Shear Girdling Phenomenon in Polymers

K. D. PAE and A. A. SILANO, *High Pressure Research Laboratory and Department of Mechanics and Materials Science, Rutgers University, New Brunswick, New Jersey 08903*

Synopsis

Hollow and solid specimens of polypropylene and solid specimens of polyoxymethylene exhibited an effect under torsional shear which is analogous to the necking usually observed in tensile tests. After reaching some critical shear strain in the postyield region localized shear deformation developed on the gauge length. As twisting was continued a dramatic decrease in the diameter of the cross section was observed. This torsional shear induced phenomenon was named girdling. The superimposition of hydrostatic pressure up to 6 kbar has a significant influence on the extent of girdle formation. Stress whitening, observed on the solid polyoxymethylene specimens was suppressed by the application of pressures greater than 1 kbar. Very large shear strains produced a ratchet-type fracture surface on the solid specimens which indicates the presence of axial, radial, and tangential strains. Qualitatively, these results are supported by the finite deformation theory of elasticity.

INTRODUCTION

During the process of investigating the pressure dependence of the torsional shear stress–strain behavior of polymers, a new phenomenon was observed which may have significant implications in understanding the material behavior and the technological application of polymers.[1,2] The phenomenon has been named girdling.

Girdling occurs when solid or hollow circular cylindrical specimens of polypropylene (PP) and solid specimens of polyoxymethylene (POM) are subjected to torsional shear stress at atmospheric pressure and ambient temperature. When the shear stress (or shear strain) reaches a critical value, localized shear banding initiates on the gauge section of the specimen. As twisting is continued a dramatic decrease in the diameter of the cross section, resembling the necking in a tensile specimen, is observed. This constriction or reduction of the cross section is the shear girdling phenomenon. The localized reduction in the specimen diameter represents the girdle. At atmospheric pressure, continued twisting of the solid specimens, results in a reduction of the girdle to a fine point in PP and to rupture in POM. Varying the magnitude of the environmental pressure from atmospheric to 5 kbar on the solid specimens influences the depth of the girdled region. At 6 kbar, girdle formation is interrupted by fracture in both polymers. The fracture which occurs is in a shear mode and the edges of the fractured surfaces have a ratchetlike appearance.

MATERIALS AND EXPERIMENTAL METHODS

The PP and the POM (Delrin 500) used in this study were purchased from commercial source as 1.27 cm thick sheets. The PP had a density of 0.905 g/cm^3 and a crystallinity of about 55% while the POM had a density of 1.425 g/cm^3 and a crystallinity of about 74%.

Journal of Applied Polymer Science, Vol. 22, 3021–3026 (1978)

0021-8995/78/0022-3021$01.00

All torsion specimens were machined to an overall length of 6.35 cm. The solid specimens had a 2.09 cm reduced section and a 0.805 cm diameter, while the hollow specimens had a 1.91 cm reduced section, a 0.954 cm o.d., and a 0.627 cm i.d.

Torsion testing of the specimens was performed in a specially designed high-pressure torsion apparatus.[2] Specimens were mounted in a torsion yoke which permitted the rotation of one end of the specimen while the other stationary end was free to elongate in the axial direction. The pressure medium used was kerosene mixed with a small amount of lubricating oil. Several test series were run with and without rubber (Evo-stik) coating on the specimens, throughout the experimental pressure range. No significant differences were observed in either the physical or mechanical behavior of the polymers as a result of the rubber coating. The shear deformation rate was maintained constant at 0.005/sec. Electrical output from the torque sensing load cell imbedded in the shaft and from a rotary variable differential transformer was treated by two carrier preamplifiers and directed to an X-Y recorder where torque-twist curves were produced.

Values of the nominal shear stress and shear strain for the hollow specimens were calculated from the torque-twist diagrams using the usual equations.[3] For a circular cross section, the maximum shear stress τ developed by the torque M applied at the outer radius R_0 of a hollow specimen having an area polar moment of inertia of the cross section J is expressed by

$$\tau = MR_0/J \tag{1}$$

The shear strain γ at the outer radius R_0 on a specimen of gauge length L, rotated through θ rad is described by

$$\gamma = R_0\theta/L \tag{2}$$

DISCUSSION OF RESULTS

Typical torque-twist curves for the solid and hollow specimens of PP tested at various pressures are shown in Figures 1 and 2, respectively, and those of solid POM in Figure 3. Calculations of the shear stress and shear strain are included only on the diagrams of the hollow specimens. Although methods have been suggested for calculating the shear stress and the shear strain for solid specimens,

