# The temperature rise on neck formation of polymers: polypropylene and polyethylene

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Polymeric materials drawn in different surrounding media show different drawing stresses. Based on these differences in drawing stress, drawn under water as against drawing in air, a simple approximate method is proposed for the measurement of temperature rise of polypropylene and polyethylene during drawing.

**(Keywords: drawing; neck formation; draw rate; temperature rise; enbironmental effects)**

## INTRODUCTION

Heat generation during the drawing of plastics materials has been known for some time[1]. Early work on the role of heating during the necking of polymers suggested that a local temperature rise in the specimen caused a neck to form and propagate[2-4]. However, specimens can be made to cold-draw at very low extension rates[5,6] or under water when most of the heat generated is lost to the surroundings. Various necking mechanisms[5-8] based on Considere's construction[6] have been reported; this construction does not involve a temperature rise at the start of neck formation. However, once the neck has formed, its propagation can be affected by subsequent temperature changes[9-11]. As a result of these observations the determination of the temperature rise during the drawing of the polymer is important in understanding the continuing deformation mechanism.

Direct temperature measurements have been made using thermocouples[4,10,12], infra-red camera[13], coloured organic crystals with melting points in the temperature range of interest[10], and fluorescent phosphors[14]; some of these techniques interfere with the deformation process and others are too complex for routine determinations. Here we propose a simple approximate method for measuring the temperature rise of a polymer during drawing. This method is based on the difference in drawing stresses of specimens drawn under water as against drawing in air; drawing is conducted at a variety of draw rates.

## EXPERIMENTAL

Stress–strain curves of cold drawn materials were determined on an Instron testing machine. A thermostatically controlled water bath, with a variable water level, was fixed on the lower grip. Specimens were drawn either completely or partially under water. The temperature of the bath can be controlled over the range 22°C–90°C with an accuracy of 0.1°C.

Sheets were cut into strips of the usual dumb-bell shape with a die (ASTM D638-V). Test specimens were extended at various rates from 0.5 to 50 cm min$^{-1}$. Unless otherwise stated the draw temperature was equal to room temperature (22°C). Drawing stress was calculated as the ratio of the drawing load to the original cross-sectional area. Since the stress is based on original cross-sectional area, it is 'conventional' rather than 'true' stress.

The polypropylene (PP) used was a commercial sheet described as PP 5225 and manufactured by Shell Development Company. It was a translucent sheet of thickness 0.80 mm containing no plasticizer but including small amounts of stabilizers. Its number-average molecular weight ($M_n$) was 50000 and weight-average molecular weight ($M_w$) was 600000. The high density polyethylene (HDPE) used was a commercial sheet 0.79 mm thick described as HDPE LB-730 also supplied by Shell Development Company.

The temperature rise during necking was measured directly using a thermocouple for selected samples. The method consisted of sandwiching a thermocouple between two dumb-bell-shaped specimens and binding the whole together with two rubber bands which themselves were in a plane perpendicular to the direction of extension. Direct contact of the rubber bands with the thermocouple was therefore avoided. The standard error of the experiment is less than 5%.

## RESULTS AND DISCUSSION

When a sample is drawn under water, the level of water in the bath can be controlled to ensure that the initial yield and part of the drawing process is carried out under water. After a certain amount of extension the neck emerges from the water and continues to propagate in air. The stress–strain curve is shown schematically in *Figure 1*. Prior to point D extension of the sample is carried out under water. It is clear that the shape of the stress–strain curve for PP 5225 drawn under water is similar to that for PP 5225 drawn in air. In region OA, the plot is approximately linear and the sample deforms homogeneously.

