer bonds. These results are discussed in terms of the interfacial morphology and the dominant bonding mechanisms in each case.

Introduction

Integrated processing of hard and soft materials is of considerable importance in applications that require tailored comfort, ergonomics and functionality. Developments in thermoplastic elastomers (TPEs) have facilitated the use of existing thermoplastic processing techniques to combine these relatively soft materials with hard thermoplastics, such as isotactic polypropylene (iPP). The most common and efficient techniques are based on sequential or overinjection processes involving rapid fusion bonding, and the resulting combinations of soft and hard thermoplastics are widely used in high volume overmolded products such as toothbrush handles, medical equipment, automotive gaskets, sports goods etc. However, there is growing interest in developing new processes and materials combinations for low volume customized production of prototypes and functional parts in e.g. the automotive industry, robotics, prosthetics and orthotics. Additive manufacturing, and fusion deposition modeling (FDM) in particular, is a highly promising means of combining different materials in a cost-effective manner to form arbitrarily complex shapes. However, it is important that the structural
integrity of the interface between the different materials be adapted to the overall requirements of functionality and performance, which usually means it should be at least as strong as the weakest component in the assembly. In both overinjection and FDM, this implies optimization of fusion bonds formed under strongly non-isothermal conditions, where a hot melt stream comes into contact with a solid substrate that is initially at a much lower temperature. Development of bond strength in non-isothermal fusion bonding processes may involve various mechanisms, depending on the physical and chemical interactions between the materials to be bonded. These mechanisms have been extensively investigated for homogeneous or reactive interfaces between amorphous [1] and semicrystalline thermoplastic polymers [2]. In either case, bond development involves establishment of intimate contact, followed by establishment of specific interactions and/or interdiffusion of the polymer chains across the interface and, finally, vitrification or crystallization of the initially molten phase(s) [3]. The time required to achieve intimate contact and interdiffusion is highly sensitive to the choice of process parameters. For the short process times usually associated with overinjection and FDM, flow at the interface is assumed to play an important role, in which case the consolidation pressure and the temperature dependence of the viscosity of the molten phase(s) are crucial for the bonding kinetics. A number of studies have focused on fusion bonding between semicrystalline thermoplastics and TPEs, thermoplastic vulcanates (TPVs) or polyolefin copolymers during overinjection [3-8]. Depending on the specific system, the variation of bond strength with temperature, pressure, time and surface roughness has been accounted for in terms of mechanical interlocking, interdiffusion, co-crystallization or a “Rouse-type fingering mechanism”, i.e. partial interpenetration of the interface over depths equivalent to the longest Rouse chain length [7]. Many of these previous studies have indicated the melt and interface temperatures to play a dominant role, but questions remain with regard to the effect of pressure, particularly at the very low effective levels associated with FDM. The present study is aimed at improving our understanding of the mechanisms governing bonding at TPE-iPP interfaces through both mechanical and morphological characterization of iPP overinjected with TPE under a range of processing conditions, with the further aim of interpreting the behavior of interfaces prepared at low pressure by FDM using similar materials.

Table I: Materials Data.

<table>
<thead>
<tr>
<th>Batch</th>
<th>Type</th>
<th>Melting Temperature*** [°C]</th>
<th>Recommended Processing Temperature* [°C]</th>
<th>Hardness*</th>
<th>Tensile Strength [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>iPP Homopolymer A</td>
<td>168</td>
<td>160 - 240</td>
<td>60 Shore A</td>
<td>9.0* (7.0**)</td>
</tr>
<tr>
<td></td>
<td>SEBS Compound A</td>
<td>152</td>
<td>180 - 240</td>
<td>55 Shore A</td>
<td>6.9* (4.3**)</td>
</tr>
<tr>
<td>2</td>
<td>iPP Homopolymer B</td>
<td>169</td>
<td>160 - 240</td>
<td>105 Rockwell</td>
<td>34.0*</td>
</tr>
<tr>
<td></td>
<td>SEBS Compound B</td>
<td>157</td>
<td>160 - 200</td>
<td>55 Shore A</td>
<td>13.7*</td>
</tr>
<tr>
<td>3</td>
<td>SEBS Compound C</td>
<td>160</td>
<td>160 - 200</td>
<td>85 Shore A</td>
<td>13.7*</td>
</tr>
</tbody>
</table>

* From the materials supplier’s datasheet, **tested at a strain rate of 2 mm/s as described in the experimental section, ***determined by differential scanning calorimetry (DSC, TA Q200) at a heating rate of 10 °C/min.

