

Melt Elasticity and Viscosity of Neoprene WB at High Shear Rates

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INTRODUCTION

Most factory elastomer processing equipment subjects the polymer to high shear rates. ASTM standard tests of processibility, Mooney viscosity and Williams plasticity, are determined at shear rates under 2 sec.⁻¹. A number of examples have been found where comparative values from low shear rate tests were not valid at high shear rates. For such elastomers the magnitude of the high shear rate viscosity cannot be predicted from low shear tests. High shear rate equipment such as a capillary rheometer is required.

Capillary rheometer data are prevalent in the literature. The raw data of force required to extrude at a range of speeds are useful for comparison of polymer melts. However, to understand the processing of polymers requires that basic properties of such melts be determined. By using long capillary tubes it is permissible to neglect the entrance effect and approximate the viscosity. Pipe lines can be designed with this information. Entrance effect is defined as the added length of capillary (expressed as number of diameters) needed to account for the extra pressure drop occurring near the entrance of the capillary. The entrance effect increases as the elasticity of the polymer melt increases.¹

In processing equipment, the entrance effect is important and, therefore, must be evaluated, not neglected. For example, extrusion orifices are often only about as long as the equivalent diameter. Others are longer but taper so that they are more nearly like orifices with short length to diameter ratios than like long tubes. Philippoff and Gaskins² note that for short dies viscosity has a secondary contribution to resistance to flow compared to the elastic type forces. Also, in the calendaring operation, passing the elastomer through the nip between rotating cylinders involves a length of travel during shear that is of the same order of magnitude as the distance between the rolls. In the complex geometries of processing equipment, the various components of the stress tensor can be exerted in a totally different way than in the capillary rheometer. Stresses must be separated and their application understood before predicting processing of a

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polymer melt. A method of separating viscous and elastic properties is described and applied to Neoprene WB. The method is an extension of that described by Philippoff and Gaskins and applied to polyethylene by Bagley.³

A principle of corresponding rates of shear at different temperatures is introduced for shear stress, melt elasticity, die swell, and extrudate roughness. Construction of composite curves by shifting data at different temperatures along a logarithmic frequency axis has been reviewed recently by Ferry.⁴ He has applied such a method extensively to dynamic measurements on solid polymers during the past decade.⁵ Vertical shifts for temperature density corrections are employed. This correction is small and has not been used in the present work because it did not improve the composite curves. Smith⁶ obtained a reduced variable stress-strain composite curve for elongation of polyisobutylene up to 100% and temperatures between -54 and 85°C . DeWitt⁷ predicted that dynamic and steady flow viscosity should be identical if an unambiguous strain rate in steady flow is used. His conclusion is based upon an equation of state formulated from classical Maxwell assumptions. Padden and DeWitt⁸ state that superposition procedures used for dynamic data are apparently applicable to the viscosity and pressure data with rate of shear taking the place of frequency. In a paper printed after the conclusion of this work, Ito⁹ uses such a method on consistency curves for acrylic resins.

The present work incorporates some of these concepts in extending the superposition principle for extrusion. Important variables in this process, smoothness of extrudate surface and die swell, are shown to have a critical shear rate-temperature condition at which the minimum entrance effect also occurs. This critical generalized shear rate is, therefore, a property of the polymer.

EQUIPMENT AND PROCEDURE

The capillary rheometer used in this study is of the constant-speed-piston type employing a compression load cell to record force (Fig. 1). The steady-state forces required to extrude polymer through each of a series of

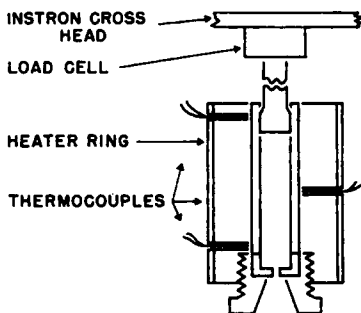


Fig. 1. Capillary rheometer cross section schematic.

circular orifices varying in length and diameter at many piston speeds were obtained as previously described by McCabe and Mueller.¹⁰ Extrudates were collected and surface appearances rated. Die swell was calculated as percentage increase in equivalent diameter from weight per unit length of sample compared to the orifice diameter. Data cover the shear rate range of 0.4–11,000 sec^{-1} at temperatures from 80–125°C.

Orifices used are 0.0153, 0.0306, and 0.0460 in. in diameter with length to diameter ratios (L/D) of 2, 9, and 16 for each diameter. Since the analysis of the data requires comparison between results on different dies, close tolerances on die dimensions and orifice edge sharpness is necessary. Orifice diameters were determined with a calibrated microscope; edge sharpness was checked regularly during runs. Force readings were obtained on orifices of different diameters which ensures that complicating effects such as thixotropy and slip at the wall are minor.¹ Furthermore, the analysis of data used here causes error from such sources to be placed in the residual standard error and thus separated from the studied effects.

