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Tensile properties of flow-formed polypropylene pipe

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The effects of varying the percentage reduction on the tensile properties of flow-formed polypropylene pipes were investigated. Flow-forming, which is a single-point cold rolling process, was performed by using two rollers in a single pass on a conventional lathe machine. Specimens were cut at different orientation angles to the pipe direction. The load–extension behaviour of the flow-formed material showed that the phenomena of yielding and cold drawing gradually become less prominent above 30% reduction. These phenomena were also functions of the orientation angle. From the variations of tensile properties with orientation angle, it was concluded that flow-forming can produce high anisotropy, especially above 30% reduction. Improvements in yield and tensile strength were achieved after about 35 to 45% reduction. The tensile modulus increased significantly after 50% reduction. The yield strain reaches a maximum at about 50 to 60% reduction. Elongation at break decreases with increased reduction. It was noted that 80% reduction appeared to be the maximum reduction, after which the material will exhibit extremely low ductility.

1. Introduction

Flow-forming is a single-point cold rolling process in which the wall thickness of a tube or preform is reduced and the length increased without changing the internal diameter. This process, which is well established in the metal industry, is sometimes referred to as flow-forming of tubes [1–3], tube spinning [4–6] and spear spinning [7, 8]. The main limitations of the flow-forming process are primarily related to the practical limits of deformation that the material will withstand and the minimum percentage of reduction that will ensure complete material flow.

There are two modes of operation associated with the flow-forming process, namely the forward and reverse (backward) process. Fig. 1 illustrates schematically these two modes. In the forward flow-forming process, the material flows ahead of the roller in the same direction as the roller feed direction and is usually towards the headstock (spindle) of the machine. Advantages of forward flow-forming include close control of the length of the flow-formed tube and the elimination of distortion problems. In the reverse flow-forming process, the material is extruded beneath the roller in the opposite direction of the roller feed, usually towards the tailstock of the machine. Preform tubes are not clamped, but are slid over the mandrel to the headstock end of the machine.

The flow-forming process depends on primary and secondary factors. The primary factors are feed of roller, speed of rotation of mandrel, transverse feed, roller diameter, approach angle, nose radius and relief angle of roller. Factors such as the amount of prior cold working and interstage annealing are the secondary factors. The magnitude of the flow-forming forces required, the percentage of wall thickness reduction achievable and the properties of the final product are functions of the above factors. For instance, for metals a decrease in roller feed rate produces a better surface finish [9].

While the flow-forming process has been well investigated by the metal-forming industry, there does not appear to be any published work on the flow-forming of plastic tubes. The nearest process to it is the cold rolling of polymeric sheets, of which numerous reports have been made.

Gruenwald [10] reported the changes in mechanical properties of polycarbonate due to rolling. The effect of cold rolling by up to 50% of polyethylene has been reported by Rothschild and Maxwell [11]. Wilchinsky [12] studied the orientation produced by cold-rolling polypropylene using X-ray diffraction techniques. Later, he showed that the brittleness temperature of polypropylene was reduced by rolling [13]. Litt and Koch [14] studied biaxially rolled polycarbonate and polyvinyl sheets and observed unusual changes in the relaxation properties when stressed in tension or compression. Peterlin [15] found that cold rolling of high-density polyethylene increases the modulus of elasticity and ultimate tensile strength, reaching an asymptotic value beyond a draw ratio of 20. Broutman and co-workers [16–18] studied the influence of rolling on a number of amorphous polymers such as polycarbonate, acrylonitrile–butadiene–styrenes, polysulphones and polyphenylene oxides. Bahadur and Henkin [19] investigated the ductility of rolled acetal, Nylon 66, polyvinyl chloride

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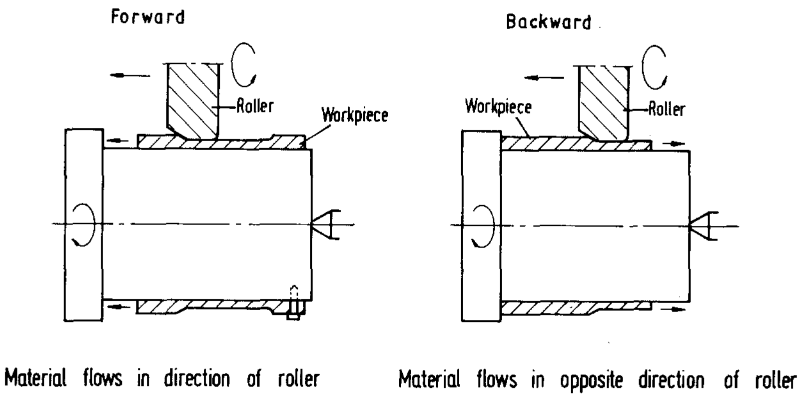

