POLYFLOW: A TREATISE ON INVERSE DIE/MANDEL DESIGN FOR HIGH CONSISTENCY SILICONE ELASTOMER

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Abstract

To date, manufacturing experiences low production yields when extruding complex cross-sections with high consistency silicone rubber (HCR). In the extrusion process, shear is imparted into the material causing both shear thinning and elastic effects which make the die/mandrel design uncertain. Computational Fluid Dynamic methods [POLYFLOW] were utilized to model the flow characteristics of the material through the die/mandrel to determine their proper shape with respect to the required extrudate. Non-linear viscoelastic constitutive models correlating rheology with the actual flow dynamics were utilized in the software to achieve this end. The die/mandrel design developed through the modeling techniques demonstrated their invaluable need by boosting production rates as high as 167%, and decreasing waste and set-up time 18 fold respectively. Finally, the process developed in this paper should be utilized to improve existing and future designs where complex profiles cause long set-up times and high scrap rates.

Introduction

High consistency silicone rubber (HCR) has been extruded for over 30 years. As with all product lines, applications have developed where complex profiles with high tolerances are required. In the past, fabricators have suffered low process yields on these products, however as competition evolved these losses were no longer acceptable. The two major contributors to low process yields include set-up time and size control.

Previous work on die/mandrel design focused primarily on utilizing shear thinning CFD models to predict robust designs (1). Their contention was that the non-uniform velocity profile at the die/mandrel exit formed the design. That effort launched the utilization of POLYFLOW to predict high tolerance die/mandrel designs for a non-linear viscoelastic fluid.

This work targeted a refined design methodology to predict high tolerance complex die/mandrel shapes to eliminate these problems. The contention of this method was to capture both the velocity profiles at the die/mandrel exit along with the material's rheology to fully capture its swell profile. To develop this technology, a complex profile was selected where average set-up times were several hours in length suffering hundreds of pounds of waste. The complex profile consisted of five tubes connected by a thin web. Each web contained a v-notch used as a tear sight for stripping back the individual lumens or tubes (Figure 1).

Material Rheology

The first development step was to understand the flow characteristics of HCR. Several rheological tests were performed to understand the fluid’s response to simple flows (2). Two different types of data were gathered: The first type involved understanding the viscous nature of HCR, while the second involved its elastic response.

Viscous data was gathered on a ROSAND twin bore capillary rheometer. The viscosity vs. shear rate data gathered ranged from three to 3862 sec⁻¹. The procedure was repeated eight times to statistically distinguish the test noise (Figure 2).

The elastic nature of HCR was captured through a Rheometrics RDS-2 dynamic mechanical rheometer. The storage and loss moduli were gathered on the same material lot via frequency sweep on parallel plates. Data ranging from 0.005 to 100 sec⁻¹ at 0.085% strain was allowed through the use of Time Temperature Superposition (Figure 3). Additional viscosity vs. shear rate was obtained during the test which extended the capillary rheometer data (Figure 2).

Attempts were made to perform a frequency sweep on the first normal stress difference. This normal force can be correlated back from the storage modulus, but only within the linear region of the material. This correlation is of little value when considering the processing rates of an extrusion operation, therefore an independent measure of this property would be useful to better characterize the material. However, HCR’s normal stress difference was excessive and overloaded the measurement transducer yielding no results. Further investigation found this rheometer as capable as any other device, therefore a method to obtain this data for HCR was not found.
Relaxation time measurements were also completed on the sample to obtain additional elastic properties. Between parallel plates, a 0.5% strain was introduced in the material as a starting point, and the time required for the material to relax was measured. From there, stress relaxation vs. time was traced, and four time constants were used to fit the data. Further data refinement at different strain levels was not completed due to the findings discussed in the, “Die Swell Calibration,” section.

**HCR Rheology vs. Numerical Models**

At this point, the best fitting numerical model could be selected based on viscosity and elasticity data. This data was utilized in PM3, a curve fitting module within POLYFLOW, to match the rheological data with a numerical model. The viscosity or shear thinning nature of HCR was easily fit by shear thinning, linear, and non-linear viscoelastic models (Figure 2). However, the storage and loss moduli would not fit any viscoelastic model (Figure 3). The differences were marked, and any approximations would yield unpredictable results.