The polymer used in this study is Neoprene WB. It is a commercial grade of polychloroprene elastomer which possesses superior processing characteristics.

METHOD OF CALCULATION

Viscous and Entrance Effect

Polynomials were fitted to the force F vs. Newtonian shear rate ($8 \times$ mean velocity/diam.) data for each temperature and L/D using all data

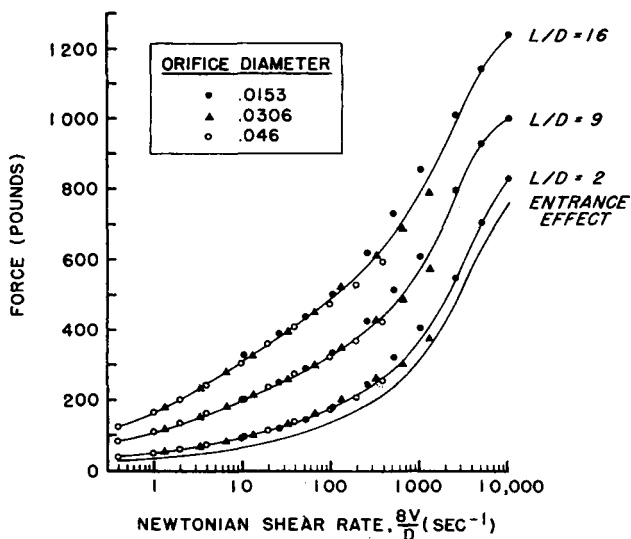


Fig. 2. Force required to extrude Neoprene WB at 80°C. through orifices of several diameters and length to diameter ratios (L/D) vs. Newtonian shear rate. Curves are calculated values.

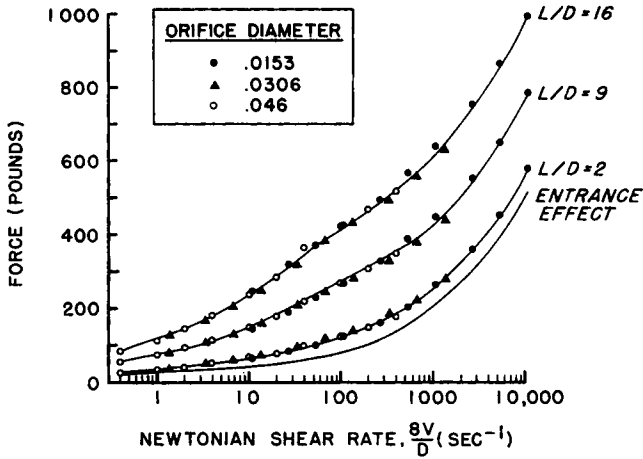


Fig. 3. Force required to extrude Neoprene WB at 100°C. through orifices of several diameters and length to diameter ratios (L/D) vs. Newtonian shear rate. Curves are calculated values.

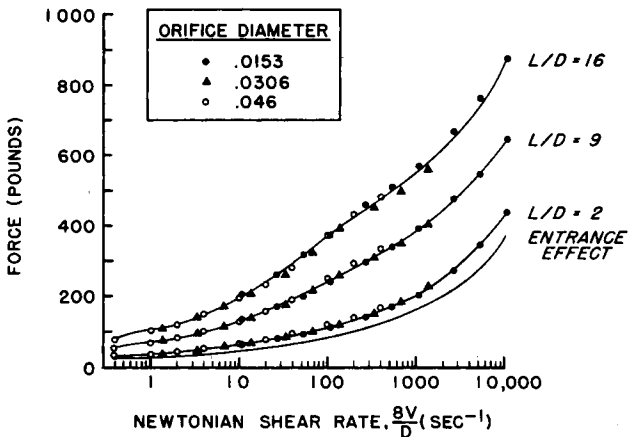


Fig. 4. Force required to extrude Neoprene WB at 125°C. through orifices of several diameters and length to diameter ratios (L/D) vs. Newtonian shear rate. Curves are calculated values.

collected with the three different orifice diameters. Letting $X = [\log(8V/D) - 1.779]/2.216$, the general expression is the following:

$$F = b_0 + b_1X + b_2X^2 + b_3X^3 + b_4X^4 + b_5X^5 + b_6X^6 + b_7X^7 \quad (1)$$