Figure 1 Schematic drawing of the forward and backward flow-forming processes.

and polycarbonate. Their conclusion was that ductility and extensibility increase with reduction, with the former reaching a maximum and falling thereafter. Dhingra *et al.* [20] extended their study of unidirectional rolled polypropylene to bidirectional rolling. Their aim was to relate property changes with the corresponding changes in both molecular orientation and crystal morphology. The crack growth under static and fatigue loading in cold-rolled polycarbonate and polyvinyl chloride were studied by Kitagawa *et al.* [21]. Their results showed that significant improvement can be achieved in the resistance to static and fatigue crack growth of the rolled material.

Evidently, it is clear that flow-forming of tubes, which is closely related to bidirectional cold rolling, will produce significant changes in the properties of polymer tubes. In a previous article [22] the tensile and pressure yield behaviour of flow-formed polypropylene pipe using a single roller was reported. In that article, the extraordinary deformation behaviour of flow-formed polypropylene pipes when subjected to pressure testing was highlighted. Fig. 2 shows the highly ductile mode of deformation of a flow-formed polypropylene pipe when compared to a polypropylene pipe that had not been flow-formed. Such behaviour has been attributed to anisotropy of the mechanical properties of the polypropylene pipe. However, such anisotropy has not been thoroughly studied.

This paper describes the effects of varying the percentage reduction on the tensile properties at different orientation angles to the pipe extrusion direction of flow-formed polypropylene pipes using two rollers, in the forward flow-forming process.

2. Experimental procedure

2.1. Material

The pipe material used was a copolymer of polyproplene produced by ICI and supplied by George Fisher Ltd (see Fisher [23] for further details). The polypropylene pipes, which come in a beige colour, had an external diameter of 50.5 ± 0.1 mm and internal diameter of 40.6 ± 0.2 mm. Only those that were within 40.6 ± 0.05 mm were used in the flow-forming process. The tight tolerance for the internal diameter was necessary, since the pipe needs to slide over a steel mandrel for the flow-forming process.

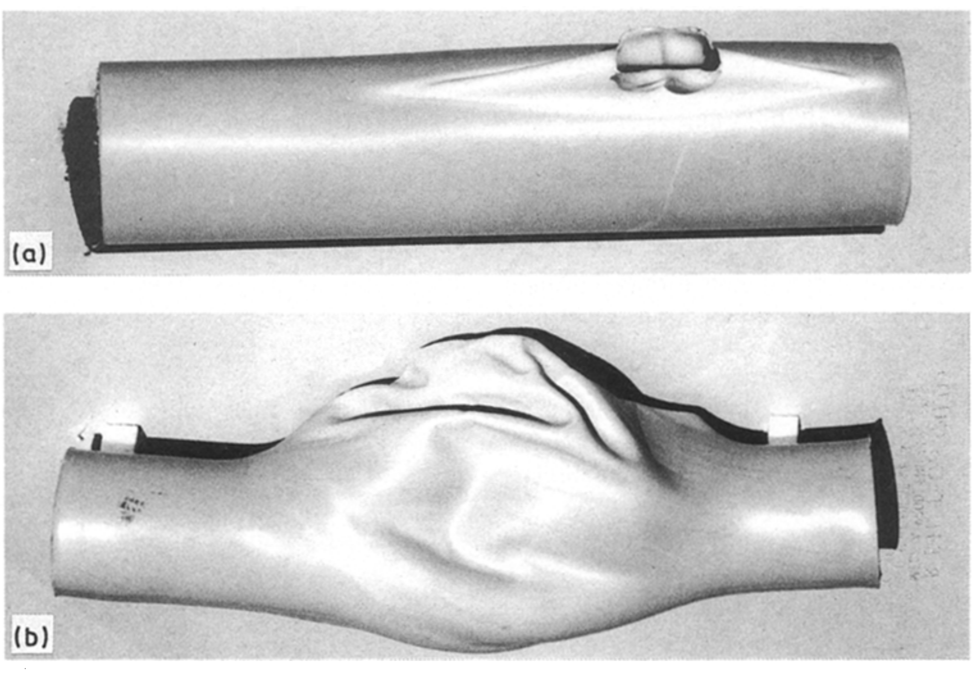

Figure 2 Pressure rupture behaviour of (a) an unflow-formed pipe, and (b) a flow-formed pipe showing ductile mode of rupture.

