Plastics Research Online
10.2417/spepro.006931

Novel indicator of weld line strength in extruded parts

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A combined numerical and experimental approach provides an improved understanding of the correlation between flow conditions and the strength of weld lines.

Weld lines form when two or more flow fronts in a fluid merge, or when the flow encounters an obstacle that forces two portions of the fluid to separate (and then rejoin at the end of the obstacle). These weaknesses (i.e., the weld lines) can be the consequence of specific molecular orientations in the stream/weld direction (causing inadequate entanglement of two independent fronts).[1,2] Alternatively, when the fluid fills an empty cavity, the weld lines may occur because the two fronts are at a relatively low temperature and form a 'skin' of trapped air.[3] Although weld line formation has been known since extrusion and injection molding processes were first implemented, to date, this problem has mainly been studied in the latter cases.[4–19]

Despite the lack of research on weld line formation during extrusion, it has been shown that weld lines form in these cases whenever hollow profiles are produced or when flow separators are used.[20] Furthermore from a numerical modeling study,[21] it has been demonstrated that an optimized spider-leg geometry can be used to achieve a relative fatigue life of 90% for a material (compared with that for a region without any weld lines). In contrast, the relative fatigue life of the same material was only 10% when it was extruded with a typical geometry. In subsequent work,[22–24] different spider-leg extrusion geometries were tested and the elongational stress in the material was found to be most effectively reduced by a spider-leg rear-end angle of 60°C.

To extend these previous studies of spider-leg effects in extrusion, we have combined experimental and numerical approaches to investigate how the location of the spider leg affects the mechanical properties of rectangular (in cross section) extruded profiles.[25] For our numerical simulations we used the Giesekus model[26] with fitting parameters that we obtained from a rheological characterization of an extrusion-grade polystyrene (Polystyrol 158K, provided by BASF). With this model we were able to produce a reliable method to predict the stresses and velocity fields inside the extrusion die (impossible to achieve experimentally) that we used for our tests (as shown in Figure 1).

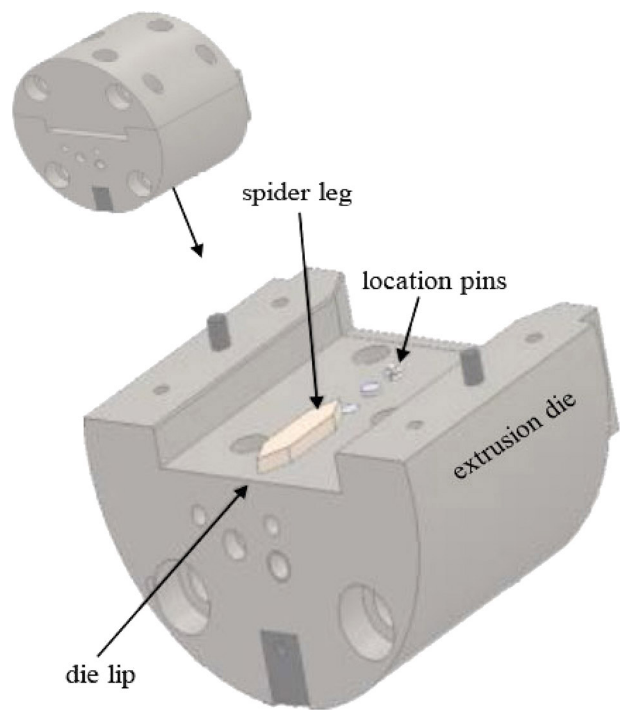

Figure 1. Schematic diagram of the extrusion die prototype used in the experimental work. For scale: the spider leg has a length of 28mm (see Figure 2).

The experimental and numerical studies were performed under the same conditions (i.e., polymer, spider leg location, extrusion temperature, and flow rate).

Our prototype extrusion die (designed to allow systematic studies of the effect of weld lines in extrusion to be conducted) includes a moveable spider leg, a positioning/fixing system, as well as a tool for changing the spider leg location.[27,28] With this die, we were thus able to produce several different polystyrene samples by positioning the spider leg at three distinct locations (d_1, d_2, and d_3, as shown in Figure 2) and by using three different screw speeds. These speeds corresponded to mass flow rates of 4.0, 5.3, and 6.3kg/h (or average outlet velocities