Experimental

Materials

Two different batches of iPP and TPE were investigated in the overinjection studies, as summarized in Table I. The TPEs were all compounds of poly(styrene-ethylene/butylene-
styrene) (SEBS) with iPP and unspecified processing additives. An iPP-rich phase, with a somewhat lower melting point than that of the iPP homopolymers owing to the presence of oil-based plasticizers, formed a continuous matrix in each of the TPEs, while the major phase, SEBS, formed discrete elastomeric inclusions, in which the polystyrene blocks acted as physical crosslinks [9-11]. This was assumed to ensure a good solubility parameter match with the iPP substrate during fusion bonding. Because the TPEs from Batches 1 and 2 were too soft to be printed by FDM, an alternative grade (SEBS Compound C in Table I) was chosen for this purpose, together with iPP Homopolymer B from Batch 2.

![Figure 1: Overinjected butt joint specimen geometry (all dimensions in mm; the arrow indicates the injection direction).](image)

Table II: Injection Molding Parameters.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>iPP</th>
<th>Batch 1</th>
<th>Batch 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injection Temperature, $T_i$ [°C]</td>
<td>220</td>
<td>240</td>
<td>220</td>
</tr>
<tr>
<td>Mold Temperature, $T_m$ [°C]</td>
<td>40</td>
<td>40,80</td>
<td>40,110</td>
</tr>
<tr>
<td>Injection Pressure, $I_p$ [bar]</td>
<td>800</td>
<td>220,370,555,820</td>
<td>650</td>
</tr>
<tr>
<td>Hold Pressure, $H_p$ [bar]</td>
<td>500</td>
<td>200</td>
<td>100,200,300,600</td>
</tr>
<tr>
<td>Hold Time, $H_t$ [sec]</td>
<td>2.5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Surface Roughness, $R_a$ [µm]</td>
<td>-</td>
<td>0.3</td>
<td>0.3,2</td>
</tr>
</tbody>
</table>

**Specimen Preparation**

Dog bone-shaped tensile specimens with butt joints (Figure 1) were prepared by overinjection using an Arburg 270s 250 KN injection molding machine. A specimen of iPP was first molded under the injection molding conditions specified in Table II, cut in half using a diamond saw and the resulting surface polished using sandpaper with a grit size of either 2000 or 220 in order to vary the surface roughness. Each polished iPP half-specimen was then preheated to the mold temperature chosen for overinjection, reinserted into the mold and overinjected with TPE.

The effects of temperature and pressure were studied at a fixed overinjection hold time of 5 s for the materials from Batch 1 and 2 (Table I), and under non-isothermal fusion bonding conditions, i.e. with different injection and mold temperatures, so as to simulate the temperature profiles expected during FDM. The effect of surface roughness was also studied for Batch 2. Table II summarizes the full range of parameters investigated. For Batch 1, the TPE melt was in contact with the iPP insert during the injection phase, so that pressure was applied to the iPP insert surface during both the injection and hold phases of the overinjection cycle. For Batch 2, the injection pressure was used to inject the TPE melt to close to the iPP insert surface, but it only entered into contact with the iPP during the hold phase, so that the hold pressure defined the effective bonding pressure in this case.
FDM of iPP and TPE was carried out using an E3D BigBox printer with a single head printing set-up equipped with a metal hot-end (0.4 mm diameter nozzle) and heated bed as shown in Figure 2. The printer was modified to incorporate an insulated enclosure in order to stabilize the ambient conditions and reduce warping of iPP during printing. The iPP and TPE filaments, of 1.75 mm in diameter were prepared using a Prism TSE 16 TC bench-top twin-screw extruder (Thermo Electron) with the processing conditions given in Table III. The iPP layers were then printed according to the parameters listed in Table IV to the specified height and the filament then changed to TPE so as to form a symmetric butt joint specimen with a nominal cross-section of $0.8 \times 10$ mm$^2$ and a total length of 20 mm. The 3D models were created in Solidworks® (Dassault Systèmes) and Simplify3d® slicing software was used to create the G codes for FDM.