2.2. Forward flow-forming process

Fig. 3 shows the general set-up of the forward flow-forming experiment. A conventional lathe was used. A steel mandrel, which was designed to have a sliding fit to the internal diameter of the polypropylene pipe, was secured by the four-jaw chuck at one end and a tailstock at the other end. The tool post was removed so as to mount the twin-roller flow-forming tool on the cross-slide of the lathe. Twin rollers of 120 mm diameter, 10 mm edge radius, 30° forward angle and 5° relief angle were used. The reasons for using two rollers were to improve on the dimensional accuracy and to reduce bowing effects of the flow-formed pipes. These were the major problems when a single roller was employed in our previous work [22]. The speed of rotation of the mandrel was set at 185 r.p.m. and the feed rate of the twin rollers was at 0.3 mm rev^{-1}. All specimens were flow-formed in one single pass by the twin rollers over the polypropylene pipe. Reductions of 30, 50, 60 and 76% were made. The percentage reduction (RD) was calculated as

$$\%\text{RD} = \frac{\text{Reduction in thickness of pipe} \times 100}{\text{Original thickness of pipe}}$$

2.3. Tensile testing

Dumb-bell shaped tensile specimens were cut according to the ASTM standard (D638, Type IV) from the

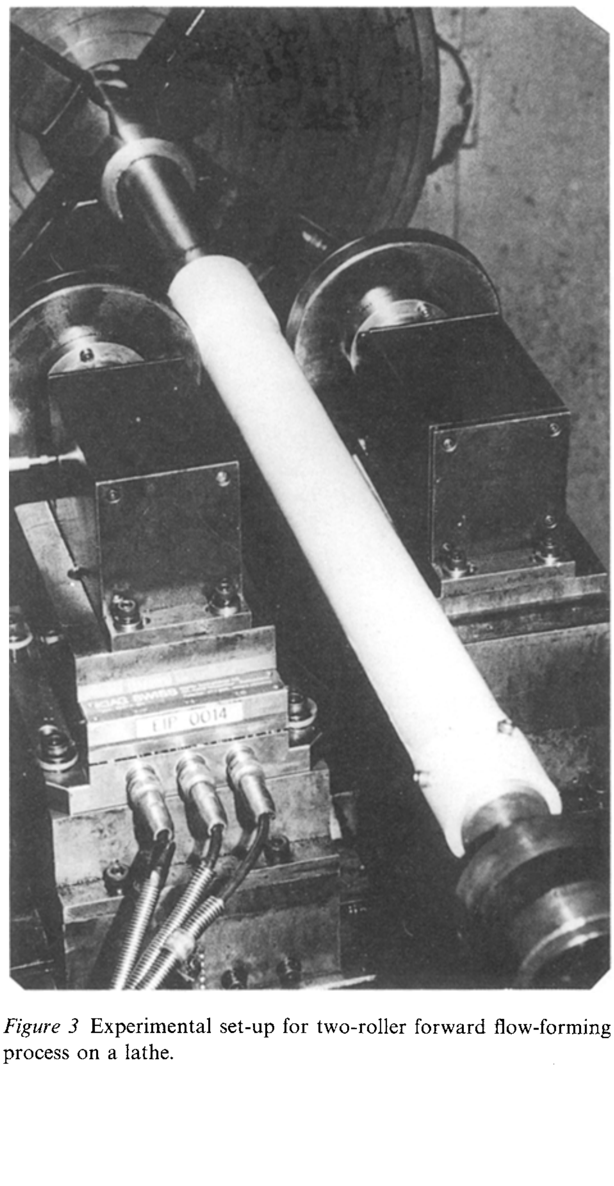

Figure 3 Experimental set-up for two-roller forward flow-forming process on a lathe.

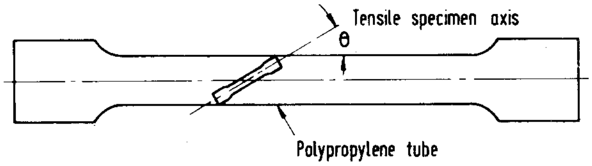

Figure 4 Definition of orientation angle.

flow-formed tubes, so that their axes were inclined at various orientation angles. The orientation angle (θ) was defined as the angle between the helical flow-forming direction and the extrusion direction of the pipe (see Fig. 4). Significant care was taken to ensure that all surfaces of the specimen were free of visible flows, scratches or imperfections. The marks left by coarse machine operations were carefully removed with a fine abrasive paper (grade No. 00). The width and thickness of the test specimens were measured at three positions in the gauge section by using a micrometer with an accuracy of $\pm$ 0.02 mm. The arithmetic mean was used to represent the average value of the three positions.

