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Effect of material characteristics of polyolefins on weld line morphology and its correlation to mechanical properties

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The effect of a weld line on the tensile, tensile impact and environmental stress cracking properties of a number of polyethylene (PE) and polypropylene (PP) samples has been investigated. The observed mechanical behaviour has been correlated to material properties, and also to the weld line morphology. PE samples differed in branching, molar mass (M_w) and molar mass distribution (MWD), whereas the PP samples differed in nucleation. The morphology of the weld line formed in injection moulding was analysed by optical microscopy and transmission electron microscopy. The mechanical strength was studied by tensile, tensile impact and constant tensile stress methods. In polyethylene samples with a high M_w, the weld line area was seen through the skin layer to the shear layer, and even down to the beginning of the core layer. The effect of a high M_w on morphological changes was diminished by a broad MWD. Short chain branching limited the morphological change solely to the skin layer. Both PP samples were morphologically rather homogeneous. The weld line created a V-notch on the surface that acted as a crack initiator in mechanical tests and thus reduced the mechanical strength of the weld line samples. The V-notch mainly hid the effect of the morphology on the mechanical properties. © *1998 Chapman & Hall*

1. Introduction

Weld line fracture is a common source of mechanical failure in injection moulded articles. Therefore, the influence of material and processing variables on the weld line behaviour is of great commercial interest.

Whenever separate flow fronts of polymeric materials join, a contact area known as a weld line or a knit line, is formed. When a polymer melt is injected through opposite gates, a weld line is formed in the middle of the moulding (Fig. 1) [1–3]. This type of "cold" or "butt" weld lines exhibit morphologies and properties different from the bulk [2, 4, 5]. A surface defect, called a V-notch, is also clearly visible to the naked eye [4].

The weld line strength of polymers can be improved by optimizing the injection moulding parameters. In practice the weld line strength and morphology are mainly affected by the melt and mould temperatures [5–8].

From a materials point of view, the best weld performance is obtained when molecular entanglement or diffusion across the weld interface occurs. The degree of molecular entanglement increases with molar mass. Thus improved weld line properties are induced by a high molar mass [9].

In injection moulding the environmental stress cracking resistance (ESCR), tensile properties and impact strength are the most important properties of the final product. In many applications these properties suffer because of weak weld lines. The objective of this work is to study the relationships between material characteristics, the weld line structure, and performance of different polyethylene and polypropylene grades. The polyethylene samples chosen for this study differ in their molar mass, molar mass distribution and short chain branching. The effect of the nucleation on weld line properties of polypropylene samples is also reported.

2. Experimental procedures

2.1. Materials

The polyethylene (PE) and polypropylene (PP) samples were commercial grades produced by Borealis. The high density polyethylene samples, PE-HD1, PE-HD2 and PE-HD3 were blow moulding grades, and the linear low density polyethylene, PE-LLD was an injection moulding grade (5.95 wt % 1-butene comonomer). The polypropylene samples, PP1 and

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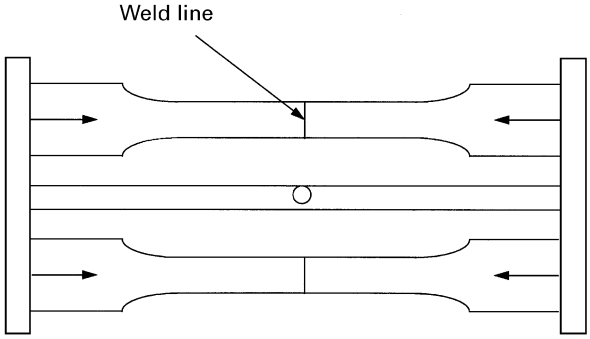

Figure 1 Mould cavity for tensile specimens with a weld line. Arrows show the injection points.

PP2, were non-nucleated and nucleated samples of injection moulding grades material, respectively. The material characteristics of the samples are listed in Table I.