The plot is non-linear in region AB, at point B the specimen thins to a smaller cross-section at some point, i.e., a neck is formed. In region BC a neck becomes visible

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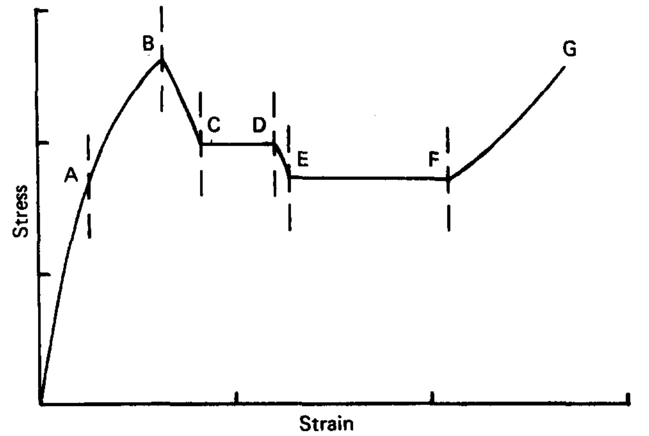


**Figure 1** Stress–strain curve for PP 5225 drawn in a water bath in which the liquid level is controlled

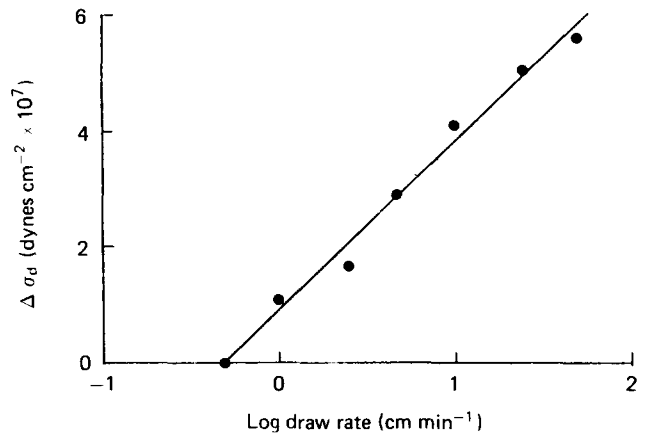


**Figure 2** Effect of draw rate on $\Delta\sigma_d = \sigma_{CD} - \sigma_{EF}$ for PP 5225

at the location of the most intense deformation bands on the gauge. At point C one boundary of the neck becomes more clearly defined and propagates in region CD. The stress $\sigma_{CD}$ is taken as the drawing stress of the sample drawn under water. In region DE the propagating end of the sample neck emerges from the water and continues to propagate in air; $\sigma_{EF}$ is the drawing stress of the sample drawn in air. Stress $\sigma_{EF}$ is less than $\sigma_{CD}$ and this abrupt drop in stress is presumably caused by a temperature difference, in the neck region of the sample, between samples drawn in air and those drawn under water. The thermal conductivity of water at 300 K is $1.46 \times 10^{-3}$ cal $s^{-1}$ $cm^{-1}$ $K^{-1}$, which is twenty-three times as large as that of air. Heat generated drawing a sample under water can be more easily removed. As a result the draw temperature of the specimen drawn under water at some temperature is effectively less than that of the specimen drawn in the air at the same nominal temperature. *Figure 2* shows the difference in drawing stress ($\Delta\sigma_d = \sigma_{CD} - \sigma_{EF}$) as a function of draw rate from 0.5 cm $min^{-1}$ to 50 cm $min^{-1}$. This stress difference increases as the draw rate increases and is presumably related to changing temperature differences. If the relationship between temperature and drawing stress is known, then the temperature difference between drawing in air and drawing under water can be calculated.

*Figure 3* shows the drawing stress of PP 5225 drawn under water as a function of draw temperature from 22°C to 75°C at a rate of 1 cm $min^{-1}$; the drawing stress of PP 5225 under water decreases linearly as draw temperature increases. The slope of this line is equal to $-1.7 \times 10^6$ dynes $cm^{-2}$ $°C^{-1}$.

Based on data shown in *Figures 2* and *3* one can derive the temperature difference $\Delta T_1$ in the region of the propagating neck for PP 5225; $\Delta T_1$ represents the difference between drawing in air and drawing under water as a function of draw rate (*Figure 4*). Despite the fact that the thermal conductivity of water is much greater than that of air one cannot assume that drawing a polymer under water can be considered as an isothermal process. The small temperature rise $\Delta T_2$ for PP 5225 drawn under water was measured as a function of draw rate using a sandwiched thermocouple (*Figure 4*). The total effective temperature rise $\Delta T$ of PP 5225 drawn in air is equal to the sum of $\Delta T_1$ and $\Delta T_2$ (*Figure 4*).