The data and the curves calculated by regression analysis are shown in Figures 2, 3, and 4 for temperatures of 80, 100, and 125°C. Coefficients of the polynomial equations appear in Tables I, II, and III. The residual estimates of the standard deviations are graphed in Figure 5 to show the

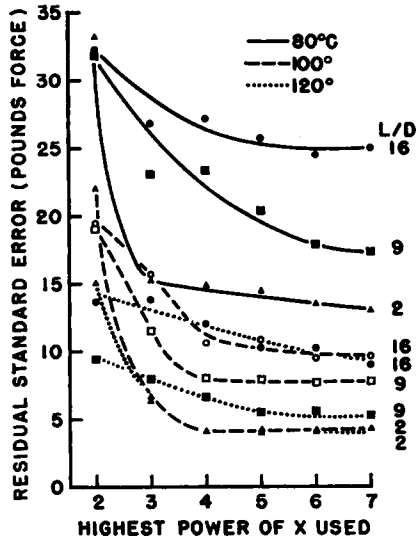


Fig. 5. Residual standard error after adding each term to the polynomial force equations.

goodness of fit. Note that the standard deviations for 100 and 125°C. are close in value while that at 80°C. is much higher.

Viscous and entrance effects were separated employing the usual principle of a linear relationship between pressure drop and orifice length.^{1,2} An equivalent expression in terms of total measured force F , entrance force F_E and viscous force per unit L/D , f , is as follows:

$$F = F_E + f(L/D) \quad (2)$$

At each temperature the total force is given by three polynomials, one for each L/D . Since the L/D 's are equally spaced at values of 2, 9, and 16, a "least-squares" fit of eq. (1) in terms of these polynomials can be readily determined. The viscous force per unit L/D is obtained by subtracting the polynomial expression for the equilibrium force F_2 with the $L/D = 2$ orifice from the polynomial F_{16} with $L/D = 16$ and dividing by the difference in L/D as follows:

$$f = \frac{F_{16} - F_2}{16 - 2} = \frac{1}{14} [b_0 - b_0' + (b_1 - b_1')X + (b_2 - b_2')X^2 + \dots + (b_7 - b_7')X^7] \quad (3)$$

where primes refer to the coefficients of the indicated force polynomial. The equilibrium force polynomial F_9 for $L/D = 9$ does not enter the "least-squares" solution for f as shown in eq. (3).

The true equilibrium flow shear stress at the wall of the tube τ_e is obtained from the viscous force per unit L/D .

$$\tau_e = \Delta P/4(L/D) = (A/4)f \quad (4)$$

TABLE I
Polynomial Coefficients for Neoprene WB at 80°C.

Predicted force or stress	b_0	b_1	b_2	b_3	b_4	b_5	b_6	b_7							
F_{16} (lb.)	4.46077	+	4.01196	+	1.52692	+	3.88299	+	3.27104	-	2.07945	-	2.47402	-	0.26265
F_9 (lb.)	2.97960	+	3.25499	+	1.00578	+	0.01939	+	5.13673	+	6.72014	+	3.67752	-	5.41540
F_2 (lb.)	1.55669	+	2.38397	+	1.32751	-	0.58616	+	3.33816	+	6.47487	-	1.90086	-	4.37771
F_E (lb.)	1.13215	+	2.17036	+	1.15858	-	1.76766	+	3.95852	+	9.20437	+	2.31567	-	5.99729
τ_e (dynes/cm. ²) ($\times 10^{-4}$)	3.2369	+	1.8147	+	0.2222	+	4.9816	-	0.0747	-	9.5350	-	0.6389	+	4.5868

TABLE II
Polynomial Coefficients for Neoprene WB at 100°C.

Predicted force or stress	b_0	b_1	b_2	b_3	b_4	b_5	b_6	b_7							
F_{16} (lb.)	3.85337	+	3.99223	-	0.73804	-	0.58579	+	4.41293	+	2.23748	-	2.16540	-	1.14310
F_9 (lb.)	2.43580	+	2.86119	+	0.42391	-	0.51720	+	2.18379	+	2.31166	-	0.86858	-	1.08494
F_2 (lb.)	1.13892	+	1.44769	+	1.12851	+	1.50177	+	1.05703	-	0.54834	-	0.33861	+	0.30983
F_E (lb.)	0.73102	+	1.13156	+	1.47146	+	1.47492	+	0.39386	-	0.45731	+	0.05012	+	0.29462
τ_e (dynes/cm. ²) ($\times 10^{-4}$)	3.0257	+	2.8359	-	2.0807	-	2.3269	+	3.7404	+	3.1052	+	2.0361	-	1.6195

TABLE III
Polynomial Coefficients for Neoprene WB at 125°C.