**Die Swell Calibration**

HCR’s exhibit large normal stresses and long relaxation times when exposed to small strains. HCR is highly filled with reinforcing fillers which lead to this type of behavior. Even under moderate shear, the relaxation time of an HCR system leads to Weissengberg Numbers between 25 and 50. At this level of non-linearity, only a non-linear viscoelastic model could provide accurate results for predicting die swell. Because no scientific direction existed, the next step involved “calibrating” a model to predict die swell across several shear rates. This was accomplished by measuring die swell across various shear rates and die land lengths. Two dies with 0.325 cm diameter holes were fabricated. One had a 0.140 cm land, and the other a 0.018 cm land. The experiment involved a single lot of material, and both dies were used to make solid rods of HCR at various rates. Without curing or stretching, the extrudates were measured directly out of the die with calipers.

Both dies were simulated via POLYFLOW with two different non-linear viscoelastic models, the Giesekus-Leonov (G-L) and Phan-Thien-Tanner (P-T-T) techniques. Both techniques involve solution of the Navier-Stokes and Momentum Equations necessary for CFD. But, their respective constitutive equations with respect to the stress tensors are different which give rise to die swell.

Several iterations were completed to calibrate the models’ die swell at a particular shear rate. From there, the models’ accuracy were tested across the other experimental shear rates and die land length. From the data gathered, the G-L technique proved to be the most robust for predicting HCR die swell (Figures 4 & 5).

Attempts to improve the G-L technique by introducing multiple relaxation times gathered from the rheological tests failed. Further calibration was completed, but the results were not positive. In fact, the model over-predicted the swell, and increased the computational time (Figure 5). From this effort, the multiple relaxation time models were no longer considered.

**Computational Approach**

As stated above, the five lumen consists of five tubes, connected by four thin webs, where each web is v-notched along the axis of the extrudate (Figure 1). The tolerances, OD’s being +/- 0.015 cm, ID’s being +/- 0.013 cm, and width being +/- 0.035 cm did not allow for much error considering the number of features. The overall extrudate’s width to height, or 7:1 aspect ratio, contributed the greatest difficulty. More explicitly, die flow is similar to pipe flow, fluids travel down the center faster than when next to the wall. Therefore, the die shape for each lumen would be slightly different to compensate for the wall’s interaction (3).

However, with the number of geometrical features, the ability to compute such a large problem was not attainable. Based on calculations, a problem this size would require several Gigabytes of memory. Because this was not available, the aspect ratio difficulties were subverted by taking advantage of the profile’s repetitive geometry (Figure 1). Two different shapes exist within the profile. Each could be computed separately, then combined to assemble the final solution. The quarter lumen with the web was computed three dimensionally, because further simplification did not exist. The end lumens, which have no outside webs, were computed two dimensionally as a simple tube.

The inverse solution technique developed by POLYFLOW was utilized to deliver the computational solution. This technique is unique to the industry, because it modifies the die/mandrel land to deliver the prescribed shape. With other CFD tools, the analysis would be completed and one would manually iterate on the die/mandrel lip to achieve the desired results. Polyflow’s invaluable technique saves the user many hours of manual remeshing time by essentially making it the unknown when solving the free surface equations (4, 5).
Computational Results

Streamlines for the 2D case and the velocity profiles parallel to the extrusion direction for the 3D case are shown in Figures 6 & 7 respectively. These plots illustrate the large die swell which occurs with high consistency silicone elastomers. Moreover, the solid render of the velocity profile, Figure 7, illustrate the high gradients existing within the die / mandrel. As shown, the high shear rates occur at the surface where the material exits the die/mandrel (free surface). At this point, the material exhibits excessive non-linear behavior from the shear and free surface boundary condition requiring special attention of the mesh within this area. More simply, a single element cannot calculate huge gradients across itself, i.e. it won’t resolve the flow and stress equations. It takes several elements of specific geometry within a high shear area to resolve the viscous and elastic flow equations accurately for convergence.

The geometrical results of the two and three dimensional cases illustrated above yield similar OD and ID (within 5%). The 2D case achieved higher convergence, 100% vs. 58%, when in comparison to the 3D model, which led to three findings. First, the 2D case had a tighter mesh which improved its ability to resolve the flow and stress equations without suffering extensive computational time. Second, high shear stresses existed in the web area of the 3D model causing Weissenberg Numbers between 27 and 30. A refined mesh might subvert this limitation, however the computational resource, IBM RS6000-390 with 256 Megabytes of RAM, was the limiting factor. Finally, the OD and ID shapes for the 3D case would probably not change with further evolution since the 2D case yielded similar results upon 100% convergence. Therefore, further simulation beyond this point was not completed.

