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Comparison of bending stiffness of six different colours of copolymer polypropylene

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Abstract

This paper compares the bending stiffness of 5 different colours of copolymer polypropylene (CCP) with that of natural copolymer polypropylene (NCP). Flesh coloured and natural sheets are supplied thicker than other pigmented sheet. The bending stiffness of a specimen may be defined as EI, i.e. the product of E, Young's modulus of elasticity and I, the 2nd moment of area.

Strips of "as supplied" (AS) and "post-draped" (PD) specimen were clamped and subjected to bending to assess the effect of pigmentation on bending characteristics. The gradient of the graph of bending deflection δ versus bending moment enables EI to be estimated. The process of thermoforming polypropylene reduces EI, the bending stiffness. However, the manual draping and vacuum procedure introduces so many variables that it is difficult to quantify the effect of pigmentation. The E of a bent specimen may be estimated from the gradient of the graph of δI versus bending moment. In the case of AS sheet, the effect of pigmentation on E is inconclusive. PD specimens indicate a significant reduction in E due to thermoforming. This was verified by an electron-microscope study of AS and PD specimens.

Draping an ankle-foot orthosis (AFO) results in a non-uniform wall thickness. The results of this study with respect to the effects of pigmentation on the bending stiffness of AFOs are inconclusive. More detailed studies require to be completed in order to confirm which factors are responsible for this non-uniformity in wall thickness and consequent variation in bending stiffness.

Introduction

The use of CCP in paediatric orthotics has grown in popularity over recent years, in an attempt to improve the "cosmesis" or acceptability. This use of CCP has been associated with uncertainty as to the consistency of the mechanical properties between colours.

One of the major clinical concerns of the orthotist is the ability of an AFO to resist bending in the sagittal plane. The AFO bending normally occurs in the vicinity of the ankle joint. The success or failure of most AFOs lies with the ability of the orthosis to control ankle joint position and/or motion.

This study establishes the bending stiffness of NCP and compares it with that of 5 different colours of CCP.

A number of researchers have studied the bending stiffness of different AFOs. Yamamoto *et al.* (1993) reported on the plantar/dorsiflexion and inversion/eversion bending stiffness of a selection of different orthoses fitted to a normal limb. The 3-dimensional bending stiffness of a polypropylene AFO was reported by Klasson *et al.* (1998). Lunsford *et al.* (1994) reported on the variation in wall thickness of 3 AFOs thermoformed from the same sheet over the same plaster model. The variation in wall

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thickness of 4 AFOs thermoformed from the same sheet over a plaster model was as reported by Golay *et al.* (1989).

Method

Typically 3mm thick extruded polypropylene is used in paediatric orthotics. The following colours of polypropylene sheet were obtained from an established supplier of "prosthetic/ orthotic" grade materials:

- natural
- royal blue
- asian brown
- flesh tone
- poppy red
- fluorescent green

The supplier's thickness specification of flesh coloured and natural sheets was 3.1mm ±5% and for the other four colours 3.0mm ±5%. All sheets were copolymer polypropylene with approximately 5% ethylene and <2% pigment. The test specimens were prepared as follows.

Three (3) strips of each colour, each 200mm long and 30mm broad, were cut from the AS sheet by a technician. A 3mm hole was drilled on the centre line of each strip, 30mm from the end of the AS specimens, as shown in Figure 1.

As a monitor of the effect of a typical orthotic manufacturing process, single sheets of each colour were heated in an oven at 180°C for 9 minutes. The hot sheets were then vacuum moulded over a steel rectangular mould and left overnight to cool. PD specimens were cut from the moulded sheet by another technician to provide 3x200mm long strips, 30mm broad. As with the AS specimens, a 3mm hole was drilled on the centre line of each strip, 30mm from the end of the PD specimens.

The thickness and breadth dimensions of the AS and PD specimens were measured using a micrometer at 2 locations, one at mid-length and the other 10mm from the end with the 3mm hole. The measures were taken by 3 orthotists in order to take account of individual differences in using the micrometer. The variation in breadth measurements identified the accuracy to which the 2 technicians cut the specimens, following the same instructions. The variation in the thickness measurements identified whether thermoforming had any effect on the thickness dimension.

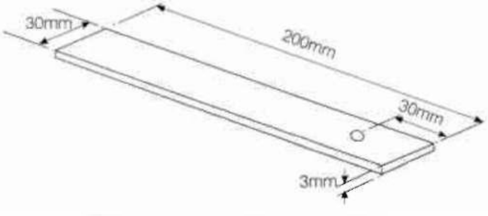


Fig. 1. "As supplied" test specimen.

