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Tensile and pressure rupture behaviour of flow-formed high density polyethylene pipes

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Structurally altered high density polyethylene pipes were produced by flow-forming, a point rotary cold rolling process. The process was performed by using three rollers on a conventional lathe machine. The variation of mechanical and pressure rupture properties (tensile strength, yield strain, toughness and hoop stress) with percentage reduction was studied. The stress–strain behaviour of the flow-formed pipe exhibited less yielding and cold drawing as percentage reduction increased. Significant increase in the tensile strength was observed for reductions above 20%. Improvement (exceeding 300%) of toughness was observed in the axial and hoop direction. Pressure rupture tests revealed that the hoop stress of the flow-formed pipes increased only after 50% reduction. Both tensile and pressure rupture tests revealed that the ductility also increased with percentage reduction. This was well demonstrated by the extensive bulging during pressure rupture tests. Scanning electron micrographs revealed a significant amount of structually altered macrofibrils in the flow-formed pipe.

(Keywords: flow-forming; polyethylene; tensile properties)

INTRODUCTION

Flow-forming constitutes a unique method of producing structurally altered material in a plastic pipe with marked improvement in properties. It is a solid deformation process, performed on a rotating mandrel in which the thickness of a tube is reduced and the length increased without changing the internal diameter. Since it is chipless, there is no loss of material. This process is established in the metal forming industry where it is sometimes referred to as flow-turning of tubes[1], tube spinning[2-4] and shear spinning[5,6]. It is normally carried out under room temperature conditions. The flow-forming process can be schematically represented as in *Figure 1*. A conventional lathe is usually used. The plastic preform (in the form of a pipe) is slipped over a rotating steel mandrel which is held in place by the tail-stock of the lathe. As the mandrel rotates the rollers also rotate. The rollers are normally attached on to the cross-slide of the lathe. By moving the rollers in the radial direction of the pipe, different reductions can be achieved. The mechanics of flow-forming are similar to those of cold rolling. Numerous reports on the cold rolling of polymeric sheets have been made[7-17] and by drawing a reference from these reports, the marked improvements of flow-forming can perhaps be better understood. However, in contrast to cold rolling of sheets where the contact area is a line, flow-forming is a rotary point contact deformation. By changing the speed of rotation and feed-rate, different deformation patterns resembling screw threads having a characteristic helical angle can be obtained. This helical reinforcement resembles that of composite filament winding.

Two previous articles[18,19] reported the remarkable improvement in tensile and pressure yield behaviour of flow-formed polypropylene pipes using single and twin roller flow-forming configurations. The improvement was attributed to the structurally altered state of the polymer and the presence of a cold worked compressive stress layer on the innermost part of the pipe. However, no other reports have been made on other types of plastics. This paper describes the effects of flow-forming on the tensile and pressure rupture behaviour of high density polyethylene (HDPE) pipes using a new three-roller design.

EXPERIMENTAL

Material

The pipe material used was a copolymer of polyethylene produced by Eurapipe and supplied by ERIKs Ltd[20]. The black polyethylene pipes had an external diameter of 50.5±0.1 mm and internal diameter of 39.4±0.2 mm. In this study, only pipes within 39.4±0.05 mm were used in the flow-forming process. The close tolerance was necessary to facilitate the sliding of the tube over the steel mandrel during the flow-forming process.

Flow-forming process

A conventional lathe with a three-jaw chuck and a tail stock was used as in a previous study for polypropylene pipes[19]. A steel mandrel, designed to provide a sliding fit to the internal diameter of the polyethylene pipe, was

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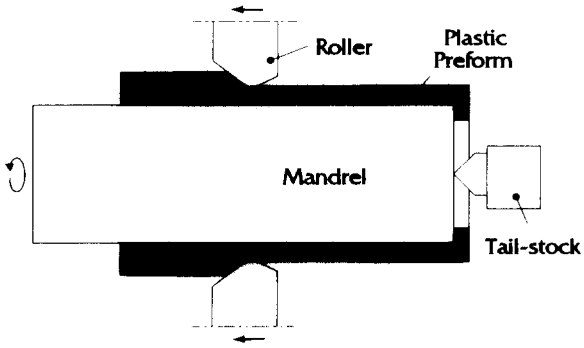