Tensile tests were carried out on an M30K (J.J. Lloyd) tensile machine, using a force–extension recorder (PL 3 XY/T) and friction grips. All tests were carried out at 23 $\pm$ 1 °C and 70 $\pm$ 5% relative humidity. A test extension speed of 12.7 mm min^{-1} was used for all tests. Five specimens for each %RD and each orientation angle were tested so as to establish an average value of the tensile properties. The tensile properties measured were the yield strength, tensile strength, yield strain, breaking strain and secant modulus. The yield strength and tensile strength were defined as the load at yield and the maximum load at break divided by the original cross-sectional area, respectively. The yield strain and the breaking strain were defined as the extension at yield and extension at break divided by an effective gauge length of 35 mm, respectively. The secant modulus at 14% strain was used as a measure of the modulus of the material.

3. Results and discussion

3.1. Load–extension behaviour

In order to investigate whether the original unflow-formed polypropylene pipes exhibited any anisotropic behaviour, specimens were cut at orientation angles of 0, 10, 20, 30, 45 and 60° to the pipe extrusion direction. This method of cutting the specimens will inevitably introduce some errors in the load–extension measurements. This is because of the small diameter of the pipe, and for $\theta > 20°$ the curvature of the tensile test specimens that were cut out from the pipe became quite large. As a result, the specimens were aligned straight by flattening them manually just before putting them in the jaws of the gripping device of the tensile testing machine. However, this is an experimental difficulty which cannot be overcome easily. Since the load that is required to straighten the specimens is generally less than 15 N, it is deemed small when compared to the tensile load at yield of about 400 N or more. (One could actually cut out annulur rings as in ASTM D2260, but this would entail making different sets of gripping devices for different orientation angles. This was not pursued for reason of ease of experimentation). A total of five specimens were used for each orientation angle. The shapes of the load–extension curves for the unflow-formed pipes were all similar. The load increased initially until the yield point, after which it dropped and was followed by extensive cold drawing before it ultimately ruptured. The similar load–extension behaviour for all θ values indicated that the unflow-formed polypropylene pipes were isotropic, contrary to our initial belief that the tensile properties may be significantly different, especially at $\theta = 0°$ (that is, in the direction of pipe extrusion) where it was assumed that greater alignment of molecular chains due to the extrusion process would give rise to higher tensile properties. The isotropic nature of the pipe indicated that the alignment of molecular chains was small and/or the temperature just after extrusion was sufficiently high and the time long enough to induce complete crystallization with little preferred chain alignment in a particular direction.

The flow-forming process, being a contact-point rolling process, similar to cutting threads on a shaft (except that it is chipless and hence without loss of material), will exhibit helix lines like that of threads on a shaft. Fig. 5 illustrates the formation of the helix lines using two rollers. It is believed that the tensile properties of the material will be maximal when the specimens are cut along the helix angles (this is equivalent to the tensile properties along the rolling direction for the cold rolling of polymeric sheets). Hence, for reductions of 30% and above, specimens were cut in the orientation of the helix angle as well.

Figs 6 to 9 show the load–extension behaviour for reductions of 30 to 76%, respectively. Significant differences can be observed in each case. As the percentage reduction increases, the phenomenon of load drop (yield point) gradually became less prominent and totally absent in many cases above 30% reduction. Similar observations were also made by Broutman and Patil [16] who studied the cold rolling of ABS, polyphenylene oxide, polysulphone, polycarbonate and PVC. They observed that the yield point (tested in the rolling direction, which in the flow-forming of plastic pipe corresponds to the helix angle) became less conspicuous after 30% reduction in thickness and was totally absent at higher reductions. This result was also noted by Grancio [24] who studied the influence of rolling on the properties of amorphous polymer, by Wilchinsky [13] who studied the reduction of brittleness in polypropylene due to cold rolling, and by Dhingra *et al.* [20] who studied the relationship between mechanical properties and structure in rolled polypropylene. However, the presence of the yield point is also a function of θ. For instance, at 50% reduction (Fig. 7) and 60% reduction (Fig. 8), the yield point reappears at $\theta = 60°$. For 75% reduction (Fig. 9), the yield point can be seen for $\theta = 30°$ and less prominently for $\theta = 20$ and 45°.

The extent of cold drawing, which is defined by the region of the load–extension curve when the load remains almost constant with increasing strain after the yield point, also changes appreciably with the percentage reduction and with θ. In the case of the 30% reduction (Fig. 6) the extent of cold drawing was highest when $\theta = 0$ and 60° and smallest for θ between 10 and 20°. Similar observations could also be made for 50 and 60% reduction. At 76% reduction, cold drawing becomes less conspicuous and it is questionable whether cold drawing can be defined in these curves.