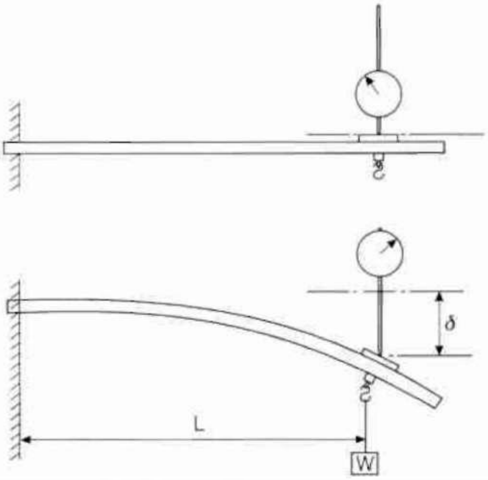


Fig. 2. Bending test apparatus.

The AS and PD specimens were positioned horizontally and clamped at one end. When subjected to a load W at a distance L from the clamp, as shown in Figure 2, the deflection of the specimen (δ) at the load point in the direction of the applied load is:

$$\delta = WL^3/3EI \qquad \text{(Equation 1)}$$

Where W =m x g
m =the suspended mass (kg)
g =acceleration due to gravity $9.81\,ms^{-2}$
L =horizontal distance from the clamped end to the load point
WL =applied moment
E =Young's modulus of elasticity
I =2nd moment of area of the beam =$(\text{breadth} \times \text{thickness}^3)/12$
EI =Bending stiffness or flexural rigidity

A clamped dial gauge measured the vertical deflection at the load point of each AS and PD specimen. A metal adaptor was fitted to the 3mm hole in the specimens. The dial gauge contacted the flat top surface of the adaptor while masses were suspended from the hook on the under-surface of the adaptor. A 0.05kg hanger was suspended from the hook at a distance L=80mm from edge of the clamp. Incremental masses of 0.05kg were applied in a consistent "cushioned" procedure and left for 1 minute before measuring the vertical deflection. Deflections δ were measured during increasing and decreasing load cycles specimens to minimise any differences caused by the effects of creep and shock loading. Bending moments of 39Nmm, 79Nmm, 119Nmm and 159Nmm were applied and the corresponding deflections δ were noted. This procedure was repeated for all AS and PD specimens.

Equation 1 may be expressed as:

$$\delta = (L^2/3EI)\text{Moment}$$

$L^2/3EI$ may be determined by plotting δ versus the applied moment and determining the gradient of the graph. The bending stiffness may be estimated from this gradient and the effect of pigmentation and thermoforming on the bending stiffness of the coloured specimens may be assessed by comparing the differences between the AS and PD specimens.

If the thickness or breadth dimensions vary along the length of the specimens, this affects I of the specimen and hence the deflection. As an approximation for variations of I, rather than plotting δ versus applied moment the Equation 1 may be re-written as:

$$\delta I = (L^2/3E)WL$$

$$\text{Deflection x 2nd Moment of Area} = (L^2/3E)\ \text{Moment}$$

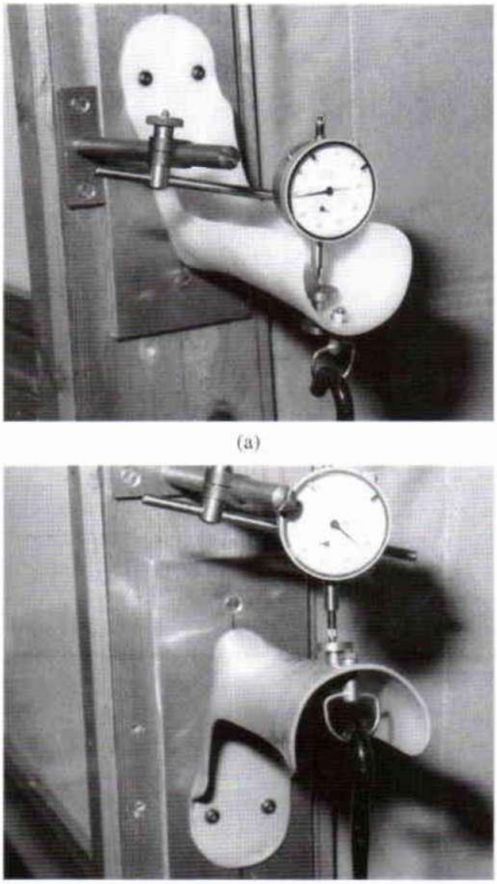
By plotting δI versus the applied moment and determining the gradient of the graph, E may be estimated. The effect of pigmentation and thermoforming may be assessed by comparing the differences in the estimated E values of the AS and PD specimens.