Predicted force or stress	b_0	b_1	b_2	b_3	b_4	b_5	b_6	b_7							
F_{10} (lb.)	3.26447	+	4.49661	+	0.38887	-	5.23519	+	1.57020	+	9.46829	-	0.48365	-	4.81834
F_9 (lb.)	2.14833	+	2.9198	+	0.87475	-	2.13523	+	0.29033	+	4.07471	+	0.16358	-	1.95134
F_2 (lb.)	1.01805	+	1.33160	+	0.78509	-	0.14984	+	0.31897	+	1.52360	+	0.18049	-	0.71860
E_g (lb.)	0.69948	+	0.88140	+	0.93760	+	0.76241	-	0.07783	-	0.08512	+	0.38043	+	0.13976
τ_e (dynes/cm. ²) ($\times 10^{-4}$)	2.5040	+	3.5278	-	0.4416	-	5.6684	+	1.3946	+	8.8555	-	0.7403	-	4.5709

where ΔP is the pressure drop across the capillary due to viscous forces and A is the area of piston driving the elastomer through the orifice. τ_e is, therefore, expressed in polynomial form with constants shown in the tables.

The "least-squares" estimate of the entrance force is then calculated using the polynomials at the three L/D 's:

$$F_E = \frac{1}{3} (F_2 + F_9 + F_{16}) - 9f = \frac{1}{3} [b_0 + b_0' + b_0'' + (b_1 + b_1' + b_1'')X + (b_2 + b_2' + b_2'')X^2 + \dots + (b_7 + b_7' + b_7'')X^7] - 9f \quad (5)$$

The regression coefficients are listed in the tables. The entrance effect is expressed as equivalent L/D 's, e , for any shear rate and each temperature.

$$e = F_e/f \quad (6)$$

Shear Rate Correction

The shear rate at the wall shown in Figures 2, 3, and 4 is based upon parabolic velocity distribution across the capillary as would be obtained for a Newtonian fluid. The distribution is not parabolic for Neoprene WB; it is a viscoelastic material and the velocity distribution is intermediate between parabolic and uniform. The true equilibrium flow shear rate at the wall γ can be calculated from the following equation:¹¹

$$\gamma = \frac{3n + 1}{4n} \cdot (8V/D) \quad (7)$$

where

$$n = \frac{d \log \tau_e}{d \log (8V/D)} \quad (8)$$

The true equilibrium shear stress has already been determined as a polynomial function of $\log (8V/D)$ for each temperature. Therefore, n can be evaluated as follows:

$$n = \frac{1}{\tau_e} \cdot \frac{d\tau_e}{d \log (8V/D)} = \frac{1}{\tau_e} (b_1 + 2b_2X + 3b_3X^2 + 4b_4X^3 + 5b_5X^4 + 6b_6X^5 + 7b_7X^6) \quad (9)$$

However, in obtaining the derivative for evaluation of this equation, the deficiency of the empirical polynomial model in the extremes of shear rate becomes apparent. The polynomial is not consistent with expected values outside the shear rate range studied. Therefore, the polynomial can rise or fall rapidly beyond the range of the data. Between the last two data points at either extremes the derivatives reflect this behavior and are, therefore, not useful in the shear rate correction. Rather than use this correction on part of the data only, the results have been presented as functions of Newtonian shear rate. The method outlined here will be useful when a model whose derivatives follow the expected behavior is used.

RESULTS AND DISCUSSION

Flow Properties

The original data for each of the three temperatures are presented in Figures 2, 3, and 4. For each L/D , the force vs. shear rate plots illustrate that the flow curves are independent of the orifice diameter. All data points were used in fitting the curves. There is a small trend to lower force values at the highest shear rates for each orifice. This could be due to heat generation. Since the flow curves for Neoprene WB depend only upon the temperature and L/D , the separated viscous and elastic properties of the polymer become functions of only the shear rate and temperature. The true equilibrium shear stress for each temperature as calculated from eq. (4) is shown in Figure 6. The general pattern in shear stress rises with increasing shear rate and with decreasing temperature. The drop in shear stress at the highest shear rate and 80°C. is probably not real as the effect of viscous shear heating is greatest under these conditions and could account for this behavior.

The entrance force obtained from eq. (5) is plotted for each temperature on the graphs with the original data (Figs. 2, 3, and 4). Note for all temperatures how large this force is compared with the total measured force; this is most pronounced for $L/D = 2$. Figure 7 shows the length of orifice equivalent to this entrance effect expressed in number of orifice diameters as determined from eq. (6). In this form the entrance effect falls slightly at low shear rate to a minimum and then rises very rapidly with increasing shear rate for each temperature.