![3D printer schematic](image)

Figure 2. FDM Bigbox E3D printer and schematic showing the E3D hot-end (nozzle, heated/cooled zone and filament path).

**Table III: Filament Extrusion Parameters.**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>iPP-B</th>
<th>SEBS C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extrusion Temperature [°C]</td>
<td>185</td>
<td>195</td>
</tr>
<tr>
<td>Die Temperature [°C]</td>
<td>180</td>
<td>175</td>
</tr>
<tr>
<td>Pulling Speed [m/min]</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Average Filament Diameter [mm]</td>
<td>1.75 +/- 0.2</td>
<td>1.75 +/- 0.1</td>
</tr>
</tbody>
</table>

**Table IV: FDM iPP-TPE Printing Parameters**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>iPP-B</th>
<th>SEBS C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extrusion Hot-End Temperature [°C]</td>
<td>220</td>
<td>240,250</td>
</tr>
<tr>
<td>Bed Temperature [°C]</td>
<td>30,60,90</td>
<td>30,60,90</td>
</tr>
<tr>
<td>Layer Height [µm]</td>
<td>200</td>
<td>200</td>
</tr>
</tbody>
</table>
Morphological Characterization

Optical Microscopy

Sections from the interface region of the specimens were embedded in an epoxy resin (PELCO® Eponate 12™ Kit with BDMA). They were then further smoothed using a stainless steel razor blade in a microtome at room temperature and a diamond knife at -60 °C. The specimens were observed by optical microscopy in reflected light (OM, Olympus BH-12). Selected micromed surfaces were etched in a freshly prepared solution of H$_2$SO$_4$, KMNO$_4$ and H$_3$PO$_4$ in the weight ratios of 64.3:3:32.7 respectively for 2 minutes, and then rinsed and sonicated with distilled water and hydrogen peroxide [12]. Fracture surfaces were observed in reflected light without additional surface modification.

Scanning Electron Microscopy

Selected specimens were observed by scanning electron microscopy (SEM, Philips FEI XLF30-FEG) in secondary-electron mode. The specimens were coated with carbon in order to avoid charge accumulation and a maximum acceleration voltage of 2 kV was used throughout.

Roughness Measurements

The roughness of the iPP insert prior to overinjection was measured using a Tencor Alpha-Step 500 surface profiler with a spatial resolution of 10 μm. Measurements were taken from different zones of multiple specimens to give an average roughness ($R_a$), which is the arithmetic mean of the difference in height of the surface peaks and valleys.

Mechanical Testing

The bond strength of the overinjected butt joints was measured using a Walter+Bai LFM Universal Testing Machine, with a 1 kN load cell. The gauge length was 75 mm and a strain rate of 2 mm/s was maintained until failure of either the interface or the bulk TPE (failure was never observed in the iPP). For the fusion deposited butt joints, the bond strength was measured using a miniature tensile testing apparatus (Minimat, Rheometric Systems) mounted on an optical microscope (Olympus SZ-STU2). The gauge length was 10 mm and a strain rate of 2 mm/min was maintained until failure of either the interface or the bulk TPE. In each case, the average bond strength was calculated from the mean force at failure for 5 different samples.

Results and Discussion

Effect of Temperature and Pressure on Overinjected Butt Joints

Increasing the injection pressure at a mold temperature of 40 °C, a constant hold pressure of 200 bar and a hold time of 5 s resulted in a clear increase in the bond strength of the materials from Batch 1 with a surface roughness of 0.3 μm, as shown in Figure 3. On the other hand there was no apparent influence of injection pressure under these conditions when the mold temperature was increased to 80 °C.