Figure 1 Schematic diagram of the flow-formimg process on a plastic preform

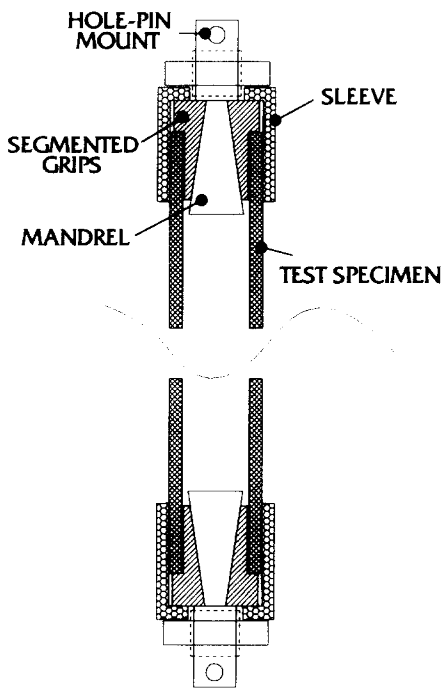

Figure 2 Friction grips used in the tensile testing of pipes (after ASTM D2105)

secured by the three-jaw chuck on one end and the tail-stock at the other. A three-roller device[21] was used. The tool post was removed to facilitate the mounting of the flow-forming tool assembly on the cross-slide of the lathe. This configuration was employed to improve the dimensional accuracy as well as to eliminate roller alignment problems. Each roller had a form radius of 5 mm. Mandrel speed was set at 48 rev min^{-1} and the feed-rate was 0.2 mm rev^{-1}. A range of reductions up to 70% were made and the percentage reduction (%RD) was calculated as %RD = reduction in thickness of pipe × 100/original thickness. Coolant was used in order to avoid excessive heating of the polyethylene during flow-forming.

Tensile testing

The flow-formed pipes were tensile tested according to the ASTM standard D2105. Significant care was taken to ensure that all surfaces of the specimens were free of visible flows, scratches or imperfections. Tensile tests were carried out on an M30K (J.J. Lloyd) tensile machine, using a force-extension recorder (PL 3XY/T) and a set of frictional grips. These grips provide firm holding of the tube specimens by virtue of the segmented grips and the mandrel (*Figure 2*). All the tests were carried out at 23 ± 1°C and 50 ± 5% relative humidity. A test extension speed of 12.7 mm min^{-1} was used. The specimens, each 200 mm in length (L_0), were tested up to 100% strain (defined as extension/L_0). Tensile strength (maximum load/initial cross-sectional area of pipe), strain at yield and the relative axial energy absorption (area under the stress–strain curve until 100% strain) were calculated from the stress–strain diagrams.

Pressure rupture test

The pressure rupture test conducted on the flow-formed tubes followed closely the ASTM standard D1599. This is a short-time pressure rupture test. Due to the limited length of the mandrel, the length of the pipes was restricted to about four times the outer diameter of the pipe. A schematic representation of the pressure test set-up is shown in *Figure 3a*. The test set-up comprises the M30K (J.J. Lloyds) tensile testing machine and a hydraulic cylinder (pressurizing system), a constant-temperature bath, pressure gauge and the pipe test plug assembly (*Figure 3b*). The test plug assembly consists of two components, namely the male and female rods and the test plugs. This assembly gave a restrained end configuration to the short-term pressure rupture tests. All tests were conducted at 23 ± 2°C and the flow-formed tubes were pressurized using water as the test fluid. Prior to test, the tubes were conditioned in a constant temperature bath at the temperature mentioned earlier. The flow-formed pipes were then filled completely with the test fluid. Great care was taken to ensure that no air was entrapped within the pressure line or for that matter in the entire pressure test set-up. With the test specimen completely immersed in the bath, water was introduced into the tube at 10 $\mathrm{cm}^3\,\mathrm{s}^{-1}$ via the actuation of the hydraulic cylinder by means of the constant cross-head movement of the tensile testing machine. The ruptured specimens were removed and the rupture behaviour analysed. From the output of the pressure transducer, the increase in hoop stress with volumetric strain can be obtained for each %RD. The volumetric strain (ε_v) was calculated from the equation:

$$\varepsilon_v = \text{change in volume/initial volume of pipe}$$

Calculation of the hoop stress was based on the formula:

$$\sigma_h = P(D - t)/2t$$

where σ_h = hoop stress (MPa), P = internal pressure (MPa), D = average outer diameter (mm) and t = minimum wall thickness (mm).

The maximum hoop stress was calculated from the hoop stress *versus* volumetric strain plot. The energy expended by the pipes on rupture was calculated from the area under the plot of σ_h *versus* ε_v. This was defined as the hoop energy absorption so as to differentiate from the axial energy absorption obtained from the tensile tests.