These curves show that a change in temperature is equivalent to a shift in shear rate. This is demonstrated in Figures 8 and 9 which are master curves for true equilibrium shear stress and entrance effect. They are obtained by shifting the curves horizontally from Figures 6 and 7

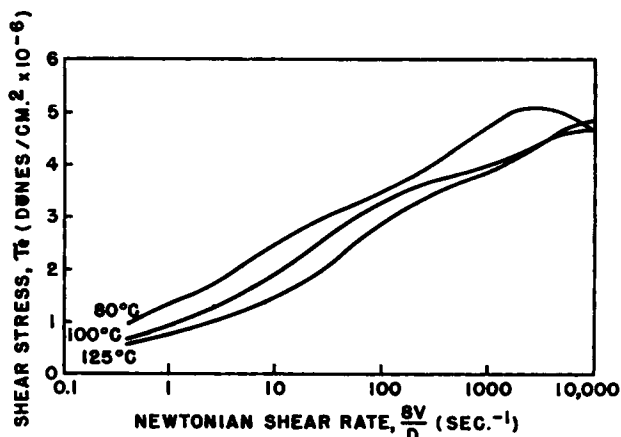


Fig. 6. True equilibrium shear stress vs. Newtonian shear rate for Neoprene WB at 80, 100, and 125°C.

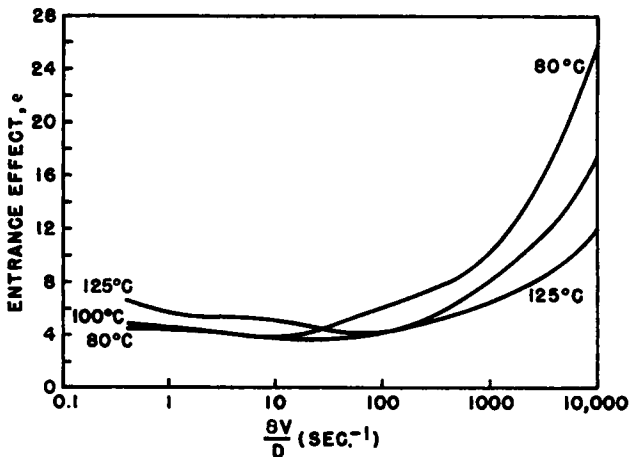


Fig. 7. Entrance effect vs. Newtonian shear rate for Neoprene WB at 80, 100, and 125°C.

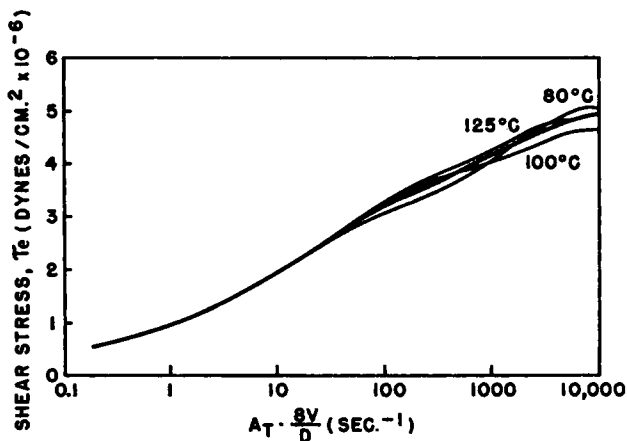


Fig. 8. True equilibrium shear stress curves at 80, 100, and 125°C. superposed by shifting shear rate scale a standard amount $\log a_T$, which depends only on temperatures.

respectively, until the curves for the various temperatures superpose (100°C. is arbitrarily selected as the reference temperature). The same shift in shear rate is used for both of these properties and for extrudate swell and roughness as described in the next section. The ordinate of these graphs is a generalized Newtonian shear rate; it is $8V/D$ multiplied by a factor, a_T , which depends only upon temperature. Selecting 100°C. as the reference temperature means $a_{100} = 1$. The 80°C. curves are shifted $\log a_{80} = +0.44$ and the 125°C. ones, $\log a_{125} = -0.38$ to superimpose the 100°C. results. Agreement is good considering the separation of viscous and elastic effects involves differencing the polynomial approximations of the data. The minimum entrance effect is near $a_T 8V/D = 20$