Single sheets of each colour were heated in an oven at 180°C for 9 minutes and then vacuum moulded over identical plaster casts to form AFOs. Each AFO was trimmed to the same landmarks to allow direct comparisons. The wall thickness of the 6 AFOs was measured with a micrometer at the following locations:

- the medial malleolus;
- the lateral malleolus;
- the sole plate;
- the proximal aspect of the calf section.

A set procedure was adopted for the bending tests on the AFOs. First, an outer acrylic resin shell was laminated over an AFO and the master mould. A metal plate was then drilled and threaded with 3x5mm holes. These 3 holes were transferred to the sole plate of the laminated shell. An additional 2 holes, 3mm and 5mm, were drilled on the centre line of the calf section of the laminated shell, at 30mm and 20mm respectively from the edge of the proximal calf. Each of the AFOs was fitted intimately within the inner wall of the laminated shell. The 5 holes in the laminated shell were transferred accurately to each of the AFOs.

The metal plate, incorporating the 3 threaded 5mm holes, was attached to a vertical wall so that each AFO could be bolted to the plate with the calf located in a "horizontal" position. A metal adaptor, with 2 flat platforms, was fitted to each AFO through the 3mm hole located 30mm from the proximal calf edge. A clamped dial gauge in contact with the platform of the adaptor accurately measured vertical displacements. Masses were suspended from the AFO using the D ring attached to the 5mm hole located 20mm from the proximal calf edge. A 0.4kg hanger was suspended from the adaptor at the proximal calf edge and masses were added to the hanger in increments of 1kg up to a maximum of 5kg. The corresponding deflections were noted 1 minute after each increment of load was applied. The


(a)

(b)

Fig. 3. (a) AFO plantarflexion test. (b) AFO dorsiflexion test.

maximum mass of 5.4kg suspended from the D ring resulted in the application of a maximum moment of 9.2Nm.

With each AFO bolted to the metal plate as shown in Figure 3a, plantarflexion moments were applied and the dial gauge measured the corresponding deflections. The mounting plate was freed, inverted and re-attached to the vertical wall. Each AFO was re-bolted to the metal plate as shown in Figure 3b, with the D ring re-attached to apply dorsiflexion moments while the dial gauge measured the corresponding deflections. This test procedure was adopted to establish if the bending stiffness of the AFOs was influenced by:

(1) the addition of pigments; or

(2) the typical orthotic production procedure.

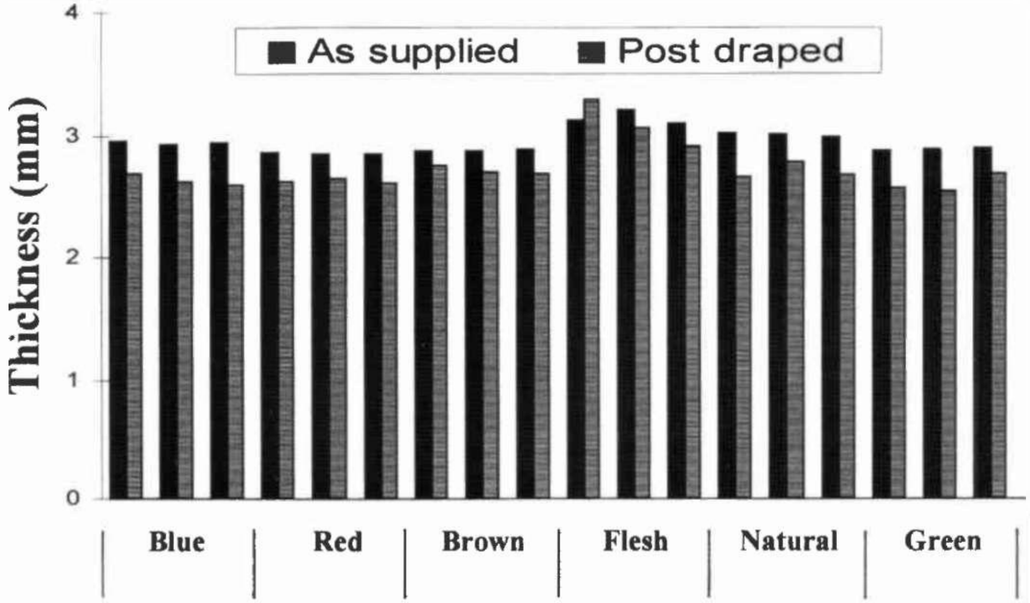
Results

The mean thickness and breadth measurements of AS and PD specimens are presented in Graphs 1 and 2 respectively. The I values, calculated from Graph 1 and 2, are presented in Graph 3.