RESULTS AND DISCUSSION

Stress–strain behaviour of flow-formed HDPE pipe

Figure 4 illustrates the typical stress–strain curves of the flow-formed pipes at several percentage reductions

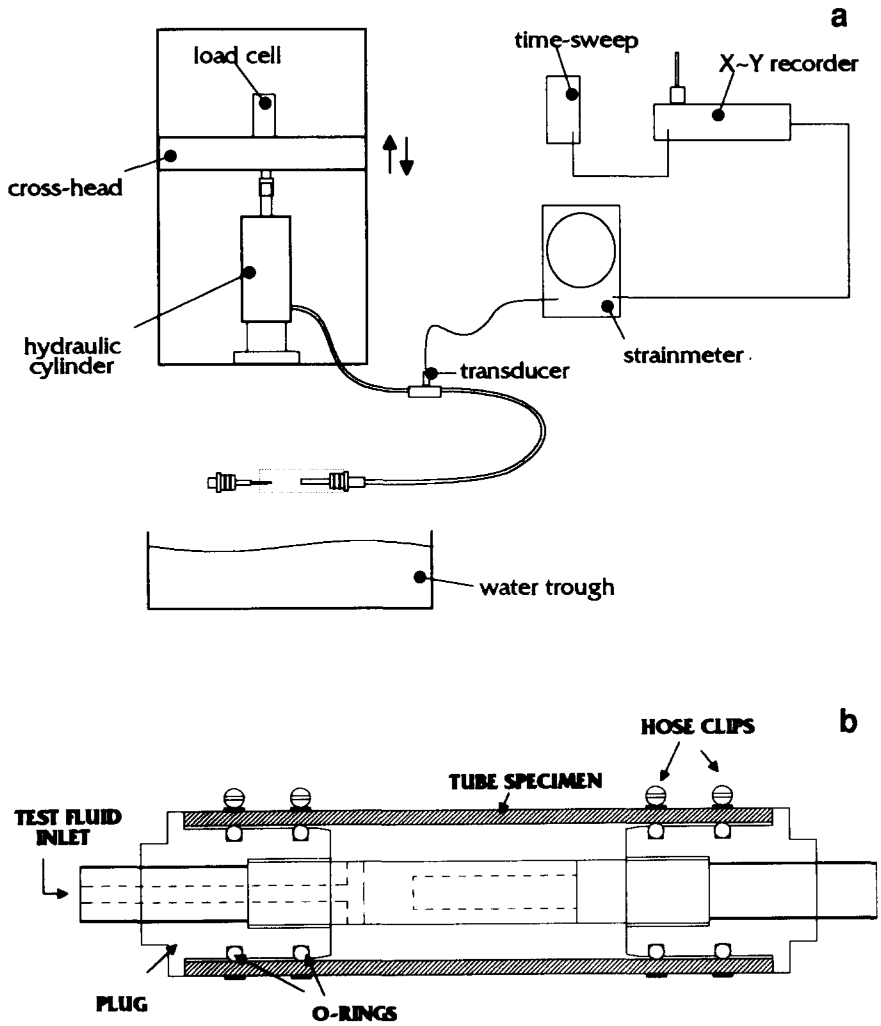

Figure 3 (a) Short-term pressure rupture test set-up. (b) Test plug assembly for pressure rupture test

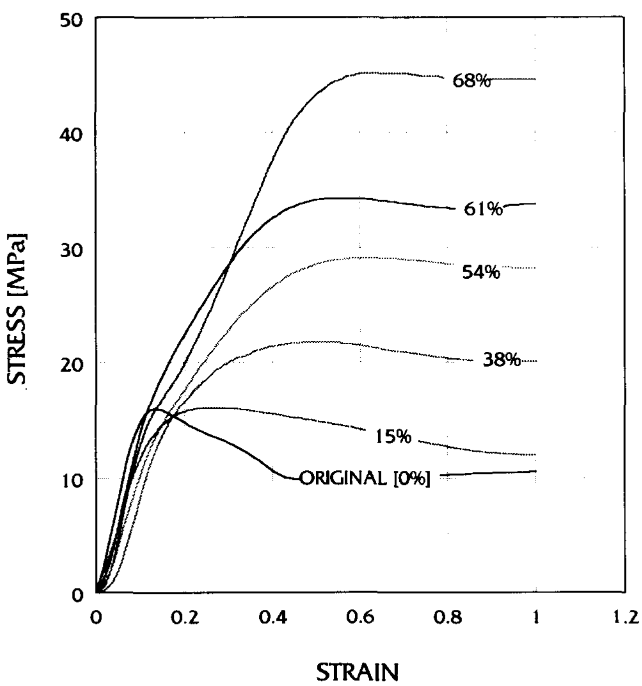

Figure 4 Stress–strain behaviour of flow-formed HDPE pipes

up to 68% RD. Significant differences can be observed in each case. (The abnormally non-linear portion of the 68% RD curve at the early stages of deformation before yielding could be the result of some slipping at the frictional grips.) As percentage reduction increases, the phenomenon of load drop (yield point) gradually becomes less prominent. Such observations were also made by Broutman and Patil[12] who studied the cold rolling of ABS, polyphenylene oxide, polysulfone, polycarbonate and PVC. Similar observations were also made by Grancio[22], who analysed the influence of rolling on the properties of amorphous polymer, and Wilchinsky[9] who studied the reduction of brittleness in polypropylene due to cold rolling. Dhingra *et al.*[16], who studied the relationship between mechanical properties and structure in rolled polypropylene, also made similar observations.