Weissenberg Limitations

The Weissenberg or Deborah Number is the ratio of the material’s characteristic relaxation time to its characteristic flow time. By using this number, along with the strains within the flow regime, the response of a viscoelastic fluid, be it linear or non-linear, can be predicted. Within this flow regime, the shear rates ranged from 1800 - 2000 sec⁻¹, and the relaxation time constant was 3.065 x 10⁻² sec. Multiplying these numbers yield a Weissenberg Number between 27 - 30. At these levels, the flow regime is highly non-linear, and any time driven rheological property becomes independent. In this case, because the models were calibrated by “extrusion rates vs. die swell” this fact made little impact. The problem is that the Weissenberg limitations originate from the numerical techniques and element discretization used to interpolate the flow regime. Therefore, with the current numerical techniques within POLYFLOW the flow regime can not be resolved, nor can the limitations be subverted.

Experimental Die / Mandrel

The five lumen die/mandrel tooling was fabricated to verify the modeling results obtained. The die was wire EDM’d from tool steel using the 2D results for the outside two holes, while the 3D results were used for the center three holes. Although POLYFLOW predicted the cannula should be slightly elliptical, they remained round for the initial experiment.

A 2.5" diameter extruder and horizontal oven were utilized to conduct the experiment. The 12 runs completed studied six speeds across two different material lots to evaluate the sensitivity of speed and lot variation. The following five findings evolved:

1. The numerical solution was not sensitive to lot variation.
2. The OD of the outside lumens were smaller than the center three.
3. The outside lumens’ ID’s were smaller and possessed less ovality than the center three lumens.
4. All of the lumen’s ID’s were too small, and needed to be increased.
5. The extrusion rates demonstrated a 127 to 167% speed increase without loss of size stability.

Unfortunately, the risk taken with modeling only one lumen caused difficulty with the overall solution.

Production Die / Mandrel

From the experimental tooling, the following adjustments were completed:

1. The outside two holes in the die were increased proportionally to compensate for the wall effects.
2. The mandrel OD’s were increased to compensate for the above findings.
3. The center three mandrels were cold formed to the shape prescribed by the POLYFLOW solution.

With the same extrusion process, two campaigns studied the set-up’s size stability over time at two different line speeds. The first campaign ran at 1.7 times current line speed for 60 minutes, while the second ran at 1.3 times current line speed for 75 minutes. From the experiment, four conclusions resulted:

1. The five lumen’s OD’s and ID’s were within 0.005 cm and 0.0025 cm respectively.
2. The center three elliptical mandrels compensated for the ovality condition experienced in experiment one.
3. The overall width of the component was narrow with respect to the tolerance because the stretch induced by the oven belt wasn’t numerically considered.

Conclusions

A die/mandrel design technique was developed where CFD was used in conjunction with empirical engineering techniques. As the tools (hardware/software) develop with time, complex shapes will become more easily handled and eliminate the empirical modifications.

A five lumen die/mandrel design was developed which reduced set-up time and waste 18 fold while increasing production by a factor of 1.7. Because the 1/4 symmetry model could not be computed, the overall flow could not be predicted making empirical die/mandrel modifications necessary.

The single relaxation time Giesekeus-Leonov model (non-linear viscoelastic differential technique) best represented HCR when in comparison with other non-linear models.

The highly non-linear viscoelastic rheology of HCR was difficult to simulate because of Weissenberg Limitations and present day numerical techniques.

References


![Figure 1](image)
Five Lumen Profile
Figure 2
Viscosity vs. Shear Rate

Viscosity (dyne*sec/cm²)

RDS-2 Data
ROSAND Data

Power Law Model
\[ \eta = 8.77 \times 10^3 \text{ dyne*sec/cm²} \]
\[ n = 0.1 \]

Shear Rate (1/sec)

Figure 3
Storage and Loss Moduli

Modulus (dynes/cm²)

RDS-2 Data
Storage Modulus
Loss Modulus

Giesekus-Leonov Model
\[ \eta = 3.4 \times 10^4 \text{ dyne*sec/cm²} \]
\[ \text{relax} = 3.056 \times 10^2 \text{ 1/sec} \]
\[ \alpha = 0.4 \]
\[ \text{ratio} = 1.5 \times 10^2 \]

Frequency (1/sec)
Figure 4
0.018 cm Land Exp. vs. Numerical Die Swell

Figure 5
0.140 cm Land Exp. vs. Numerical Die Swell
Figure 6
Streamlines of the 2D Case

Figure 7
Velocity Profile Parallel to the Extrusion Direction for the 3D Case