In order to understand the load–extension behaviour in relation to the yield point and extent of cold

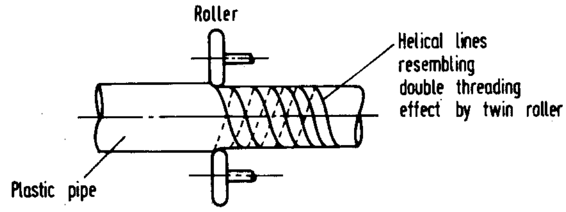

Figure 5 Schematic drawing illustrating the formation of helical lines during the flow-forming process.

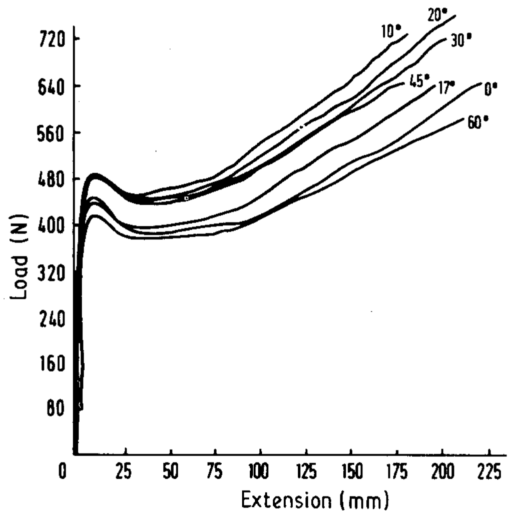

Figure 6 Load–extension curves for specimens flow-formed to 30% reduction.

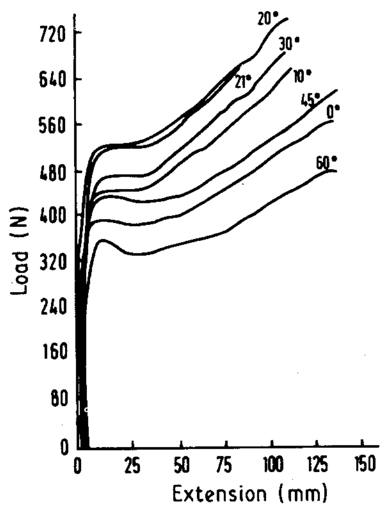

Figure 7 Load–extension curves for specimens flow-formed to 50% reduction.

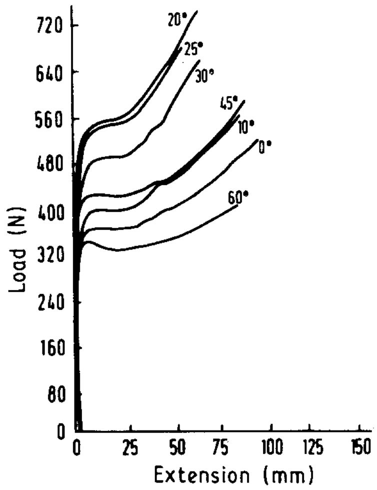

Figure 8 Load–extension curves for specimens flow-formed to 60% reduction.

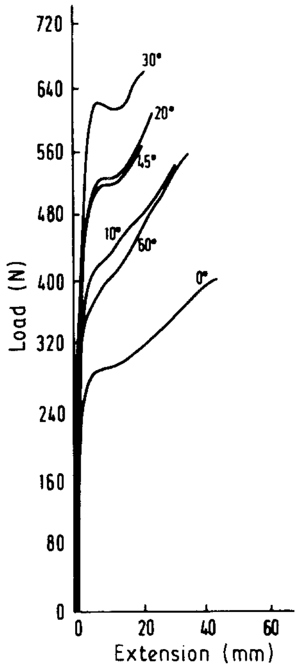

Figure 9 Load–extension curves for specimens flow-formed to 76% reduction.

drawing, one needs to consider the changes of morphology with deformation. Since polypropylene is semicrystalline, the mechanisms of deformation studied by Peterlin [15] seemed most appropriate.

It is generally accepted that the initial deformation is related to distortion of the spherical spherulites to somewhat ellipsoidal shape near the yield point. Studies by Samuel [25] also confirmed this. Once pass the yield point, massive structural changes with chain sliding and tilting occur, and the crystalline blocks break up into smaller crystalline blocks stacked on top of one another and interconnected by tie molecules to form macrofibrils. This process occurs during the cold drawing stage. The formation of macrofibrils will continue until the structural integrity of the initial crystalline blocks is all exhausted. (However, 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.)