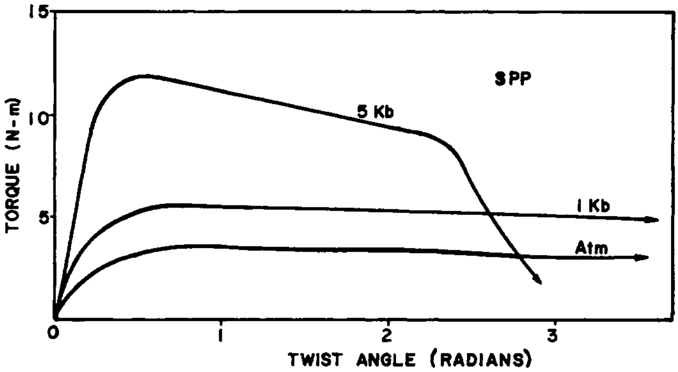

Fig. 1. Typical torque-twist curves for solid PP specimens at various pressures.

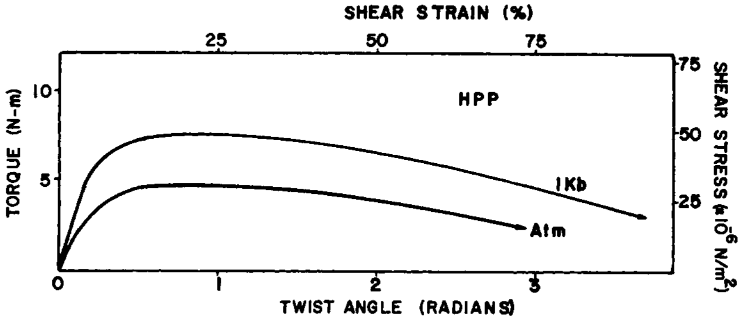

Fig. 2. Typical shear stress–strain curves for hollow PP specimens at various pressures.

no values will be given here.[4] A more detailed treatment of these data will be presented in another report.[5]

Observations made at atmospheric pressure revealed that the girdle formation on the solid specimens of both materials proceeds through definite stages. First, as the torque in the postyield region reaches a critical value localized shear banding occurs on the gauge section of the specimen. Second, as shear band development continues, the rate of increase of the torque with respect to the twist approaches a minimum value when the torque attains its peak. Simultaneously visible evidence of large scale stress whitening uniformly encircles the gauge section. Third, as rotation of the specimen continues formation of a girdle within a narrow region where shear banding is concentrated becomes visible and the magnitude of the torque falls slowly. Fourth, with continued twisting the girdle deepens and the deepening continues unless fracture intervenes. Examples of girdle formation in both PP and POM are shown in Figures 4 and 5, respectively.

Girdling continues to a fine point in the solid specimens of PP tested at atmospheric pressure. At pressures greater than 5 kbar, fracture occurs in the girdle in a shear mode. For the hollow POM specimens girdling did not form at all pressures; instead, buckling and shear fracture compete as a mode of failure. Girdling formed in all of the solid POM specimens except those tested at 6 kbar where fracture occurs without girdle.

A measurable increase in the length was observed on both the PP and POM specimens deformed beyond the yield point. Presumably, changes in the di-

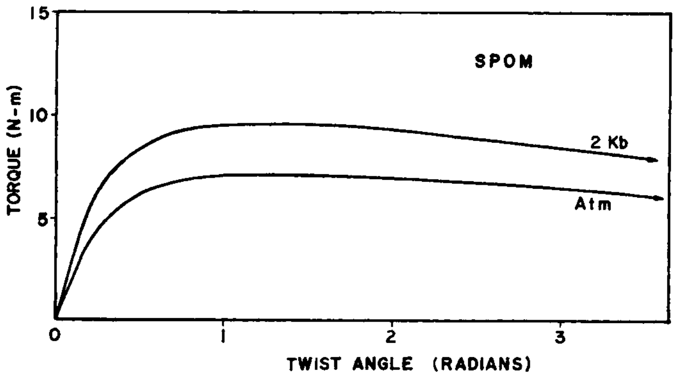

Fig. 3. Typical torque-twist curves for solid POM specimens at various pressures.