One can perhaps better understand the stress–strain behaviour by considering the changes of morphology with deformation. Since polyethylene is semicrystalline, the deformation mechanism studied by Peterlin[11] seems most apt. It is generally accepted that the initial deformation is closely related to the distortion of the spherical spherulites to somewhat ellipsoidal shape near the yield point. Samuels[23] has also confirmed this in his study. Massive structural changes will occur once the yield point is exceeded. Chain sliding and tilting will take place, and the crystalline blocks break up into smaller crystalline blocks stacked on top of one another. These blocks are interconnected by tie molecules and these collectively form macrofibrils. This process occurs during the cold drawing stage. The macrofibrillar structure is stronger than the initial spherulitic structure, especially in the tensile axis, thus it can accommodate higher tensile load. This accounts for the increase of load after cold drawing. The macrofibrils will continue to form until the structural integrity of the initial crystalline blocks is exhausted. (Note however, that this mechanism may be superseded by a competing mechanism, which is related to void coalescence, to form cracks which grow and ultimately lead to fracture.) *Figure 5* shows a typical scanning electron micrograph of a failed specimen at 70% RD. The formation of fibrils in layered configuration and void coalescence to form cracks between layers can be seen clearly.

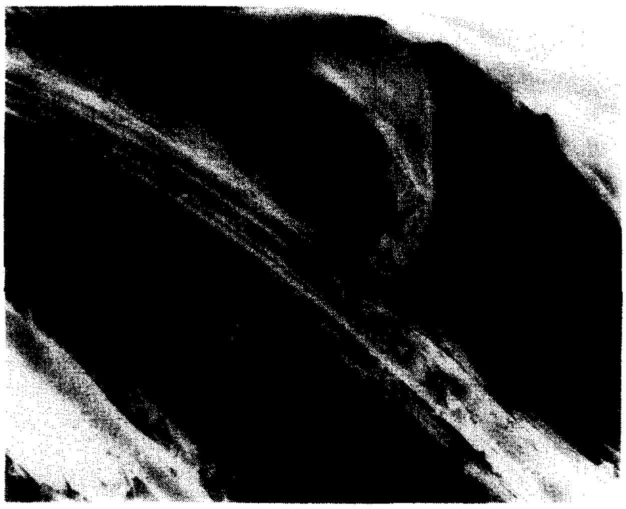

Figure 5 Scanning electron micrograph of a failed flow-formed specimen

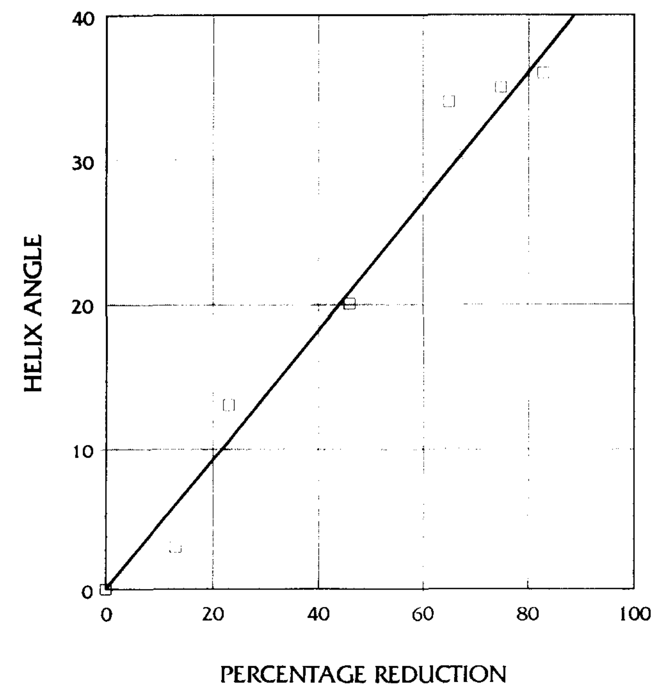

Figure 6 Variation of helical angle with percentage reduction

Flow-forming, being a contact-point rolling process, exhibits helical lines like the threads on a shaft (except that it is chipless and hence without loss of material). As can be seen in *Figure 6*, the helical angle increases linearly with %RD. It ranges from a few degrees to about 35° at 70% RD. The tensile properties have been shown to be maximal along the helical angles[19], which is equivalent to the tensile properties along the rolling direction for cold rolling of polymeric sheets. The greatest structural change should therefore occur in regions close to the helical angle. The helical conformation of highly drawn macrofibrils leads to high anisotropy of the structurally altered pipes.