The macrofibrillar structure is much stronger than the initial spherulitic structure, especially in the tensile axis, and hence the macrofibrils can support a higher tensile load. This explains the increase in load after cold drawing. At sufficiently high loads, the macrofibrils themselves begin to break up into even smaller entities of crystalline blocks to form microfibrils. Breedon *et al.* [26] have shown good transmission electron micrographs of these microfibrils. On further increase of load, if the competing mechanism of crack growth has not superseded chain sliding and structural transformation, a point is reached where the fibrils can no longer support the load and the fibres themselves ultimately fracture.

Now in flow-forming, as in cold rolling, an improvement in tensile properties appears only after the percentage reduction has exceeded that of the yield strain of the material. This is supported by the results of other researchers [14–22]. The polypropylene pipe material has a yield strain of about 22%. In other words, for percentage reduction of 30% and above, the material is being flow-formed in the regions just after the yield point or in the cold-drawn region where fibrillar structures are present. One would therefore not expect a yield drop to be observed in such cases. However, unlike cold rolling which is a line-contact cold-forming process, flow-forming is a point-rolling process with triaxial forces acting on each contact point [22]. There is, therefore, a high probability that not all the initial material is strained beyond the yield strain. This probably accounts for the presence of the yield and extensive cold drawing observed for the 30% reduction at all orientation angles and for some orientation angles (especially $\theta = 60°$) for higher percentage reductions, up to 60% reduction. Interestingly, the yield point was obvious for the 76% reduction at $\theta = 30°$ corresponding to the helix angle at that reduction. It is believed that the yield point and small cold-drawing region here are due to the structural change from macrofibirils to microfibrils.

3.2. Effect of flow-forming on yield strength and tensile strength

The variations of yield strength and tensile strength for various orientation angles at different percentage reductions are similar. A typical example is shown in Fig. 10 for the yield strength. For 0 and 30% reduction the changes in yield and tensile strength with orientation angle are negligible. This is indicative that below 30% reduction the material is, apparently, still isotropic. For reductions of 50, 60 and 70%, it is obvious that a maximum is seen at an orientation angle close to the helix angle. This indicates that flow-formed pipes at high reductions are very anisotropic and that the maximum yield and tensile strength lie along a direction close to the helix angle of the pipe. It is interesting to note that although there is a general increase in properties with reduction (Fig. 11), significant improvement is only achievable after 35 to 45% reduction. The maximum percentage increase for the

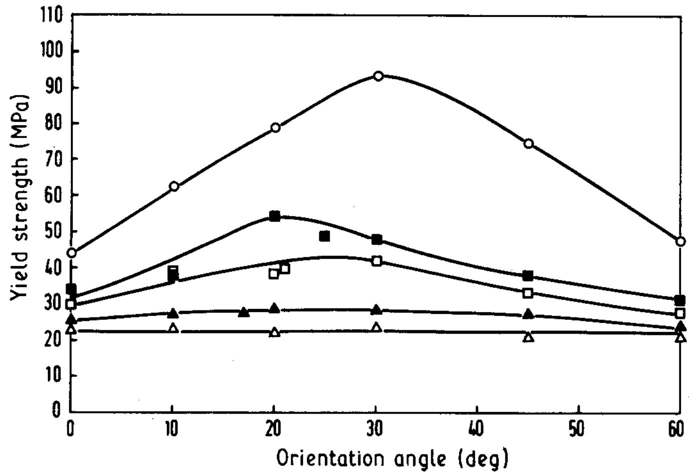

Figure 10 Variation of yield strength with orientation angle. Reduction: (△) 0%, (▲) 30%, (□) 50%, (■) 60%, (○) 76%.

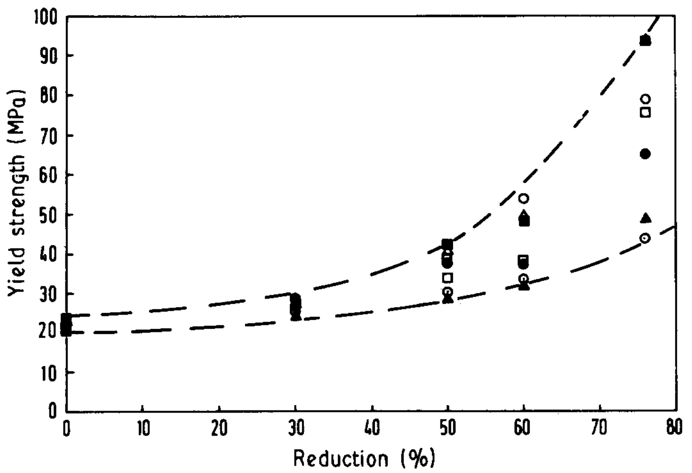

Figure 11 Variation of yield strength with percentage reduction. Orientation angle: (⊙) 0°, (●) 10°, (○) 20°, (■) 30°, (□) 45°, (▲) 60°, (△) helix angle.

yield strength exceeds 350%, while that of the tensile strength exceeds 250%. These represent a remarkable improvement over the unflow-formed material.