It is assumed that the interface temperature, $T_{\text{in}}$, was close to the average of the mold temperature, $T_m$, and the injection temperature, $T_i$ [13] i.e. 140 and 160 °C for $T_i = 240 °C$ and
$T_m$ of 40 and 80 °C respectively. It was therefore inferred from the melting point data given in Table I, taking into account possible migration of the TPE plasticizer across the interface, that $T_m = 80$ °C may have been sufficient to cause at least partial melting of the surface of the iPP insert under the conditions of Figure 3. Previous investigations of iPP-iPP fusion bonds [2] nevertheless indicate a $T_m$ of 160 °C to be insufficient to raise the fracture energy of the bonds to that of bulk iPP even after much longer hold times than those considered here. Moreover, for an estimated $T_m$ of 170 °C, iPP-iPP bond strengths obtained under an applied pressure of 200 bar are significantly lower than for low pressure bonding (∼ 20 bar), owing to a concomitant increase in the melting point of the iPP. Indeed, the highest injection pressures employed here are predicted to increase the melting point of iPP by as much as 30 °C with respect to DSC values obtained at ambient pressure [14], so that if melting does occur under the conditions of Figure 3, it is expected to do so during the hold phase. Any such melting may promote intimate contact and possibly co-crystallization and interdiffusion between the iPP and the iPP matrix of the TPE, accounting for the relatively good bond strengths observed for $T_m = 80$ °C. The corresponding fracture surfaces indicated mixed adhesive failure at the interface and cohesive failure of the TPE adjacent to the interface (Figure 4b). The cohesive strength of Batch 1 TPE injected and tested under the same conditions was at least 3 MPa (the TPE specimens did not break at the maximum deformation obtainable with the present set-up). This is presumably close to upper limit to the effective bond strength that could be achieved for the Batch 1 materials and was hence consistent with the maximum observed bond strengths of 3 to 3.6 MPa.

![Figure 3](image)

*Figure 3. Average bond strength as a function of the injection pressure for the Batch 1 materials with an insert surface roughness, $R_a$, of 0.3 µm at mold temperatures, $T_m$, of 40 and 80 °C, a hold pressure of 200 bar and a hold time of 5 s.*
The surface of the iPP insert was not expected to undergo significant melting for \( T_m = 40 \, ^\circ C \), even at low injection and hold pressures, implying reduced mobility at the interface. It follows that the observed bond strengths were substantially lower than for \( T_m = 80 \, ^\circ C \) at low injection pressures, as reflected by a lack of coarse features on the fracture surfaces, implying predominantly adhesive failure (Figure 4a). However, the bond strength increased markedly with increasing injection pressure for the hold times used here, reaching values similar to those obtained with \( T_m = 80 \, ^\circ C \). Hence, extensive melting of the surface of the iPP insert was not necessary to approach the limiting bond strength defined by cohesive failure of the TPE. The observed increase in bond strength with pressure may therefore reflect both improved heat transfer and intimate contact under high pressures owing to elimination of cavities at the interface [13], and an increase in the average interface temperature owing to viscous heating and the reduced time for the melt to reach the interface.

![Figure 4. Fracture surfaces (TPE side of the interface) for the Batch 1 materials: (a) \( T_m = 40 \, ^\circ C, I_p = 530 \) bar, bond strength = 2 MPa; (b) \( T_m = 80 \, ^\circ C, I_p = 370 \) bar, bond strength = 3.6 MPa.](image)

![Figure 5. Average bond strength for Batch 2 materials as a function of hold pressure for mold temperatures of 40 and 110 °C, and insert surface roughnesses, \( R_a \), of 0.3 and 2 \( \mu m \) (continuous and hatched curves respectively).](image)

The effect of increasing the hold pressure from 100 to 600 bar at a relatively high effective injection pressure of 650 bar, but no contact between the molten TPE and the iPP insert prior to the hold phase, is shown in Figure 5 for materials from Batch 2 with different degrees of
roughness at the surface of the iPP insert. For the inserts with a surface roughness, $R_a$, of 0.3 µm, a high mold temperature, $T_m = 110 ^\circ C$ ($T_{in} \approx 165 ^\circ C$) resulted in very low quality bonds at the lowest hold pressure owing to poor consolidation. However, at higher hold pressures the bond strength increased towards the cohesive strength of the TPE (about 4.3 MPa for SEBS Compound B), although it decreased slightly between 300 and 600 bar, possibly owing to an increase in the iPP melting point with pressure. On the other hand, for $T_m = 40 ^\circ C$ the bond strength remained low over the entire range of hold pressure investigated. Increasing the surface roughness ($R_a = 2 \mu m$) made little difference to the bond strength for $T_m = 40 ^\circ C$, but resulted in a significant increase for $T_m = 100 ^\circ C$ at hold pressures of both 100 and 600 bar. The highest bond strengths were again associated with mixed adhesive failure and cohesive failure of the TPE, which may have contributed to the severe experimental scatter observed under these conditions.