In flow-forming, an improvement in tensile properties was observed only after the percentage reduction exceeded that of the yield strain of the material. This observation is supported by the results of other researchers[10–19] who studied cold rolling. The polyethylene pipe has a yield strain of about 12%. In other words, for percentage reduction of 20% and above, the material is flow-formed in the regions just after the yield point or in the cold drawn region where fibrillar structures are present. As such, the phenomenon of yield drop would perhaps be absent in such a case. Nonetheless, flow-forming, unlike cold rolling, is a point-rolling process with triaxial forces acting on each contact point. There is, therefore, a high probability that the initial material is only partially strained beyond the yield strain. This would perhaps account for the presence of yield and cold drawing observed for lower reductions. On the other hand, for higher percentage reductions, the yield point and the cold drawing extent become less prominent. This is believed to be the result of a structural change leading to the formation of fibrils.

Effect of flow-forming on tensile properties

Three tensile properties, namely, tensile strength, yield strain and axial energy absorption, were investigated. The variation of the tensile strength with percentage reduction is illustrated in *Figure 7*. Tensile strength of the flow-formed pipes at low reductions (less than 20% RD) showed minimal improvement. Significant change in the tensile strength was observed only after approximately 25% reduction. Above this %RD, the tensile strength increased exponentially with percentage reduction. This result showed coherency with the strengthening mechanism which arose as a result of the structural changes from the spherulitic to fibrillar structure. The maximum percentage increase for the tensile strength exceeds 200% at 70% RD, which is indicative of a remarkable improvement over the original material. These results are consistent with those of Dhingra *et al.*[16] who studied the cold rolling of polypropylene sheets. They found that uniaxial rolling leads to an increase in the tensile strength.

The variation of yield strain *versus* %RD is shown in *Figure 8*. The yield strain was measured at the point where the maximum load was recorded. The yield strain increases almost linearly with %RD until about 70% RD, where it appears to have reached an asymptotic value of about 65% strain. Attempts to flow-form beyond 70% RD resulted in poor surface finish. In the two previous publications[18,19] it was noted that the flow-formed

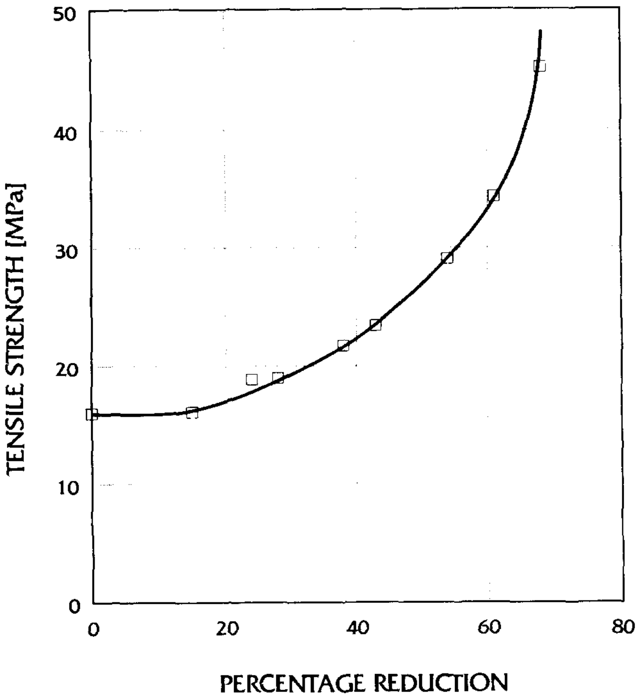

Figure 7 Tensile strength *versus* percentage reduction

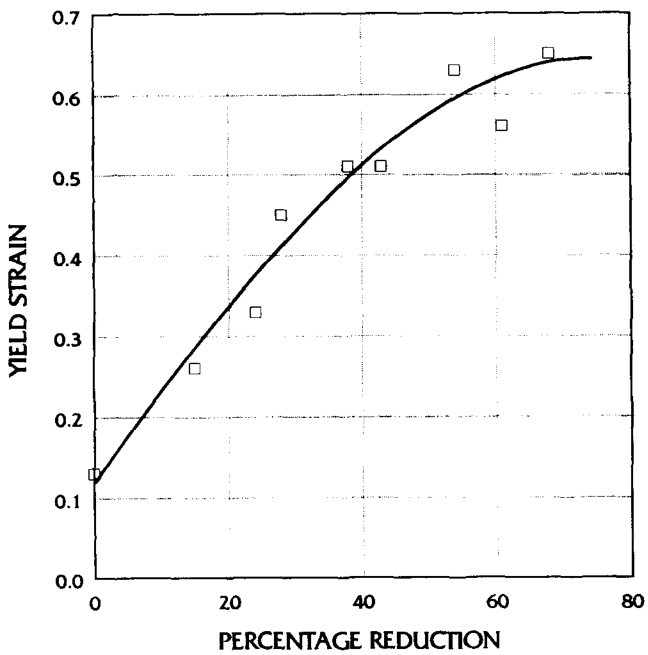

Figure 8 Yield strain *versus* percentage reduction

polypropylene reached a maximum in yield strain at about 50 to 60% RD and dropped significantly after this reduction. This drop was attributed to the loss of ductility of the polypropylene at high reductions. The higher %RD value for polyethylene showed that this value is highly dependent on the material and not so much constrained by geometrical/physical factors, such as form radius of rollers. The higher value could be attributed to the difference in melt temperature of polyethylene and polypropylene. Since the melt temperature of polyethylene is lower, the heat generated during flow-forming (rise in temperature was estimated[19] to be about 80°C), may contribute to enhancing the integrity and flowability of molecular chains.

