Complex Injection Moulded Components - Bridging the Knowledge Gap

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Abstract. Injection moulding is the predominant manufacturing process enabling the production of precise and consistent polymeric parts at a high volume. The final performance of those parts is critically dependent on their melt flow history and the current approach of testing simplified specimens produced by idealized melt flow conditions to specify new or enhanced materials is therefore not sufficient, since final parts often feature a more complex geometry. The purpose of this research is to highlight this omission by conducting high velocity impact and quasi-static tensile tests on PA-12 specimens obtained from a new concept injection moulding tool. This mould allows controlled modification of the material flow by adding specific mould tool design features which lead to the creation of a weld line, flow hesitation, or combination of both of these irregular flow phenomena and is therefore an improved representation of final injection moulded components. Furthermore, test specimens representing simplified as well as more complex geometries can be obtained from the same moulded samples, guaranteeing identical applied process conditions. The occurring microstructural differences due to the diverse melt flow history are verified using optical microscopy and Differential Scanning Calorimetry.

Keywords: Injection moulding, concept mould/mold, microstructure flow hesitation, weld lines
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ADVANCED MOULD CONCEPT

The process of injection moulding (IM) is one of the most widely employed methods for manufacturing an extremely diverse range of parts, varying in size and degree of complexity, from polymeric materials. The final quality and performance of injection moulded parts is complex and depends on specific material attributes (molar mass, molecular architecture and additive type/ concentration), as well as part and mould design and the specific process parameters required for manufacture. The final mechanical performance of a part is predetermined by its microstructure, morphology and is strongly influenced by the melt flow behavior during injection. Previous investigations dealing with different melt flow modifications were mostly focused on the influence of weld lines per se [1] and the effect of different process parameter [2], [3] or additives/ blends [4] on their mechanical strength. While these publications were often based on the comparison of test samples with and without weld lines produced using different moulds, often requiring different machine settings, the new mould enables the production of samples representing both cases with the same shot of material, ensuring identical settings, important for processing materials which are sensitive to degradation induced by oxidation, hydrolysis, or by excessive residence time. Besides weld lines, the effect of flow hesitation and combinations of both flow phenomena can be investigated by adding or removing corresponding mould features (FIGURE 1). The circular obstacle, dividing the melt flow to create a weld line can be modified in diameter and the side channels causing flow hesitation can be varied in thickness enabling the mould to be customised depending on the final application it is simulating. The side channels can also be used for ‘thin to thick’ and ‘thick to thin’ transitional flows. To understand the observed macroscopic behavior and the influence of different flow modifications on the material morphology, optical microscopy and Differential Scanning Calorimetry (DSC) were utilized.

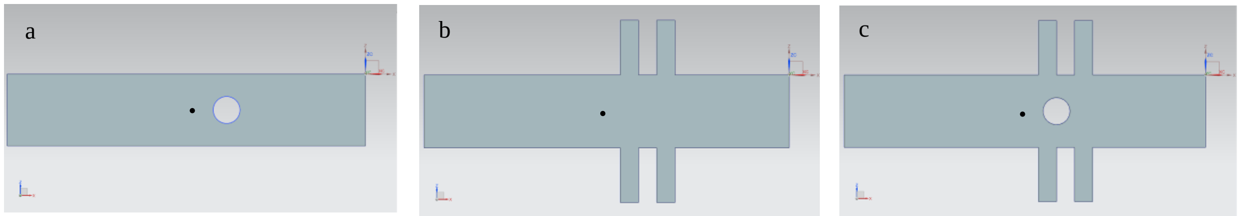

FIGURE 1. CAD representations of possible mould modifications (a) Mod 1 - weld line due to hole obstacle (b) Mod 2 - flow hesitation due to side channels (c) Mod 3 - combination of weld line and hesitation