It is also possible to calculate from a theoretical basis

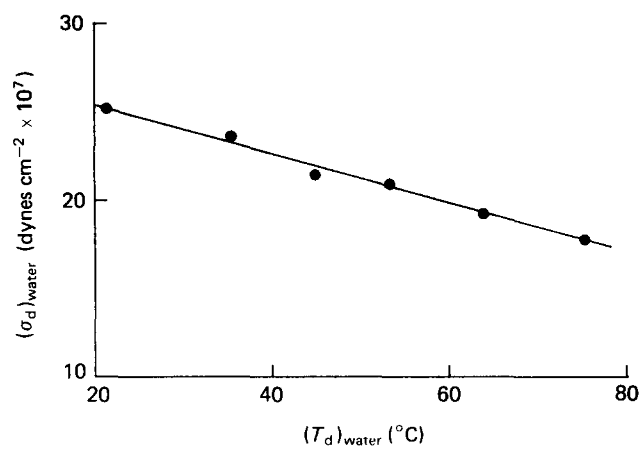


**Figure 3** Effect of draw temperature on the drawing stress of PP 5225 drawn under water at a rate of 1 cm $min^{-1}$

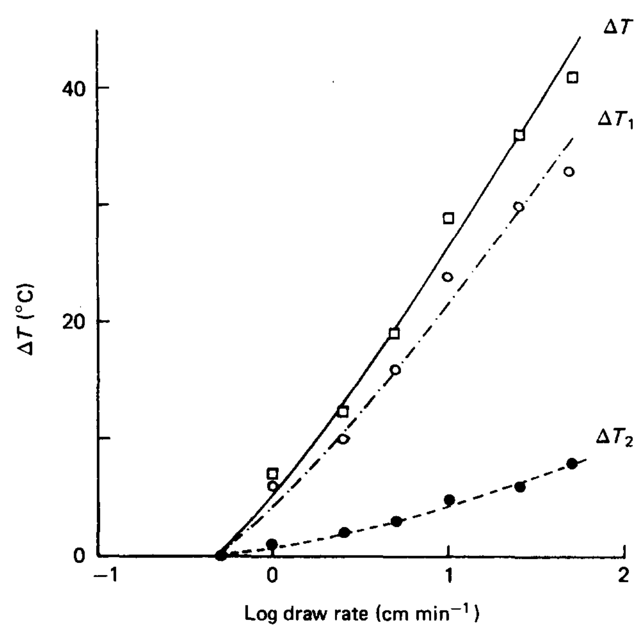


**Figure 4** Effect of draw rate on the temperature rise during necking for PP 5225. $\Delta T_1$: the temperature rise during necking for PP 5225 on the basis of the drawing stress difference. $\Delta T_2$: the measured temperature rise during necking for PP 5225 drawn under water; $\Delta T = \Delta T_1 + \Delta T_2$