Table 1 lists the bending stiffness of the AS and PD specimens, calculated from the gradient of the deflection versus moment graphs. Table 2 lists the estimated E values from the gradient of δI versus bending moment graphs of the AS and PD specimens. The mean AFO wall thickness measurements are presented in Graph 4. Graph 5 illustrates the dorsiflexion and plantarflexion

Table 1. Bending stiffness EI (Nmm^2)

	As supplied		Post-draped	
	Nmm^2	Ave	Nmm^2	Ave
Blue	90780		49844	
Blue	95665	92800	52675	51818
Blue	91954		52936	
Red	72810		58129	
Red	75117	73662	56889	56762
Red	73059		55268	
Brown	84656		57041	
Brown	79306	81692	63682	58905
Brown	81115		55993	
Flesh	90395		99225	
Flesh	99688	93750	78721	83258
Flesh	91168		71829	
Natural	84321		54841	
Natural	81115	81980	56288	53814
Natural	80503		50314	
Green	84656		59590	
Green	92352	89787	53872	68472
Green	92352		91954	



Graph 1. Variations in thickness.

stiffness of the coloured AFOs.

Discussion

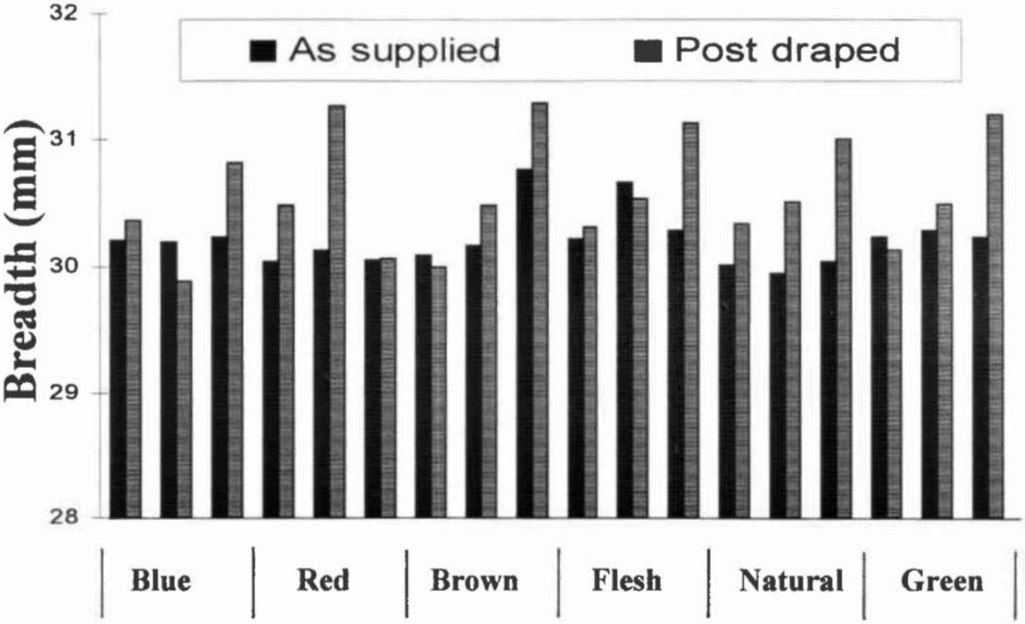
The variation in thickness of the AS specimens in Graph 1 corresponds to the supplier's specification of thickness of sheet, i.e. the flesh coloured and natural sheets were marginally thicker. Graph 1 indicates that in general the fabrication process reduces the thickness of the PD specimens relative to the AS specimens. As a rough approximation the thickness of the PD specimens reduced by 0.3mm or approximately 10% of the original thickness. However, the PD specimens were not necessarily draped from the same sheets used to cut the AS specimens. (This may explain the exception with the PD specimen, flesh 10, which indicated an increase in the PD thickness measurement).