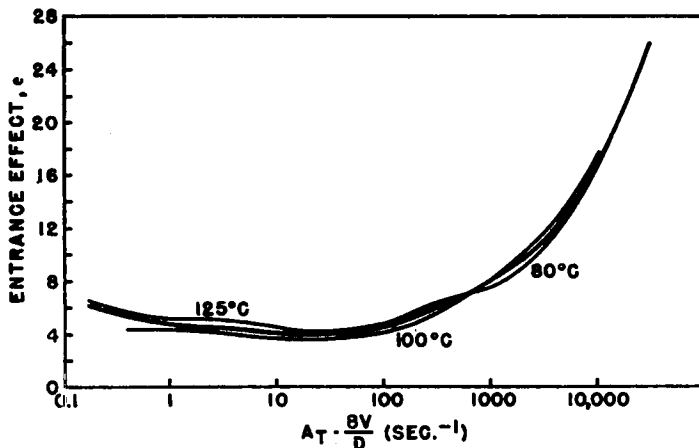


Fig. 9. Entrance effect curves at 80, 100, and 125°C. superposed by shifting shear rate scale a standard amount a_T , which depends only on temperatures.

sec.⁻¹; this is the critical condition for Neoprene WB extrusion as will be described.

Die Swell and Surface Roughness

When smooth extrudates are obtained, their die swell increases with higher shear rate. A maximum die swell is reached in the region of the transition from smooth to rough surface. Then, there is a drop in die swell, and after going through a minimum, the die swell again increases at higher shear rates (see, for example, the lower curves in Fig. 10). At certain temperatures and L/D 's the maximum and minimum points vanish and the curves show only the inflections. At 80°C. at $L/D = 2$, even these inflection points vanish. However, these are approaching limiting values of the same general phenomena described. The drop from the maximum occurs near $a_T \cdot 8V/D = 20$ sec.⁻¹, the same critical shear rate found at the minimum entrance effect. A physical explanation of the critical condition in polymer begins to oscillate at the capillary inlet as described by Tordella.^{12,13} The oscillations are due to the combined effect of elastic and viscous forces. Since oscillation requires energy, the entrance effect rises when this condition is reached. The oscillations are reflected in the appearance of the extrudate. Below this shear rate the extrudate is smooth and the entrance effect nearly constant.

Figure 10 represents 27 curves of die swell vs. shear rate with 10 data points spaced along each. Fortunately, superposition of the corresponding curves at different temperatures by the same shift of shear rate previously described has enabled much simplification of the die swell phenomena. The standard deviation of die swell values is considerably greater than that of the force readings particularly when extrudates are irregular. Thus, for reasons of space and clarity the 270 data points have not been shown.

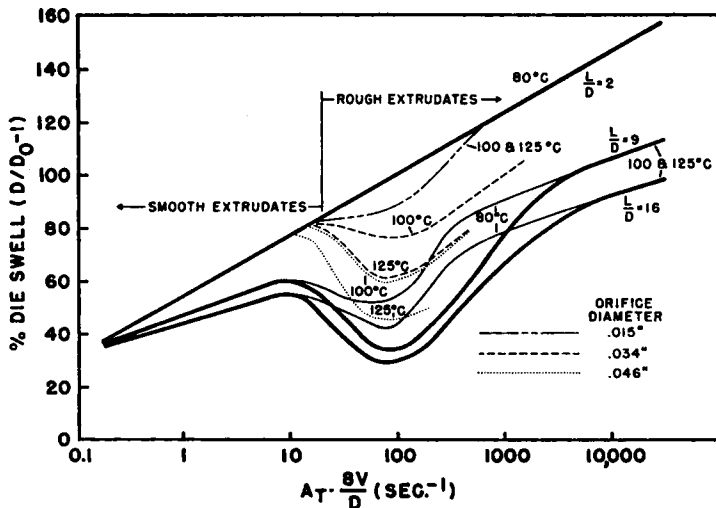


Fig. 10. Die swell and surface appearance of Neoprene WB extruded through orifices of several L/D ratios, diameters and temperatures vs. generalized shear rate.