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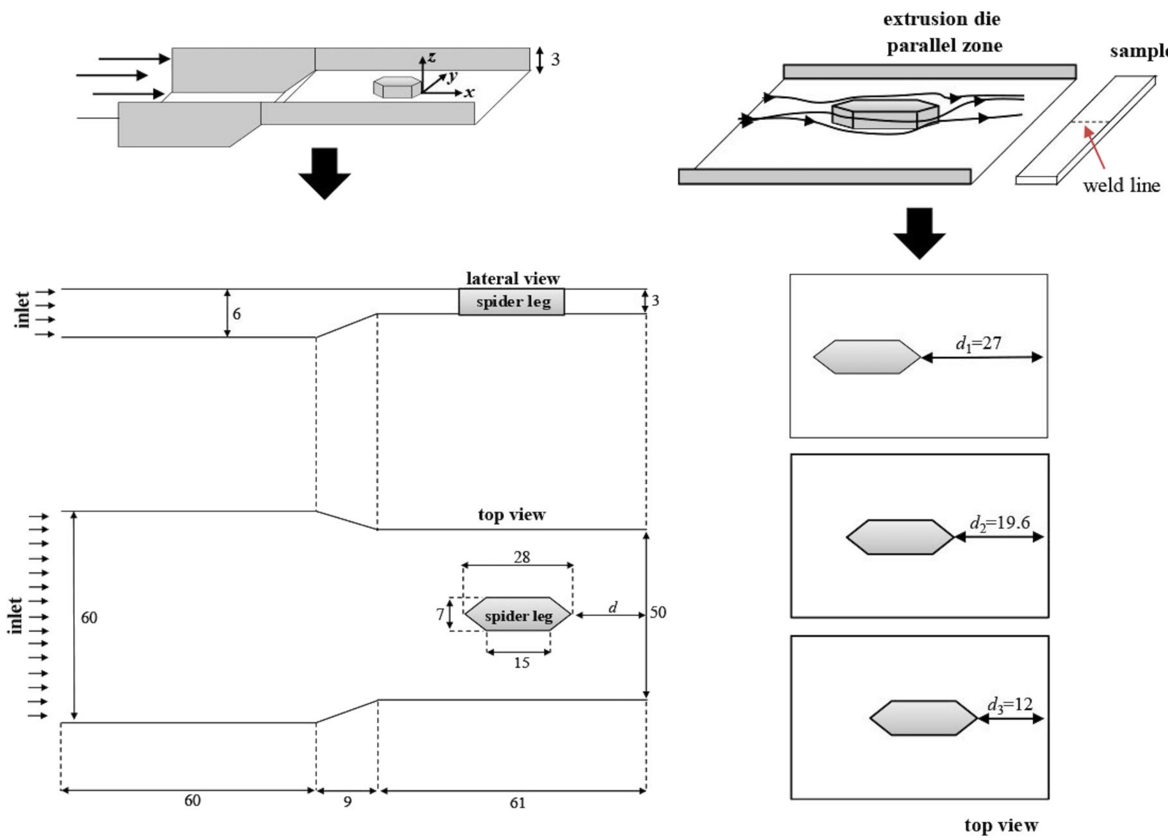

Figure 2. *Lateral and top view of the extrusion geometry modeled in the numerical simulations. All dimensions are given in mm. d_1, d_2, and d_3: Spider leg locations used for extrusion.*

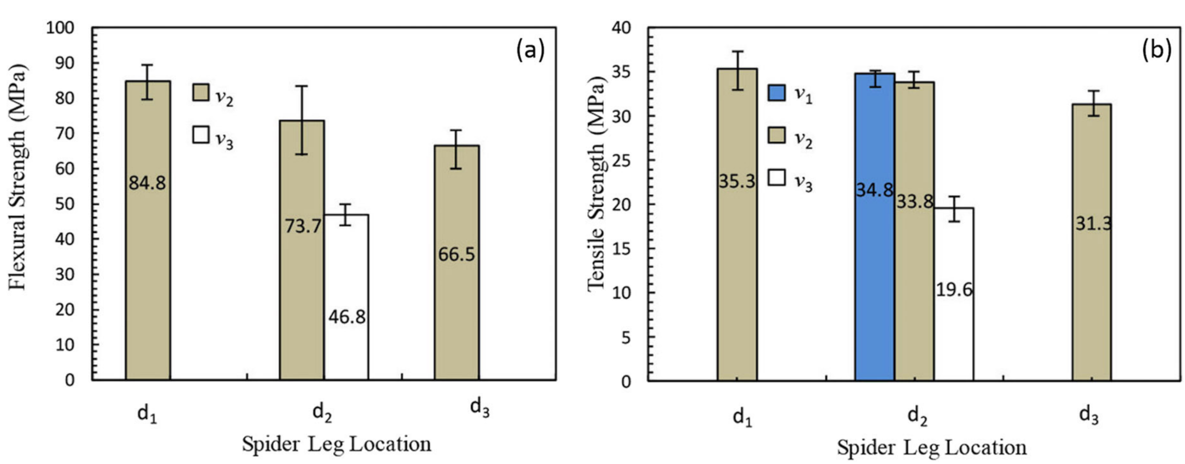

Figure 3. *Experimental results from (a) flexural and (b) tensile strength tests. The results are given for the polystyrene samples that were extruded with the spider leg at three different positions (i.e., d_1, d_2, and d_3) and for three different flow rates: 0.42 (v_1), 0.56 (v_2), and 0.67 (v_3).*

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of 0.42, 0.56, and 0.67m/min, respectively). We then cut the samples and tested them perpendicularly to the extrusion direction, i.e., so that the weld line was present at their midplane.