Graph 2 illustrates that the technician who cut the PD specimens to an instructed breadth of 30mm was not as consistent as the technician who cut the AS specimens. This highlights a typical variable in workshop standards.

The breadth and thickness dimensions at a particular location were consistent when measured by the 3 orthotists. However, there was a variation along the length of all the specimens. For example, the average breadth and thickness dimensions of the PD specimen Blue 3 at mid-length were 31.08mm and 2.64mm whereas at the hole end the corresponding dimensions were 30.56mm and 2.54mm. Based on these dimensions the I of this specimen may be estimated as 47.7mm^4 at mid-length and as 41.7mm^4 at the hole end. Some specimens "taper" towards the loaded end while others "taper" towards the clamped end. These factors influence I and hence the bending characteristics of the specimen.

For a given applied load bending deflection decreases with increasing I. The I characteristics illustrated in Graph 3 represent the average I, calculated between the mid-length and loaded end of the specimens. In general, the AS specimens display a larger I value than that of the PD specimens. However, without confirmation of the original thickness data of the pre-draped sheets, it is not possible to verify that the reduction in I was due to the drape process. (Note that the I value of each specimen is significantly influenced by the thickness of the specimen, $I = (\text{breadth} \times \text{thickness}^3)/12$).

The bending stiffnesses listed in Table 1 do not correlate with the I values presented in Graph 3. This may be due to the variation of I along the length of individual specimens. A comparison of the AS and PD rows in Table 1



Graph 2. Variations in breadth.

suggests that the thermoforming process reduces EI.

In order to allow for variations of I, the monitored bending deflections were multiplied by the appropriate I presented in Graph 3. The Young's modulus of elasticity, E, of the AS and PD specimens were estimated from graphs of δI versus moment and the results are listed in Table 2. The effect of pigmentation is inconclusive. Table 2 indicates only a small variation in E in the AS specimens. Relative to natural AS sheet, the addition of flesh, blue and green pigments may increase E, whereas red and brown pigments may reduce E. In general, the E values of the PD specimens were significantly smaller than the AS specimens. This indicates that thermoforming reduces E and that this reduction in E may be greater for particular pigments.

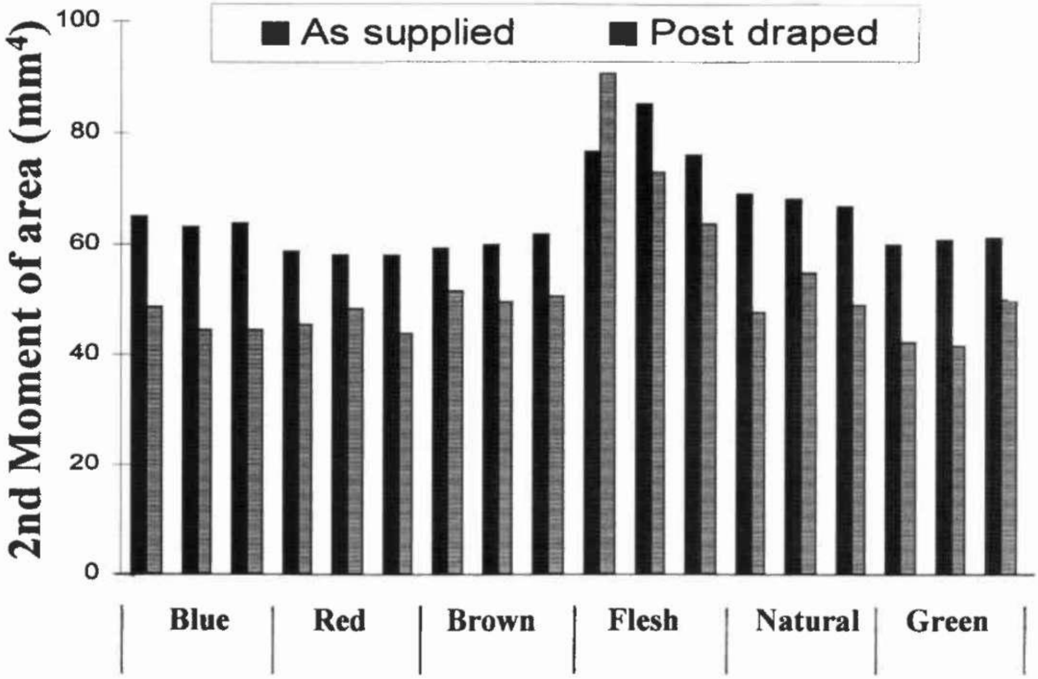
Single AS and PD specimens of each colour were examined with an electron-microscope. The electron-microscope results were inconclusive although the following were noted:

- significant differences in the AS and PD specimens were observed confirming that differences in E may be anticipated between AS and PD specimens;

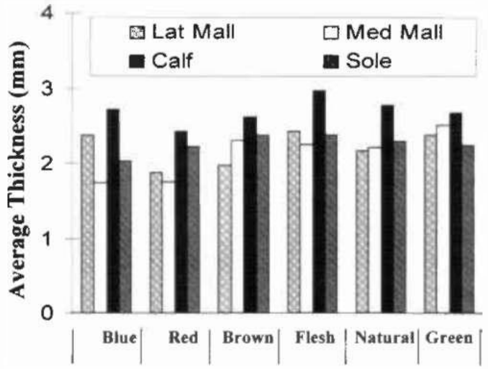
Table 2. Young's modulus of elasticity E (Nmm^{-2})

	As supplied		Post-draped	
	Nmm^{-2}	Ave	Nmm^{-2}	Ave
Blue	1400		1025	
Blue	1512	1452	1181	1131
Blue	1443		1188	
Red	1238		1276	
Red	1294	1265	1178	1236
Red	1262		1253	
Brown	1430		1103	
Brown	1323	1356	1281	1163
Brown	1314		1105	
Flesh	1603		1091	
Flesh	1168	1322	1082	1101
Flesh	1196		1129	
Natural	1225		1150	
Natural	1192	1207	1030	1068
Natural	1203		1025	
Green	1418		1408	
Green	1523	1483	1292	1513
Green	1507		1839	

- the extrusion process to produce the original sheet introduced a longitudinal formation to the polymer chains;



Graph 3. Variations in 2nd moment of area.



Graph 4. Average thickness of AFO.

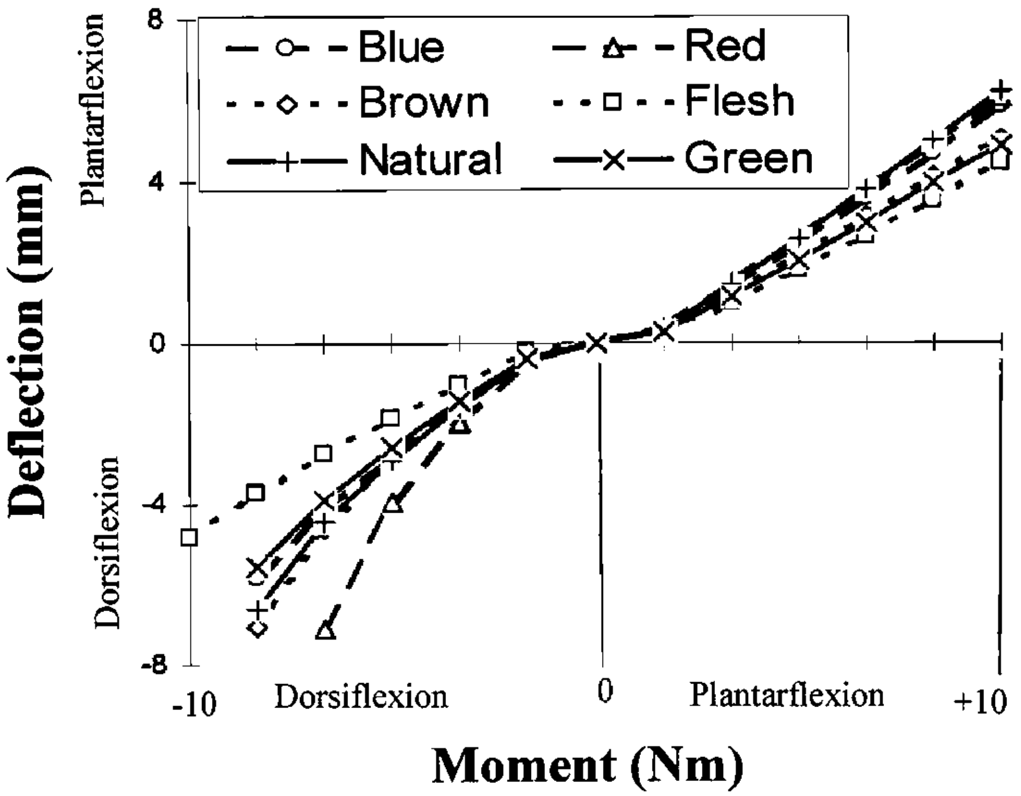
- during the extrusion process, turbulence of the "molten" copolymer occurs, resulting in non-uniformity or surface effects;
- pigmentation may encourage crystallisation of the copolymer but the degree of crystallisation varies dependent on the pigment added.