Figure 9 illustrates the variation of the axial energy absorption with percentage reduction. Energy absorption increased with percentage reduction in a similar fashion to that of tensile strength, with the maximum percentage increase for the energy absorption exceeding 200% as well. Such improvements were also noted for polypropylene[18,19]. Evidently flow-forming has improved the ability of the pipe to absorb energy and this can also be related to the structurally altered state of the HDPE material after flow-forming.

Effect of flow-forming on pressure rupture behaviour

The variation of hoop stress and volumetric strain is shown in *Figure 10* (only representative curves are presented for the sake of neatness). The shapes of these curves are interesting. For the original (0% RD) material, the hoop stress increases to a maximum of about 20 MPa and drops off rapidly to a low volumetric strain of about 60% at rupture. The volumetric strain at rupture increased to more than 130% with increasing %RD. This increase is similar to that of yield strain (*Figure 8*). Between 30 and 53% RD a region of constant hoop stress with volumetric strain was noted at maximum hoop stress (*Figure 10*). This is similar to the presence of cold drawing where the applied stress is constant during the cold drawing stage. Between 60 and 70% the hoop stress *versus* volumetric strain curve changes to one with a yield point (without a yield drop or constant hoop stress region) and then increases linearly to the maximum hoop stress. This can be seen clearly for 70% RD in *Figure 10*.

The variation of maximum hoop stress with percentage reduction is shown in *Figure 11*. Here, it can be seen that the maximum hoop stress starts to increase after about 50% RD to 33 MPa at 70% RD. This represents more that 80% increase over the original pipe.

The changes in the hoop stress *versus* volumetric strain curves are indicative of the degree of structural change

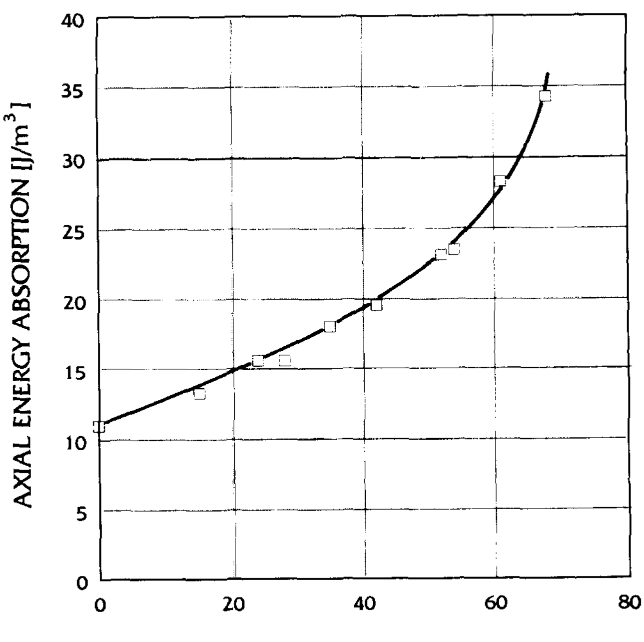

Figure 9 Axial energy absorption *versus* percentage reduction

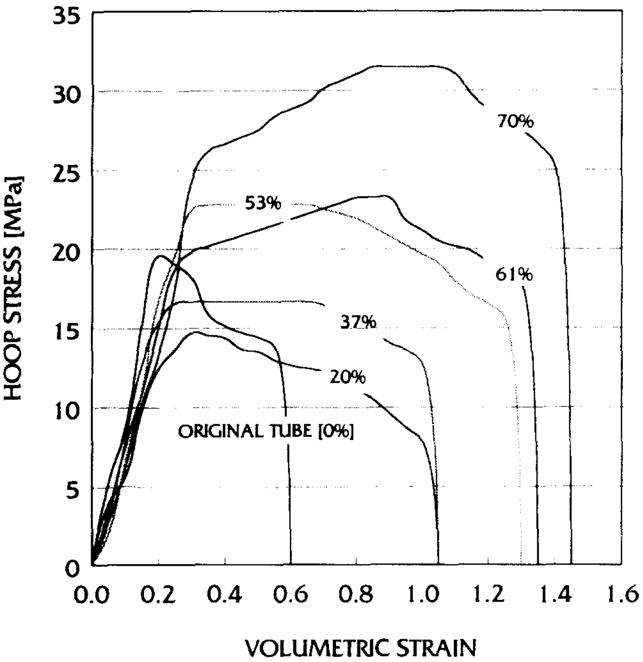

Figure 10 Hoop stress *versus* volumetric strain at various values of percentage reduction