Besides the central injection gate used within this study, two more injection locations are possible at either end of the mould (all featuring a hot runner system). These can be used to investigate differences in the melt flow path length, as well as for the creation of samples containing additional weld lines when used simultaneous. All investigations were made on Polyamide 12 (PA-12), an engineering plastic with a relatively low crystalline melting point due to its longer aliphatic chain sequences, which also confers relatively low moisture intake and superior chemical and impact resistance compared to other PAs [5]. The influence of different material flow behavior specifically on PAs has been investigated before, dominated by work on PA-6 or PA-66 while less existing literature is available for PA-12. The aim of this research investigation is to highlight the need for a more sophisticated approach when evaluating new or enhanced materials. A solution is presented in the form of a new mould concept. Test results allow predictions with regards to the final behavior of more complex injection moulded parts without being dependent on a time-consuming prototyping phase. The new mould would be even more beneficial for final part predictions when used in combination with CFD software, to obtain simulative data to complement and to predict practical outcomes [6].

Experimental

Material selection: a commercially available PA-12 was selected featuring a high degree of transparency allowed the weld line detection without additional tools and enabled consistent sample preparation. The material was injected at 250°C at an axial injection speed of 20 mm/s into the 60°C mould at three different modifications (FIGURE 1), cooling for 35s. Due to the hygroscopic nature the material was dried at 80°C prior to injection moulding and conditioned prior to the different mechanical tests to ensure reproducible test results. All test specimens were conditioned at 70°C and 62% relative humidity (ISO BS 1110) for 72 hours leading to a weight increase of 0.48%. All tests were performed on 2 mm thick samples with different geometries according to the applied standard.

Quasi-static tensile test data was obtained using an Instron 5569 tensometer operating at a speed of 0.25 mm/min during the first 0.3% strain (detected using a mechanical clip-on extensometer) and 50 mm/min afterwards with an initial clamp separation of 55 mm. ISO BS 527-2 5 Type A samples were tested normal to the flow direction regarding their tensile toughness, which was calculated using the implemented trapezoidal function in MatLab (Mathworks, Natick, USA). Instrumented falling weight impact tests were conducted on an Instron Dynatup 9250 using a 20 mm striker at an impact speed of 4.4 m/s providing an overall impact energy of around 197 J. Circular specimens with 52 mm diameter were tested in accordance with the ISO BS 6603-2 standard.

Optical microscopy was carried out to investigate the microstructure in the weld line regions using a Nikon SMZ 1500 for surface analysis and a Leica DMRX microscope, used in polarised light transmission mode, investigating crystalline microstructures on 10 μm samples prepared using a microtome and Euparal as the mountant. Additional, differences in the sample morphology extracted from the weld line region were investigated and compared to samples from identical locations (all central, 60 mm from injection gate) not containing a weld line by using DSC following the ISO BS 11357 standard on a DSC Q2000 thermal analysis device combined with a RCS 90 cooling system, both from TA instrument Inc. A heat/ cool/ heat procedure was performed on 7.6 mg (± 0.3 mg) samples, heating and cooling at 10°C/ min between 0°C and 270°C with a 5 minute isothermal pause when reaching the limits. All samples were tested with no prior thermal treatment to avoid, respectively minimise, any additional post injection structural change. The degree of crystallinity was calculated by:

$$C = \frac{\Delta H_m}{\Delta {H^0}_m} \times 100 \, [\%] \quad (1)$$

where $\Delta {H^0}_m$ = 210J g^{-1} [7] was taken as the heat of fusion for a theoretically 100% crystalline PA-12 and ΔH_m was the measured melting enthalpy for the moulded PA-12 samples.

Results and Discussion

The final properties of an injection moulded part are influenced by the melt flow behavior during the process and the occurrence of weld lines or flow hesitation can significantly change the properties of materials and moulded artefacts. Samples obtained from the new mould concept, representing four different flow modifications were tested and compared regarding their quasi-static and instrumented impact properties. The mechanical testing was followed by material characterisation using optical microscopy and DSC.

Mechanical Testing

Quasi-static tensile data was obtained from the Bluehill software completing the Instron 5569 test system. The detected results, including stress and strain at break and the resulting tensile toughness data are presented in TABLE 1.