Graph 4 illustrates a significant variation in wall thickness of the different coloured polypropylene AFOs. Lunsford *et al.* (1994) and Golay *et al.* (1989) reported similar variations in wall thickness of draped AFOs. The following factors may be responsible for variations in the wall thickness of an AFO:

(1) the thickness consistency of the original sheet;
(2) the pigmentation of polypropylene;
(3) the repeatability of the manual draping procedure;
(4) the vacuum or lack of vacuum applied.

In the same way as it is not possible to distinguish the exact reason for the variation in the bending stiffnesses of the PD specimens, so also the results for the AFOs are inconclusive. The manual draping procedure is the most likely reason for the non-uniformity of wall thickness demonstrated in Graph 4.

Graph 5 illustrates that the plantarflexion stiffness of the coloured AFOs exceeded that of the dorsiflexion stiffness. For example, the deflection of the Natural AFO when subjected to a plantarflexion and dorsiflexion moment of



Graph 5. Bends stiffness of AFO.

7.5Nm was 5.0mm and 6.6mm respectively (approximately 2° angular motion). This agrees with other researchers such as Yamamoto *et al.* (1993). The thicker Flesh coloured AFO demonstrated maximum bending stiffness or least deflection.

The theoretical predictions of the influence that trimlines or wall thickness may have on the stiffness of an AFO are presented in the Appendix. The bending stiffness and bending stress of an AFO are influenced more by the removal of material from the front edge of the AFO than by a ± 0.5mm variation in the wall thickness. In the case of a 2.5mm thick AFO, the effect on bending stiffness of a reduction in wall thickness of 0.5mm, is the equivalent to trimming only 2.6mm from the front edge of this AFO.

Conclusions

Thermoforming polypropylene reduces EI, the bending stiffness of the material. This may be due to: (a) a reduction in the thickness and hence the I characteristic; (b) a reduction in E due to the heating cycle; and (c) strain created during the vacuum thermoforming. Pigmentation of the polypropylene may have an influence on EI characteristics of the PD specimen. However, the manual draping procedure introduces so many variables that it is difficult to devise a mechanical test procedure which clearly identifies the effect of pigmentation. No conclusions can be established regarding the effect of certain pigments on the bending characteristics of AS sheet. Particular pigments may influence the bending characteristics of PD specimens.

The manual draping of an AFO and the application of vacuum results in a non-uniform wall thickness. The results of this study with respect to the effects of pigmentation on the bending stiffness of AFOs are inconclusive.

Electron-microscopy studies of the physical structure of the pigmented specimens suggest that thermoforming relieves the chain formation induced during extrusion thereby changing the structural and physical properties of the AS and PD specimens. Comments from experienced polymer researchers suggest that additional studies of pigmentation may be fraught with insurmountable problems.

Appendix

The bending stiffness of an AFO is a function of EI. For calculation purposes it is assumed that a constant moment of 10Nm is applied. It is possible theoretically to predict the influence that the trimlines or the wall thickness may have on I of an AFO.

At the anterior edge of the AFO, σ, the bending stress, may be expressed as:

σ = My/I

where M = the bending moment applied,

I = the 2nd moment of area, and

y = the distance from the centroidal axis to the anterior edge.

It is assumed that initially the AFO extends to the malleoli such that a semi-circular arc is formed, of inner radius R = 30mm and thickness t = 2.5mm. Figure 4a illustrates the horizontal cross-section of an unmodified semi-circular arc while Figure 4b illustrates the horizontal cross-section of the modified AFO with the trimline cut back by a distance d.

I about the XX axis passing through the centroid of the cross-section of the unmodified AFO (Figure 4a), may be calculated as I_{XX} = $22.8 \times 10^3 mm^4$. The distance from the XX axis to the anterior edge of the AFO, y, may be estimated as 19.9mm and the bending stress, σ, may be estimated as $8.7 Nmm^{-2}$.

A similar procedure may be followed to assess the effect of altering the trimline of the AFO.