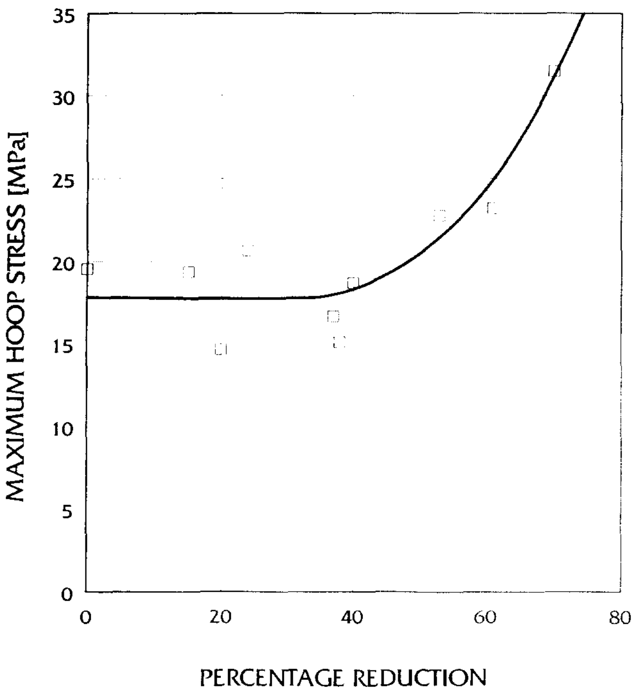

Figure 11 Maximum hoop stress *versus* percentage reduction

with %RD. The drop in maximum hoop stress at low %RD (less than 50%) may shed light on the integrity of the structural change of the material in the hoop direction. Interestingly, by referring to *Figure 4* on the stress–strain behaviour of the original material, cold drawing starts after a yield drop at about 50% strain. Although no extra work, such as X-ray analysis, was performed to determine the changes in crystallinity and lamellar structure, it can be deduced that improvement in hoop direction can only be achieved if there is cooperative cold drawing of the material. Below the strain for cold drawing, the introduction of defects during the high volumetric change brought about by the breaking up of elliptical spherulites to macrofibrils[23] during the yielding process, one expects a reduction rather than improvement in the hoop direction, an important point not noted before.

The area under the hoop stress *versus* volumetric strain curve is an indication of the energy absortion in the hoop direction. As can be seen in *Figure 12*, the energy absorption in the hoop direction increases to more than 300% of the original material. This trend is similar to the variation of axial energy absorption and %RD in the tensile tests (see *Figure 9*). Such results indicate that for polyethylene, energy absorption in both direction can be greatly improved.

The pressure rupture behaviour of the flow-formed pipes was observed and captured photographically. Some representative examples are shown in *Figure 13*. The photographs show the rupture behaviour of various tubes at increasing percentage reductions. The first pipe, the non-flow-formed tube, exhibited a less ductile fracture where little volumetric change was observed for the ruptured specimen. At 20% reduction, the pipe ruptured with the fracture lying in the direction of the helical line. However, the fracture occurred in very much the same way as the non-flow-formed pipe. Subsequently at a higher percentage reduction of 38%, the ruptured pipe exhibited a significant amount of volumetric change before fracture. At the localized area surrounding the crack, a thinned-out region of stress whitening was observed. This region represents the formation of microvoids owing to shear and lateral tensile strains between adjacent material. As before, the fracture occurred along the helical direction. For the 53% reduction specimen, rupture took place following an increased amount of volumetric change, as shown by the larger thinned-out region and the 'folds' surrounding the crack. The increase in volumetric change correspondingly denotes the increase in ductility of the flow-formed pipes. The 61% reduction specimen exhibited a further increase in the ductility as evidenced by the extensive volumetric