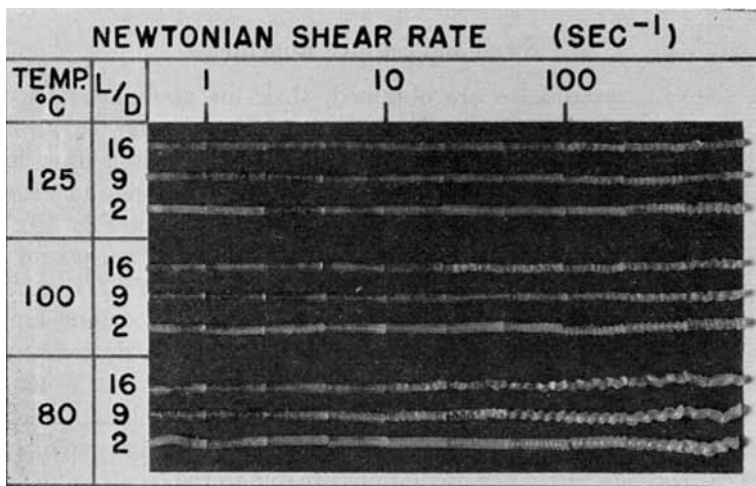


Fig. 11. Photograph of Neoprene WB extruded at 125, 100, and 80°C. through 0.046 in. diameter orifices with L/D of 16, 9, and 2. There are ten individual samples each obtained under steady-state conditions and placed in line of increasing shear rate for each orifice and temperature.

At low shear rate the die swell is a linear increasing function of shear rate. The greater the L/D , the smaller is the die swell and also the slope of the line. Polymer extrudates are smooth when produced in this region. The conclusions are valid for all temperatures and orifice diameters studied. After the critical $a_T \cdot 8V/D$ the extrudate surface starts to become rough. All die swells dip beyond the critical except $L/D = 2, 80^\circ\text{C}$. The amount

of dip in die swell for rough extrudates from the continuation of the smooth extrudate lines increases with temperature and diameter under certain conditions. This is most pronounced for $L/D = 2$ where 80°C. gives no dip but 100 and 125°C. result in progressively lower dips with increasing diameter. For $L/D = 9$ and $L/D = 16$, the 80°C. results give less dip than the higher temperatures and the effect of diameter is negligible. The results at 100 and 125°C. are similar, but 80°C. results differ considerably. It was previously noted that variability of force readings at 80°C. also had a much larger standard deviation. Larger L/D orifices always give less die swell with other variables held constant. At very high shear rates the die swell curves all tend back to the straight line extension of the smooth extrudate curve.

The appearance of extrudates is shown in Figure 11 for 90 samples from only largest diameter orifice, 0.046 in. Note that the frequency of oscillations in extrudates is higher for shorter dies at all temperatures. This is also true for the extrudates from the other diameter orifices. The frequency of the nodes is a function of elasticity, viscosity, temperature, and die geometry. The general patterns would indicate a theoretical derivation might predict this behavior, but this has not been attempted.

For dynamic measurements the main use of superposition is to extend the frequency range by varying the temperature over a relatively narrow range of frequency. Although this might prove useful for flow properties, there is definite advantage in this case of extending the temperature range by varying shear rate, which is the equivalent of frequency. The temperature range over which flow properties can be measured is limited on the high end by decomposition of the polymer and by solidification on the low end. Within this relatively narrow temperature range, it is feasible to vary the shear rate widely as described in this article.

Some Remaining Problems

Since elastomers are usually processed after compounding, the effect of such ingredients remains to be determined. Also, there are two effects which need further investigation. One is heat generation due to viscous flow at high shear rates. Heat generation has been reviewed by Metzner¹ who states that publications in this field, although mathematically extensive, do not completely solve the problem. This effect is important at high shear rates as indicated by the work of Toor¹⁴ and Gee and Lyon,¹⁵ but has been neglected in capillary rheometer studies. The other correction is for pressure drop in the polymer reservoir through which the piston must force the elastomer before it reaches the orifice. In a recent article, Skinner¹⁶ calculated that 22% of the total pressure can be in the reservoir for a power law fluid. This is expected for polymers which exhibit shear-thinning behavior. In this reservoir the shear rate is very low and the polymer viscosity, therefore, high. The reservoir to orifice cross sectional area ratio of 50–1000 usually used in capillary rheometers makes chamber pressure drop negligible for Newtonian fluids. For many shear-thinning

polymers even this large an area ratio is not sufficient to allow the chamber pressure drop to be neglected.

The author thanks C. C. McCabe and B. C. Sakiadis for helpful discussions of this subject and the Du Pont Elastomer Chemicals Department for permission to publish this work.

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Synopsis

An elastomer developed for superior processing characteristics, Neoprene WB, has been studied in a capillary rheometer from 80–125°C. and shear rates of 0.4–11,000 sec.⁻¹ Both the viscous and elastic properties of the bulk polymer are evaluated from pressure drop measurements. Per cent increase in diameter of the elastomer when extruded ("die swell") and its surface characteristics provide direct evidence of extrusion processibility. A principle of corresponding shear rates at different temperatures simplifies the understanding and application of rheometer data. Data on all responses obtained at a low temperature can be laterally superposed to higher shear rate to agree with data obtained at higher temperature. Equilibrium shear stress vs. shear rate curves show Neoprene WB undergoes shear thinning with, for example, viscosity at 100°C. dropping from over 10⁶ poise at low shear rate to 5 × 10² poise at high. The entrance or elastic effect drops very slowly to a minimum with increasing shear and then rises rapidly. This shear rate-temperature condition at which the entrance effect is a minimum is a critical condition for the polymer; it is the transition from smooth to rough extrudate. Die swell of smooth extrudates increases as the shear rate is increased but decreases with greater orifice length to diameter ratio. Above the transition the die swell of rough extrudates drops to a minimum and then rises again at still higher shear rates.