Theoretical trimline effects are presented in

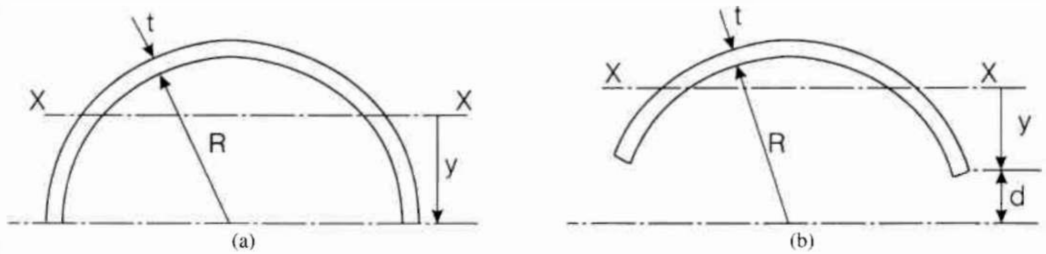


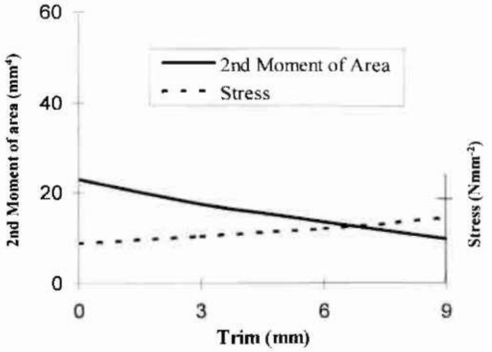
Fig. 4. (a) Cross-section of semi-circular arc. (b) Cross-section of modified AFO with trimline d.

Table 3. Effect of trimline variation

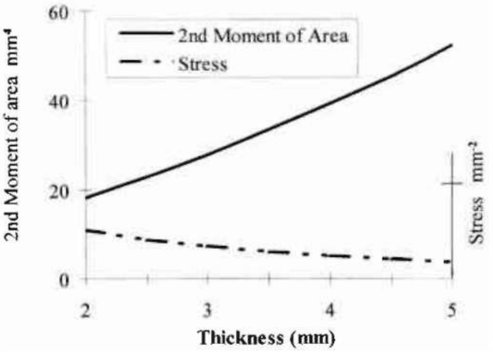
Trimline d (mm)	$I_{xx}\times10^3$ (mm^4)	y (mm)	Bending stress σ (Nmm^{-2})
0	22.8	19.9	8.7
3	17.4	18.1	10.4
6	13.4	16.2	12.1
9	9.7	14.2	14.6

Table 4. Effect of wall thickness variation

Wall thickness t (mm)	$I_{xx}\times10^3$ (mm^4)	y (mm)	Bending stress σ (Nmm^{-2})
2.0	18.1	19.7	10.9
2.5	22.8	19.9	8.7
3.0	27.7	20.1	7.3
5.0	52.5	20.7	3.9



Graph 6. Effect of trimline on 2nd moment of area (I) and bending stress (σ)



Graph 7. Effect of AFO wall thickness on (I) and (σ).

Table 3. Graph 6 illustrates the predicted effect of varying the trimline on second moment of area (I) and the bending stress (σ). Theoretically, removal of 9mm from the front edge of this AFO reduces the stiffness by 57% and increases the bending stress by 68%.

Similarly, it is possible to predict the influence wall thickness may have on the stiffness of an AFO. It is assumed that the inner radius of the AFO remains constant at R = 30mm and that the trimline of the AFO is not modified (i.e. d = 0mm). Graph 4 indicated that the AFO wall thickness varied from 2.5mm ±0.5mm. The effect of varying the wall thickness of the AFO cross-section illustrated in Figure 4a, is presented in Table 4. Graph 7 illustrates the effect of varying the wall thickness on second moment of area (I) and the bending stress (σ). Theoretically increasing t, the wall thickness of this AFO, from 2.5mm to 3mm increases the stiffness by 21% and reduces the bending stress by 25%. Reducing t from 2.5mm to 2mm reduces the stiffness by 21% and increases the bending stress by 25%. However, an increase in t from 2.5mm to 5mm increases the stiffness by 130% and reduces the bending stress by 55%.

From these calculations it may be concluded that removal of 3mm from the anterior trimline of an AFO has the same reduction in the AFO stiffness as a reduction of 0.5mm in the wall thickness of the untrimmed AFO.

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