3.3. Effect of flow-forming on tensile modulus

The variation of secant modulus with orientation angles is shown in Fig. 12. Its variation with percentage reduction is similar to that for yield strength. Generally, it can be seen that the secant modulus reaches its peak value close to the helix angle. For reduction below 50% there does not appear to be any improvement in modulus. However, from 60% reduction onwards the maximum secant modulus is more than 400% of the unflow-formed material. At the present moment there appears to be some inconsistency, in that one would expect the modulus for the specimens with 50% reduction to increase substantially above that of 30% reduction as in the variation of yield and tensile strength. But this was not observed, and for orientation angles between 0 and 10° the modulus is slightly below that of the unflow-formed material.

Initially it was thought that some strain-softening mechanism may be operating, especially if the mater-

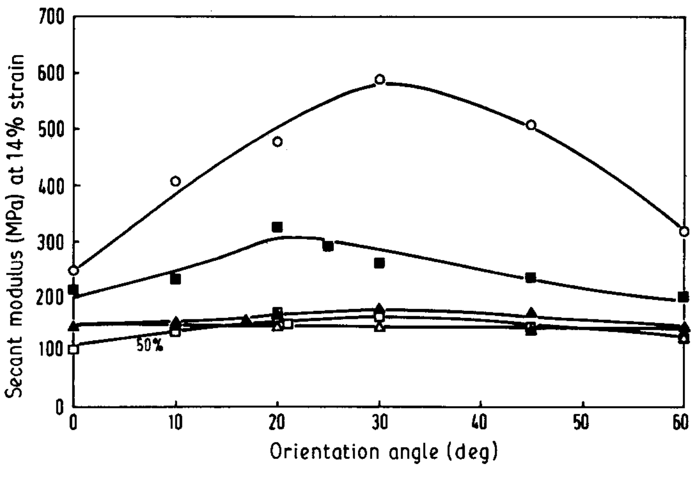

Figure 12 Variation of secant modulus with orientation angle. Reduction: (△) 0%, (▲) 30%, (□) 50%, (■) 60%, (○) 76%.

ial is flow-formed just after the yield point where the spherulites are just undergoing structural transformation. This was considered to be highly possible since flow-forming is a point-contact form of process, and not all the material, especially in the thickness direction, would have undergone the same reduction and hence deformation. However, since there is an increase in yield and tensile strength after 30% reduction, strain-hardening and not strain-softening has taken place. These therefore do not appear at the present moment to be any logical reasons for the above. A possibility may be that the secant modulus at 14% strain is not a good measure of the modulus of the material. A tangential or secant modulus at a much lower strain would be better, and this will be pursued in a later publication.

3.4. Effect of flow-forming on the yield strain and elongation at break

The variations of yield strain for various orientation angles are similar to those for yield strength. Anisotropy, in terms of the presence of a maximum close to the helix angle, is most obvious for reductions above 30%. However, there is a substantial drop in yield strain after 50% reduction, indicating a drop in ductility. This drop in ductility is most obvious if one plots yield strain against reduction as shown in Fig. 13.

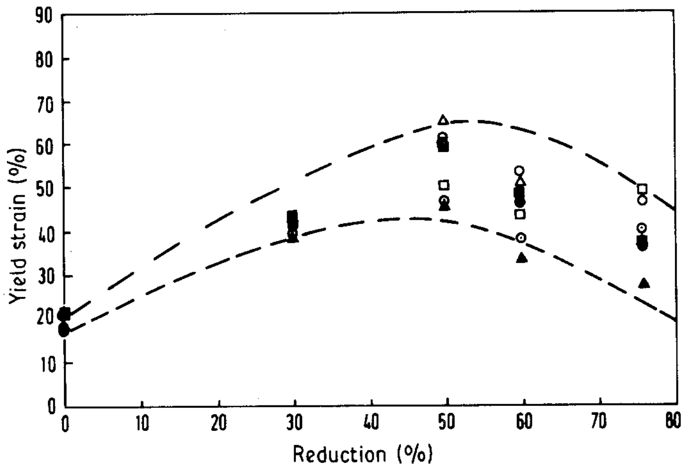

Figure 13 Variation of yield strain with percentage reduction. Orientation angle: (⊙) 0°, (●) 10°, (○) 20°, (■) 30°, (□) 45°, (▲) 60°, (△) helix angle.