Résumé

On a étudié un élastomère, néoprene WB, présentant de meilleures propriétés, au moyen d'un rhéomètre à capillaire de 80° à 125°C. et des vitesses de cisaillement de 0.4 à 11.000 sec.⁻¹. Les propriétés de viscosité et d'élasticité du polymère en bloc ont été évaluées par des mesures d'écoulement-pression. Le pourcentage d'augmentation du diamètre de l'élastomère extrudé (gonflement d'un petit cube) et les caractéristiques de la surface prouvent la possibilité de travail par extrusion. Un principe de vitesses de

cisaillement équivalentes à des températures différentes simplifie la compréhension et l'application des données du rhéomètre. Les résultats des données obtenues à une basse température peuvent être pratiquement superposés à une vitesse de cisaillement plus élevée avec les résultats obtenus à une température plus élevée. Des courbes de tension de cisaillement d'équilibre en fonction de la vitesse de cisaillement montrent que la néoprène WB subit une rupture par cisaillement, p.ex., la viscosité à 100°C. décroît de plus de 10⁶ poises à vitesse de cisaillement basse jusqu'à 5 × 10² poise à une vitesse élevée. Le début de l'effet élastique tombe très lentement jusqu'à un minimum quand le cisaillement augmente, et puis remonte rapidement. Cette condition entre la vitesse de cisaillement et la température à laquelle cet effet atteint un minimum est une condition critique pour le polymère, c'est la transition d'extrusion douce à l'extrusion rude. Le gonflement du dé d'extrudats doux augmente lorsque la vitesse de cisaillement augmente mais diminue avec un rapport plus grand de la longueur d'orifice au diamètre de celui-ci. Au-dessus de la transition, le gonflement des extrudats rudes tombe jusqu'à un minimum, puis croît à nouveau à des vitesses de cisaillement plus élevées.

Zusammenfassung

Ein auf überlegene Verarbeitungscharakteristik hin entwickeltes Elastomeres, Neopren WB, wurde in einem Kapillarrheometer bei 80 bis 125°C und Schergeschwindigkeiten von 0,4 bis 11000 sek⁻¹ untersucht. Sowohl Viskositäts- als auch Elastizitätseigenschaften des Polymeren werden aus der Messung des Druckabfalls ermittelt. Die prozentuelle Zunahme des Durchmessers des Elastomeren bei der Extrusion ("Extrusionsverdickung") und seine Oberflächencharakteristik liefern direkte Hinweise für die Verarbeitbarkeit durch Extrusion. Ein Prinzip korrespondierender Schergeschwindigkeiten bei verschiedenen Temperaturen vereinfacht das Verständnis und die Anwendung der rheometrischen Daten. Alle bei niedriger Temperatur erhaltenen Daten können zur Übereinstimmung mit Daten bei höherer Temperatur zu einer höheren Schergeschwindigkeit seitlich superponiert werden. Die Kurve Gleichgewichtsscherspannung gegen Schergeschwindigkeit zeigt, dass Neopren WB eine Scherverdünnung erleidet, wobei z.B. die Viskosität bei 100°C von über 10⁶ Poise bei kleiner Schergeschwindigkeit auf 5 × 10² Poise bei hoher Schergeschwindigkeit abfällt. Der Eintritts- oder elastische Effekt fällt sehr langsam mit steigender Scherung auf ein Minimum und steigt dann rasch an. Diese Schergeschwindigkeits-Temperaturbedingung, bei welcher der Eintrittseffekt ein Minimum erreicht, bildet eine kritische Bedingung für das Polymere; hier liegt der Übergang vom glatten zum rauhen Extrudat. Die Extrusionsverdickung glatter Extrudate nimmt mit steigender Schergeschwindigkeit zu, jedoch mit grösserem Verhältnis der Länge zum Durchmesser der Öffnung ab. Oberhalb des Überganges fällt die Extrusionsverdickung rauher Extrudate auf ein Minimum and steigt dann bei noch höherer Schergeschwindigkeit wieder an.

Received June 29, 1962