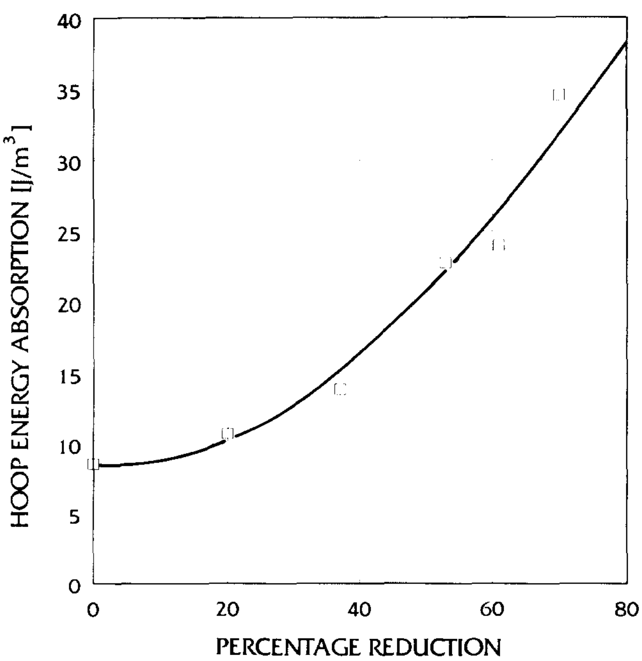

Figure 12 Hoop energy absorption *versus* percentage reduction

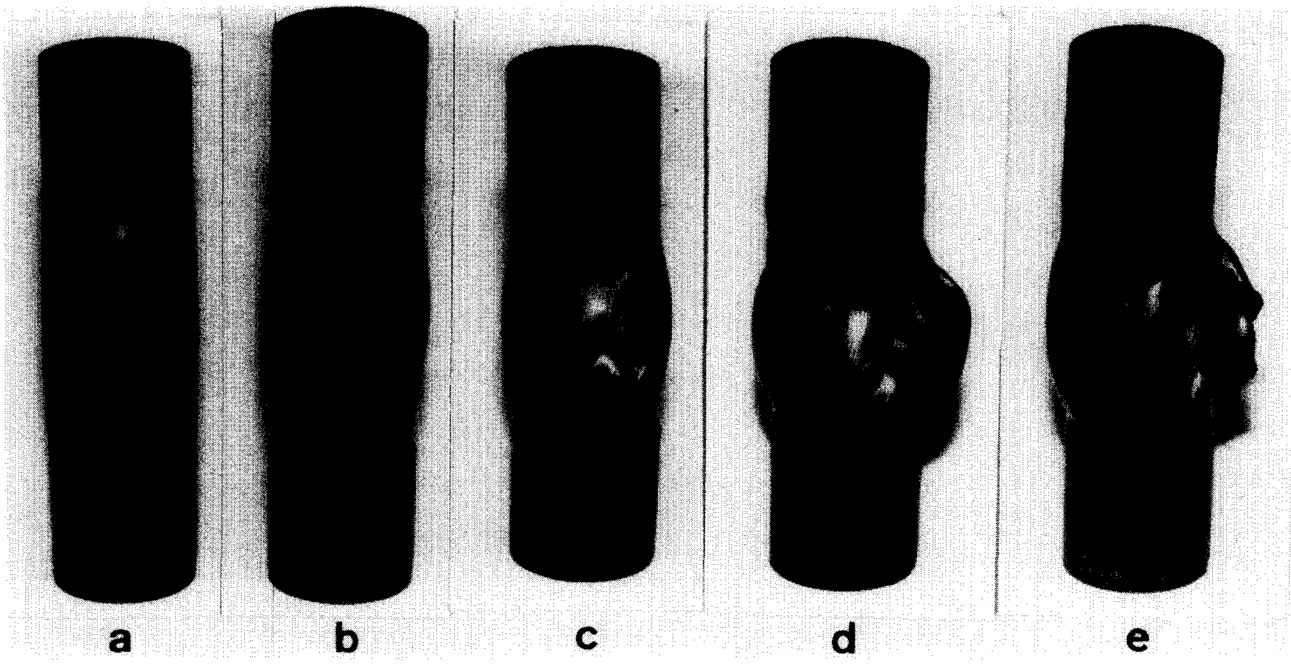

Figure 13 Pressure ruptured specimens: (a) 0% RD (original pipe); (b) 20% RD; (c) 38% RD; (d) 53% RD; (e) 61% RD

change. This extraordinary deformation behaviour was highlighted previously for flow-formed polypropylene tubes[18,19].

CONCLUSION

The variation of mechanical properties (tensile strength, yield strain, toughness, hoop stress and rupture behaviour) with percentage reduction of flow-formed polyethylene pipes, using three rollers, has been studied. The stress–strain behaviour of the flow-formed pipe exhibited less yielding and cold drawing as percentage reduction increased (in some cases above 30%, they were virtually absent). Significant increase in the tensile strength was observed for reductions above 20%. Improvement as high as 300% of energy absorption both in the axial and hoop direction with percentage reduction showed a similar trend to that of tensile strength. Pressure rupture tests conducted on the flow-formed pipes revealed that the hoop stress of the flow-formed pipes increased only after 50% reduction. The ductility of the flow-formed pipes increased with percentage reduction, as evident in the rupture behaviour of the flow-formed pipes as well as the corresponding increase in energy absorption measured. Extensive bulging was observed during the pressure rupture tests of pipes with more than 50% reduction. Scanning electron micrographs revealed a significant amount of structurally altered macrofibrils in the flow-formed pipe.

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