TABLE 1. Quasi-static tensile toughness results PA-12: Effect of different material flow modifications

Material Flow Modification	Stress at Break [MPa]	Strain at Break [%]	Tensile Toughness [J]
Mod 1 - Weld Line	29.7 ± 1.1	110 ± 2.6	14.8 ± 0.3
Mod 2 - Hesitation	50.9 ± 5.0	211 ± 25.0	34.7 ± 0.9
Mod 3 - Hesitation + Weld Line	38.1 ± 2.2	136 ± 15.9	18.4 ± 0.7
No Modifications	50.3 ± 3.4	214 ± 11.8	32.8 ± 0.6

The obtained data confirmed a reduction of tensile toughness for PA-12 samples containing a weld line (Mod 1) by up to 55% compared to unmodified and 57% compared to samples produced under the influence of flow hesitation (Mod 2). All weld line samples failed early along the actual weld line caused by the formation of a v-notch [8], consistently (2.7% standard deviation) around 110% strain. This is believed to be caused by an unbalance in spherulite size, different localised crystalline structures (presented in FIGURE 2b) established due to the unique thermal properties along the melt fronts, which probably results in reduced cooling rates and, improved spherulite growth conditions. The addition of a mould design feature (Mod 3) causing flow hesitation reduced the magnitude of this material weakness and necking continued even after the notch formation, enabled due to a supposed more homogeneous morphology within the weld line region. The obtained test data for instrumented impact testing is presented in TABLE 2.

TABLE 2. Impact results PA-12: Effect of different material flow modifications

Material Flow Modification	Peak Force [N]	Total Energy [J]
Mod 1 - Weld Line	3350 ± 10	48.3 ± 0.59
Mod 2 - Hesitation	3560 ± 10	51.2 ± 0.72
Mod 3 - Hesitation + Weld Line	3450 ± 30	46.4 ± 0.74
No Modifications	3360 ± 40	49.5 ± 0.67

The observed differences in impact behavior due to different flow modifications are less obvious compared to quasi-static tensile results. The differences between the highest data for the hesitation samples (Mod 2) and the lowest, for hesitation + weld line (Mod 3) was 4.77 J, a reduction of 9.31% with all samples showing a ductile failure. While flow hesitation increased the tensile toughness for samples featuring weld lines, it reduced the obtained total energy during impact testing. The increased peak force compared to the weld line (Mod 1) and no modification samples was accompanied by the lowest puncture deformation findings. Therefore, the positive influence of hesitation on PA-12 weld line samples is not correlating between quasi-static uniaxial and dynamic multi axial loading scenarios, although the hesitation samples (Mod 2) showed again a superior behavior.

Material Characterization

The occurring mechanical properties of a moulded material sample are predetermined on the microscopic level where certain structures are established during the injection moulding process. The observed v-notch (FIGURE 2a) developing under tension along the weld line, leading to an early breakage during the quasi-static tensile test was investigated by optical microscopy. Under polarized light (FIGURE 2b and c) the weld line area showed an increased spherulite size compared to the surrounding area.