![Figure 6. Optical micrographs of Batch 2 iPP-TPE interfaces (iPP on the right-hand side of each image) obtained for: (a) $R_a = 2 \mu m$, $H_p = 100 \text{ bar}$, $T_m = 40 ^\circ C$; (b) $R_a = 2 \mu m$, $H_p = 100 \text{ bar}$, $T_m = 110 ^\circ C$; (c) $R_a = 0.3 \mu m$, $H_p = 100 \text{ bar}$, $T_m = 40 ^\circ C$; (d) $R_a = 0.3 \mu m$, $H_p = 600 \text{ bar}$, $T_m = 40 ^\circ C$.](image-url)
Figure 7. SEM micrographs of Batch 2 iPP-TPE interfaces obtained for: (a) $R_a = 2$ $\mu$m, $H_p = 600$ bar, $T_m = 110$ °C; (b) $R_a = 2$ $\mu$m, $H_p = 600$ bar, $T_m = 40$ °C.

It is clear from these observations that both the interface temperature and the maximum pressure (either the injection pressure or the hold pressure) are important for bond strength. At relatively low mold temperatures, for which the interface temperature was well below the nominal melting point of the iPP insert, there was a transition from low to high bond strengths at the highest pressures investigated ($T_i = 820$ bar), whereas at high mold temperatures, effective bond strengths approaching the limiting value imposed by the cohesive strength of the TPE were consistently achieved at pressures as low as 200 bar. These results were broadly consistent with those of previous studies, in which the peeling force to separate overinjected TPE with a continuous iPP matrix is also found to tend to a limiting value characterized by cohesive failure in the TPE, as the TPE injection temperature, the mold temperature and the hold pressure are increased [13]. In the present case, it is concluded that intimate contact between the TPE and the iPP insert was sufficient to reach the limiting bond strength, as also reported for polyolefin copolymers overinjected onto iPP [6], for example. Even so, there was direct evidence of melting at the surface of the iPP insert at the higher mold temperatures. As seen from Figure 6 and Figure 7, while a high original surface roughness was reflected by rough interfaces at low $T_m$, the interfaces were flatter at high $T_m$, regardless of $R_a$. Moreover, as shown in Figure 8a, a distinct columnar region and shrinkage-induced voiding were visible beneath the iPP surface after bonding at high $T_m$ up to the highest hold pressures investigated, confirming extensive melting to have taken place, possibly promoted by migration of plasticizer from the TPE. Local melting in the presence of asperities may lead to enhanced interdiffusion of the iPP chains at the peaks of these asperities [15]. This would account for the enhanced bond strengths observed for the rougher iPP inserts at high mold temperatures, particularly for the lowest hold pressure, where the low bonds strengths associated with smoother inserts were due to poor consolidation, presumably owing to uncompensated shrinkage of the iPP during solidification. The lack of extensive melting at the surface of the iPP insert for $T_m = 40$ °C, reflected by the observation of equiaxed spherulites characteristic of the original iPP microstructure adjacent to the interface (Figure 8b), may hence explain the limited influence of surface roughness on the bond strength in this case.
Figure 8: Optical micrographs of etched Batch 2 iPP-TPE interfaces showing the microstructure of the iPP (left-hand side of each image): (a) $R_a=0.3 \, \mu m$, $H_p= 600 \, \text{bar}$, $T_m= 110 \, ^\circ \text{C}$; (b) $R_a=0.3 \, \mu m$, $H_p= 600 \, \text{bar}$, $T_m= 40 \, ^\circ \text{C}$.