The results of the flexural tests on the extruded samples—see Figure 3(a)—show that the tapes we produced with the spider leg at d_1 (i.e., the furthest from the flow channel outlet) have the same

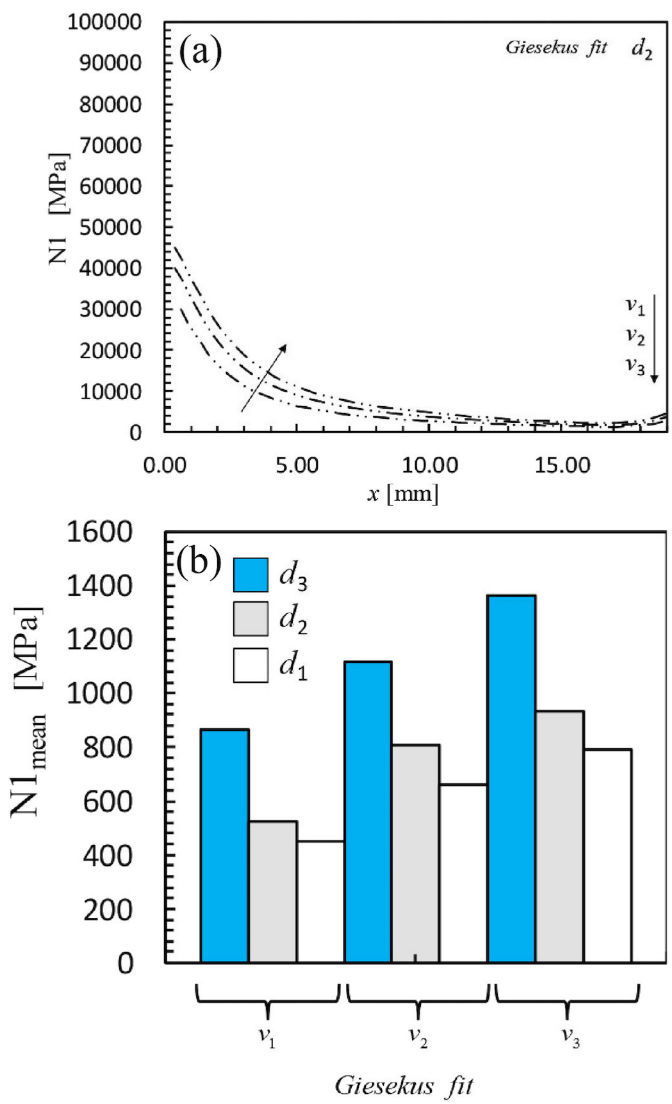

Figure 4. *(a) Variation (along the x-axis) in the simulated normal stress difference (N1), i.e., between the rear of the spider leg and the die exit. Calculation results given here are for a fixed spider-leg location (d_2) and for three different flow rates. (b) Calculated mean N1 ($N1_{mean}$), between the rear of the spider leg and the die outlet, for the three different Giesekus models used in this work (i.e., to model the three merging location and three extrusion flow rates).*

flexural strength as the samples extruded in the absence of the spider leg. In contrast, we find that the flexural strength of the sample produced with the spider leg at d_3 (the closest position to the flow channel outlet) was 22% lower than that of the reference sample (i.e., produced at an outlet velocity of 0.56m/min, without the spider leg). We did, however, observe a slight improvement in the flexural strength of the sample (a decrease of only 13% relative to the reference sample) when we moved the spider leg from d_3 to d_2. We also measured an 11% reduction in the tensile strength—see Figure 3(b)—of the polystyrene sample when we moved the spider leg from d_1 to d_3 for extrusion. Moreover, by increasing the melt flow rate from 4.0 to 6.3kg/h, we reduced the tensile and flexural strength of the samples by 41 and 36%, respectively.

As part of our numerical modeling, we calculated the first normal stress difference (N1) between the rear of the spider leg and the extrusion flow channel outlet for a range of outlet velocities. Our results—see Figure 4(a)—show that N1 decreases sharply along the channel, until a steady state is reached. We were thus able to compute the mean N1 value—see Figure 4(b)—and use it as an indicator of the weld line quality. Based on these calculations, we expected the effectiveness of the welding to increase with decreasing mean N1 values, and vice versa. This is in agreement with the actual observed trends. That is, we found that an increase in flow rate leads to an increase in the first N1. In addition, as the spider leg is moved toward the flow channel outlet, the mean N1 also increases.

In summary, we have used a combination of experimental tests and numerical simulations to investigate the use of a spider leg geometry for extrusion processes. In particular, we have studied how the location of the spider leg affects the mechanical properties of extruded polystyrene parts. The results of our work are in accordance with findings that have been previously reported in the literature, and we have therefore successfully demonstrated a new experimental- and numerical-based indicator for weld line strength. In our upcoming work, we will assess this proposed methodology by examining different materials and processing conditions.

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