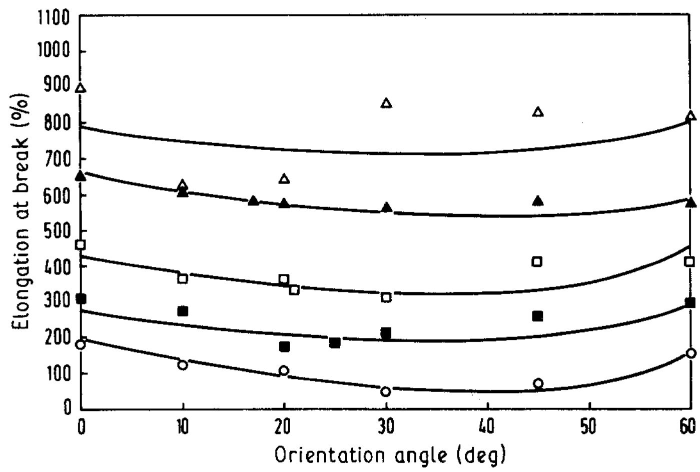

Figure 14 Variation of elongation at break with orientation angle. Reduction: (△) 0%, (▲) 30%, (□) 50%, (■) 60%, (○) 76%.

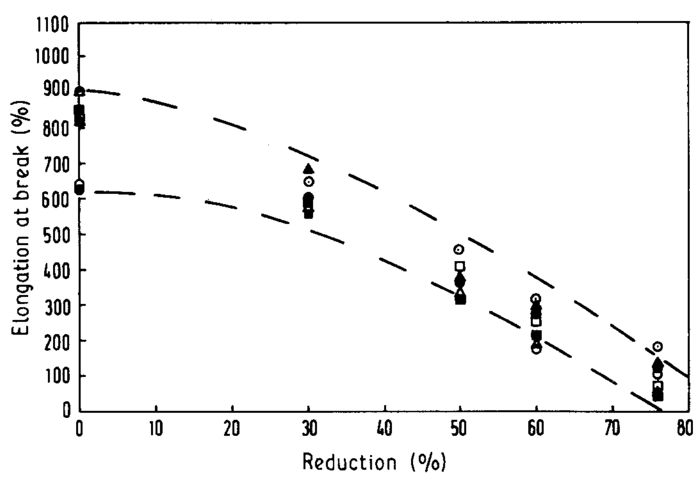

Figure 15 Variation of elongation at break with percentage reduction. Orientation angle: (⊙) 0°, (●) 10°, (○) 20°, (■) 30°, (□) 45°, (▲) 60°, (△) helix angle.

Here it can be seen that the yield strain reaches a maximum between 50 and 60% reduction, after which the yield strain decreases with increasing reduction.

The variations of elongation at break with orientation angle show a different behaviour from the rest in that no maxima were observed (Fig. 14), and it decreases with percentage reduction. There is an apparent minimum, but the substantial scatter which is to be expected for elongation at break measurement makes interpretation difficult. A plot of elongation at break against reduction indicates an important result in that above 80% reduction a highly brittle material (indicated by the very low elongation to break in Fig. 15) is produced. This may well account for the fact that flow-forming beyond 80% reduction is hard to achieve in practice.

4. Conclusions

The effects of varying the percentage reduction on the tensile properties (yield strength, tensile strength, tensile modulus, yield strain and elongation at break) at different orientation angles of flow-formed propropylene pipes, using two rollers in the forward flow-forming process, have been studied. The load–extension behaviour of the flow-formed material showed that as the percentage reduction increases, the phenomena of yielding and cold drawing gradually became less prominent and are totally absent in many cases above 30% reduction. These phenomena were also functions of the orientation angle and can best be understood by referring to the model relating deformation of spherulite to fibrils after Peterlin [15], and by noting that flow-forming is a point-rolling cold-forming process.

From the variations of tensile properties with orientation angle, it was found that flow-forming can produce a high anisotropy which becomes most prominent above 30% reduction. The maximum/minimum point of each property appears to correspond closely to the helix angle of the flow-formed pipes. Significant improvement in yield and tensile strength could only be achieved after about 35 to 45% reduction. Improvement in tensile modulus appeared to begin only after 50% reduction. It was also noted that yield strain reaches a maximum at about 50 to 60% reduction. From the measurement of elongation at break, it was seen that there was a gradual decrease with increasing percentage reduction and that 80% reduction appeared to be the maximum reduction, after which the flow-formed material will exhibit extremely low ductility.

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