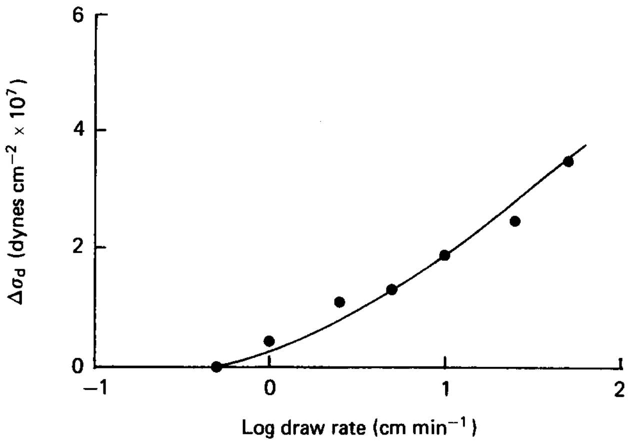


**Figure 5** Effect of draw rate on $\Delta\sigma_d = \sigma_{CD} - \sigma_{EF}$ for HDPE

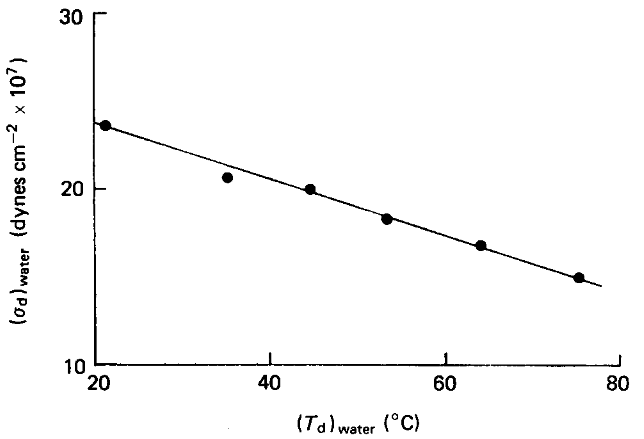


**Figure 6** Effect of draw temperature on the drawing stress of HDPE drawn under water at a rate of 1 cm min$^{-1}$

the expected maximum temperature rise $\Delta T$ if no heat was dissipated to the environment by conduction (adiabatic heating). This can be derived from an analysis of the true stress–strain curve of an assumed volume element; such an analysis has already been performed for polypropylene by Peterlin *et al.*[16]. Their results showed that when the draw rate is 50 cm min$^{-1}$, $\Delta T$ equals 39 K; for a draw rate of 5 cm min$^{-1}$, $\Delta T$ equals 24 K. Our results are close to those calculated at 50 cm min$^{-1}$; at a draw rate of 5 cm min$^{-1}$ our results are somewhat lower. This difference at lower rates is presumably due to the assumption of adiabatic heating in Peterlin's calculation, at lower draw rates this assumption will clearly be of questionable validity.

In a similar manner, the temperature rise of HDPE drawn in air as a function of draw rate can also be determined (*Figures 5*, *6* and *7*). Temperature changes in polyethylene during tensile elongation have been measured directly using a thermocouple by M. Nakamura *et al.*[12] and their results are entirely consistent with our data.

## CONCLUSION

The difference in drawing stresses of polymeric materials under water and in air depends on draw rate. On the basis of measured stress differences *versus* draw rate coupled with, drawing stress of the sample drawn under water *versus* draw temperature one can obtain the temperature rise during necking for polypropylene and high density polyethylene. This simple method should be readily applicable to a variety of other polymers.

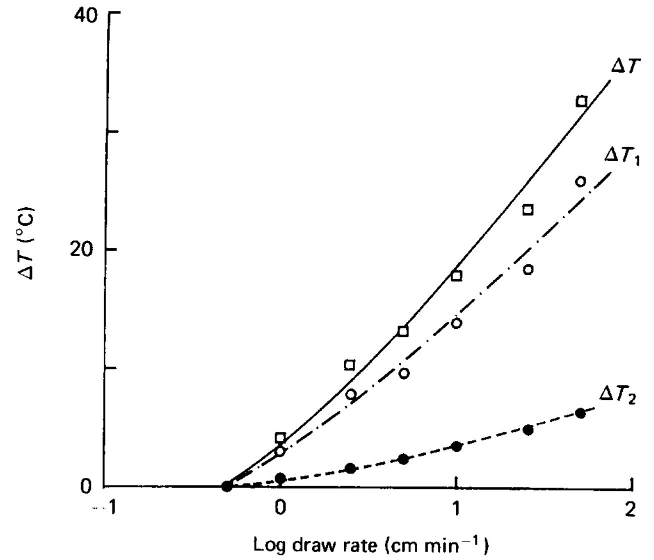


**Figure 7** Effect of draw rate on the temperature rise during necking for HDPE. $\Delta T_1$: the temperature rise during necking for HDPE on the basis of the drawing stress difference; $\Delta T_2$: the measured temperature rise during necking for HDPE drawn under water; $\Delta T = \Delta T_1 + \Delta T_2$

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