2.2. Injection moulding

Tensile bars (ISO/DIS 3167 type A: thickness 4 mm, width 10 mm) were prepared with an Engel's ES 200/50 HL device injecting through two gates at both ends of the mould, Fig. 1. The injection temperature was 201 ± 1 °C, and the mould temperature was 30 °C. The injection and holding times were 4.0 and 30 s, respectively. All the specimens had a cooling time of 20 s. The reference specimens containing no weld lines were prepared using the same conditions.

2.3. Mechanical tests

Tensile tests were performed according to ISO/R 527. The measurements were made at +23 °C using an Instron 4500 tester connected to a Series IX Automated Materials Testing System 1.04. Samples were tested at speeds of 1 (modulus) and 50 mm min^{-1}.

The tensile impact strength value of both the notched and unnotched specimens were determined at +23 °C according to ISO 8256 method A, using a Zwick tensile-impact device. The dimensions of the test specimens were 4 × 10 × 80 mm. A notch (depth 2.0 mm, angle 45° and radius 1.0 mm) was milled on both sides of the specimen at the weld line.

The environmental stress cracking resistance was only determined for the PE samples according to ISO 6252 method B, using an Innovest constant tensile load device. The sample dimensions were 4 × 10 × 60 mm. The tests were carried out at +60 °C in a 10 vol.% Igepal solution using stress levels of 5.0 MPa (PE-HDs) and 2.5 MPa (PE-LLD).

2.4. Morphology

Samples with a thickness of 10 μm were prepared for microscopical studies using a Reichert-Jung Microtom 2050 Supercut instrument and a glass knife. In order to minimize distortion all the PE-HD samples were cooled using dry ice. The PE-LLD samples were prepared using an ultramicrotome under liquid nitrogen. The slices were cut both vertically, Fig. 2a, and horizontally, Fig. 2b, from the weld line area. The horizontally cut slices were sampled from the surface and also at depths of 100, 300, 600 and 1000 μm into the 4 mm thick specimen. Optical microscopy (OM) studies were performed using a Leitz Laborlux 12POL S polarizing microscope.

TABLE I Melt flow rates, MFR, weight average molar masses, M_w, molecular weight distributions, MWD, and densities of the samples

Sample	MFR (g/10 min)	M_w (g mol^{-1})	MWD	Density (kg m^{-3})
PE-HD1	0.20[a]	121 000	6.0	958
PE-HD2	0.25[a]	204 000	20.0	958
PE-HD3	0.4[b]	217 000	8.8	955
PE-LLD	4.0[a]	81 000	4.9	917
PP1	12[c]	274 000	5.1	905
PP2	45[c]	169 000	3.0	910

[a] 190 °C/2.16 kg.
[b] 190 °C/5.0 kg.
[c] 230 °C/2.16 kg.

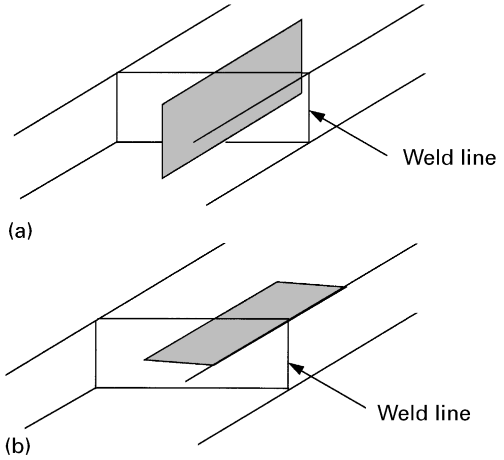

Figure 2 Schematic model of microtoming samples: (a) vertical and (b) horizontal.