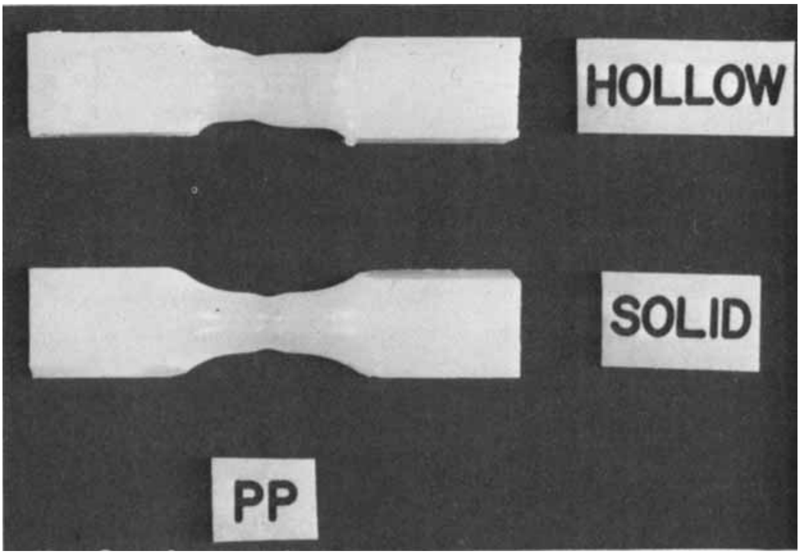

Fig. 4. Solid and hollow PP specimens tested at 1 kbar showing a well-formed girdle.

mensions also occurred during the elastic deformation of the specimens. According to the theory of finite elastic strains, changes in the length and diameter of both hollow and solid specimens subjected to finite torsional elastic strains are expected.[6–10]

Examination of the fracture surface by scanning electron microscopy (SEM) of a solid PP specimen fractured at 5 kbar shows the presence of lines generally oriented in the radial direction as shown in Figure 6 (×27). The SEM scans of the inner core of the specimen as shown in Figure 7 (×27) do show a large plastic flow of material. The deformed core describes a nebulalike pattern surrounded by torn and highly distorted material. An enlarged view (×100) of the nebula reveals that it is composed of layers of material which have been rotated about the longitudinal axis of the specimen (Fig. 8).

At this point in the understanding of girdle formation only a qualitative description can be presented. Since it is difficult to machine a perfectly cylindrical specimen or to produce a completely homogeneous material, the weakest point at which shear yielding occurs along the gauge length will be rather arbitrary. Thus shear banding initiates at points where the diameter is essentially smallest and where the shear stress required to strain the particular cross section is highest

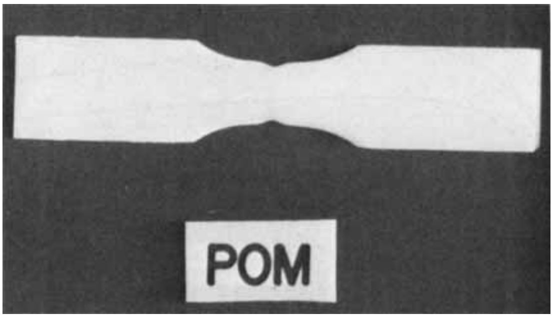

Fig. 5. Solid POM specimen tested at 2 kbar showing a well-formed girdle.

Fig. 6. SEM fractography (×27) of the edge of a solid PP specimen tested at 5 kbar.

in value. Associated with reductions in diameter is the competitive process of shear strain orientation which compensates for the increase in shear stress due to the reduced cross section of the specimen. While the two competitive processes are balanced a girdle will not form. But when the increase in the shear stress exceeds the rate of strain orientation of the polymer at the smallest diameter the shear strain becomes localized at this section and girdle forms. Girdle formation is a consequence of concentration of finite shear strains in a narrow band which produces an axial elongation as well as a reduction in the cross-sectional area.

Fig. 7. SEM fractography (×27) of the core of a solid PP specimen tested at 5 kbar.

Fig. 8. SEM fractography (×100) of the core of a solid specimen tested at 5 kbar.

References

1. A. A. Silano, Ph.D. dissertation, Rutgers University, 1976.
2. K. D. Pae and A. A. Silano, *Rev. Sci. Instrum.*, **48,** 307 (1977).
3. S. P. Timoshenko and J. N. Goodier, *Theory of Elasticity,* McGraw-Hill, New York, 1970.
4. A. Nadai, *Theory of Flow and Fracture in Solids,* Vol. 1, 2nd ed., McGraw-Hill, New York, 1950.
5. A. A. Silano, K. D. Pae, and J. A. Sauer, *J. Appl. Phys.,* **48,** 4076 (1977).
6. M. Mooney, *J. Appl. Phys.,* **11,** 582 (1940).
7. M. Reiner, *Am. J. Math.,* **70,** 433 (1948).
8. E. G. Chilton, *J. Appl. Mech.,* **15,** 362 (1948).
9. F. D. Murnaghan, *Finite Deformation of an Elastic Solid,* Wiley, New York, 1951.
10. R. S. Rivlin, *Rheology,* Vol. 1, F. R. Eirich, Ed., Academic, New York, 1956.

Received March 8, 1977
Revised September 19, 1977