**Effect of Temperature on FDM Butt Joints**

FDM printing of iPP is challenging because iPP undergoes substantial crystallization-induced shrinkage and generally shows poor adhesion [16]. Nevertheless, iPP-TPE interfaces were successfully printed as shown in Figure 9. The corresponding bond strengths, calculated from the nominal cross-sectional area of the butt joints, are given in Figure 10. At low bed temperatures, the bond strengths compared favorably with those obtained by overinjection at low hold pressures (cf. Figure 5), bearing in mind the higher strength of the TPE used for the FDM experiments (Table I). However, the bond strengths decreased significantly when the bed temperature was raised to 90°C. As seen from Figure 11d, this could be attributed directly to poor contact between the iPP substrate and the TPE, which was due in turn to excessive non-uniform shrinkage of the iPP away from the plane of the interface, the center of the iPP bed remaining molten for much longer times than those associated with the deposition of successive layers. This effect could be observed directly during fusion deposition of the iPP, which became opaque on solidification, forming a spherulitic texture (cf. Figure 8) that defined the scale of the local roughness of surface of the iPP. There was some loss of contact between the TPE and the iPP for a bed temperature of 30 °C, (Figure 11a), but contact was generally good at intermediate bed temperatures, particularly when the TPE melt temperature was increased (Figure 11c); this resulted in extensive melting of the iPP surface, an increase in bond strength by about 10 %, and mixed adhesive failure and cohesive failure of the TPE in spite of the relatively high tensile strength of this latter.
Figure 9: (a) Overview of a TPE-iPP interface prepared by FDM and (b) part of section through the interface showing intimate contact between the TPE and the iPP.

Figure 10: Average bond strengths for interfaces prepared by FDM with different bed temperatures and a TPE melt temperature of 240 °C.
Figure 11: TPE-iPP interfaces (TPE on the left-hand side of each image) prepared by FDM with: (a) $T_b = 30 ^\circ C$, $T_h = 240 ^\circ C$; (b) $T_b = 60 ^\circ C$, $T_h = 240 ^\circ C$; (c) $T_b = 60 ^\circ C$, $T_h = 250 ^\circ C$; (d) $T_b = 90 ^\circ C$, $T_h = 240 ^\circ C$.

Conclusions

It is generally accepted that increasing the interface temperature during non-isothermal fusion bonding increases bond quality and bond strength. However, in the specific case of TPE bonded to a rigid iPP substrate by overinjection or FDM, where the effective maximum bond strength is limited by the mechanical properties of the TPE, and bearing in mind that for practical reasons different grades of TPE were used for the different experiments described here, we have reached the following conclusions.

- Bonds strengths comparable with the cohesive strength of the TPE may be achieved in overmolded joints without extensive melting of the iPP substrate, provided the TPE melt temperature and pressure are high enough to ensure intimate contact.

- Using a high mold temperature to raise the interface temperature to close to that of iPP melting point is potentially counterproductive in that poor consolidation owing to uncompensated shrinkage reduces the bond strength obtained at low hold pressures.

- Raising the bed temperature in FDM may promote intimate contact and melting of the iPP at the interface. However, as in the case of low pressure overinjection, too high a bed temperature led to severe dimensional instabilities in the iPP and poor contact with the TPE under the conditions we have so far investigated.

We believe these conclusions to have a certain generality for interfaces involving soft components and provide a basis for further optimization of the FDM process parameters. The present system is nevertheless particularly well suited to fusion bonding, given that the plasticized iPP matrix of the TPE favors the various stages of formation of strong bonds, i.e. wetting, co-crystallization and interdiffusion. Moreover, the presence of a plasticizer, inferred from the relatively low melting point of the TPE, is suggested to promote local melting of the iPP substrate at interface temperatures lower than those required to form strong bonds in unplasticized iPP for comparable bonding times. The next step will be to carry out more detailed investigations of interface formation in this system, based on direct determination and/or modeling of the interface temperatures as a function of the process conditions, systematic SEM observations of the microstructure of the iPP adjacent to the interface and a fracture mechanics-based approach to characterization of the bond strength.

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