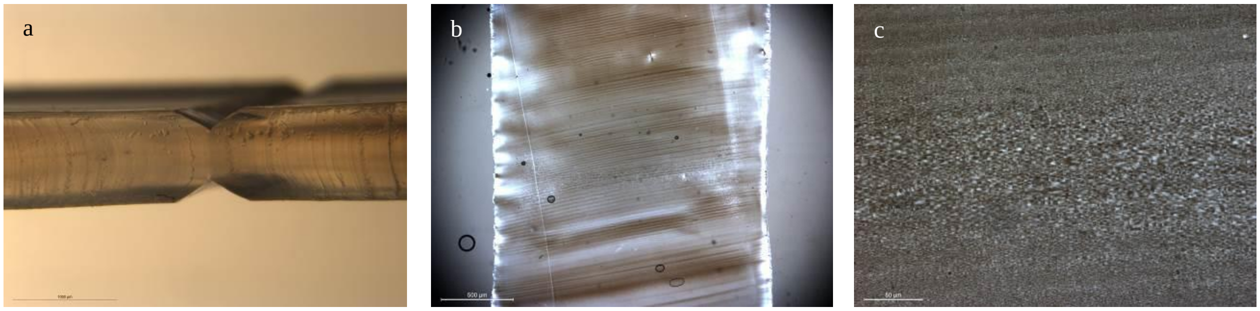

FIGURE 2. Optical microscopy findings weld-line region (a) occurring v-notch quasi-static tensile test (Nikon SMZ 1500) (b) difference in crystalline structure/ spherulite size 5x objective (Leica DMRX) (c) 40x objective (Leica DMRX)

The different crystalline microstructure within the weld line region makes the sample more prone to failure due to the occurring stress concentration under tension. While the developing v-notch on the surface of the samples is the more obvious macroscopic weakness, the final failure is caused by the poorly bonded layer along the weld line characterised by a different crystalline structure. The strength of the weld interface was improved for samples with occurring flow hesitation during the injection moulding process.
Data for the thermal behavior was obtained from DSC analysis and used to interpret the differences in mechanical properties: melt temperature, the detected enthalpy and the calculated degree of crystallinity are each presented in TABLE 4.

TABLE 4. DSC results PA-12: Effect of different material flow modifications and conditioning

Material Flow Modification	T_{Melt} [°C]	Melting Enthalpy [J/g]	Degree of Crystallinity [%]
Mod 1 - Weld Line	178.3 ± 0.4	42.6 ± 0.2	20.3 ± 0.1
Mod 2 - Hesitation	177.8 ± 0.4	52.1 ± 0.7	24.8 ± 0.3
Mod 3 - Hesitation + Weld Line	177.7 ± 0.6	46.3 ± 0.4	22.0 ± 0.2
No Modifications	178.2 ± 0.5	55.0 ± 0.6	26.2 ± 0.3

While the melting temperature is consistently found around 178°C (γ-crystalline form), matching material supplier information, a significant difference in melting enthalpy, respectively degree of crystallinity, was detected. While the samples with superior properties (Mod 2 and no modifications) showed 25% crystallinity, the results decrease for samples containing a weld line, with a higher degree when influenced by hesitation (Mod 3). These differences in morphology due to flow modifications correlate with the distinction of fracture mechanisms observed during mechanical testing, confirming weld lines as a material weakness for the investigated PA-12 material.

Conclusion

The influence of different melt flow modifications during the injection moulding process was highlighted for a commercially available PA-12 material. The mechanical properties for test specimen produced using a new mould differed by up to 57% when tested regarding their quasi-static tensile behavior and 9% with regards to impact properties due to different modifications. This highlights the fact that those investigations are essential to prevent unexpected failure of final parts with a more sophisticated geometry. Melt flow modifications leading to the formation of a weld line exhibited the highest performance decrease, weakening a part significantly compared to unmodified samples. A positive influence of occurring flow hesitation on the resulting weld line strength was observed for the uniaxial tensile properties. However, facing a dynamic multi axial loading scenario, during the impact test, the additional flow hesitation was counterproductive, decreasing the detected values. Structural features were evaluated on the microscopic scale using optical microscopy and DSC. Differences in spherulite size for weld line samples were detected as the reason for reduced tensile properties causing the creation of a notch and a stress concentration to form under tension significantly weakening the sample. A higher degree of crystallinity was detected for samples not containing a weld line, showing superior mechanical properties. Overall it can be concluded that the new tool allows the testing of new or enhanced materials and delivers more realistic results for complex geometries compared to simplified injection moulded test specimen produced by idealised melt flow conditions. More suitable design data are therefore obtained to predict the mechanical behavior of a final part, using practical or computational techniques, by paying sufficient attention to the change in performance due to differences in flow behavior when injecting more sophisticated geometries.

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