Transmission electron microscopy (TEM) samples were prepared as follows: the samples to be examined were microtomed horizontally to a specified depth from the surface. The skin layer and also the core layer (from a depth of 700 μm from the surface) were studied. A few samples taken vertically from the weld line, Fig. 2a, were also analysed. The samples were prepared using the permanganic etching technique [10]. The PE samples were etched with a mixture of potassium permanganate ($KMnO_4$), water, concentrated sulphuric acid (H_2SO_4) and orthophosphoric acid ($O\text{–}H_3PO_4$) at room temperature for 1 h. The PP samples were prepared in a similar manner with the exception that no water was present in the etching mixture and the etching time was 4.5 h. A two stage replication method was carried out for all the samples. Samples were analysed using Jeol JEM-1200EX transmission electron microscope.

Some selected fracture surfaces from the impact tests were studied using scanning electron microscopy (SEM). The surfaces were coated with carbon and gold and studied using a Jeol JSM-840A scanning electron microscope at an accelerating voltage of 5 kV.

3. Results

3.1. Optical microscopy

In the optical micrographs the weld line area of most of the samples was observed as a dark, curved orientation zone throughout the sample thickness. The interface was seen either as a dark or bright line in the middle of the orientation zone. The line was straight in horizontally cut samples as can be seen in Fig. 3. In the vertical direction, the weld line area was outlined by a curved interface surrounded by the oriented zone. Fig. 4 is a schematic model of the whole weld line area in the vertical direction, and Fig. 5 (a–f) shows the corresponding micrographs for all the samples. This curved feature or intrusion of the material through the weld zone was caused by a holding flow after sealing of the gates. The individual values of the intrusion depth, L, (Fig. 4), are listed in Table II.

The widths of the orientation zone, w, in the vertically cut specimens have been measured as a function of the depth from the surface. The accuracy of the measurements is $\pm 20\,\mu\text{m}$. These results are also listed in Table II.

3.2. Transmission electron microscopy

The surfaces of test specimens cut horizontally to a depth of about 60 μm were investigated. The surfaces were cut at a small angle so that on the reverse edge the V-notch would still appear (skin layer), whereas the other side would be cut a little deeper so that the lamella structure would be visible. This made the identification of the weld line easier.

The effect of the weld line on the morphology of both high molar mass polyethylene specimens, PE-HD2 and PE-HD3, could be seen through the skin layer to the shear layer, and even down to the beginning of the core layer. The weld line areas of the PE-HD2 and PE-HD3 samples are shown in Figs 6 and 7 respectively. The weld line interface was outlined by flat-on lamellae. This area was quite broad for the PE-HD3 sample being about 500 nm, whereas for the PE-HD2 sample with a broad molar mass distribution (MWD) the width of this area was about 300 nm. No overgrowth of lamellae across the interface was observed for the PE-HD3 sample but the interface had probably initiated the lamella growth. In some areas round this interface in the PE-HD3 sample all the lamellae were aligned perpendicular to the weld line, with parallel or randomly distributed lamellae also existing. Areas of lamella stacks oriented perpendicular to the weld line were found in regions that were 1 μm and further from the interface, Fig. 8.

In the case of the PE-HD2 sample some lamellae grew across the interface, and in the weld line area fishbone-like lamellae were observed that were oriented perpendicular to the weld line. Michler has shown this kind of fishbone structure in PE-HD samples at low draw ratios [11]. At a distance of 500 nm or more from the interface the lamellae were oriented parallel to the weld line.

In the low molar mass polyethylene samples, PE-HD1, the weld line could be identified only in the skin layer, where the V-notch was still visible.

In the vertically cut microtomes of all the PE-HD specimens the degree of orientation was much less significant than that of the microtomes cut from the surface. Neither the interface nor strongly oriented areas were found.

The weld line interface of the PE-LLD sample was outlined by lamellae oriented parallel to the weld line. In the vertical direction a well developed banded spherulite structure was observed throughout the weld line area. Neither orientation nor spherulites aligned next to each other were seen at the weld line area. However, the spherulite size was slightly reduced and also an increasing number of non-spherulitic areas were observed in the weld line area compared to other regions.

The weld line affected the morphology of non-nucleated polypropylene, PP1, only in the skin layer of the specimen. Underneath the skin and the V-notch,

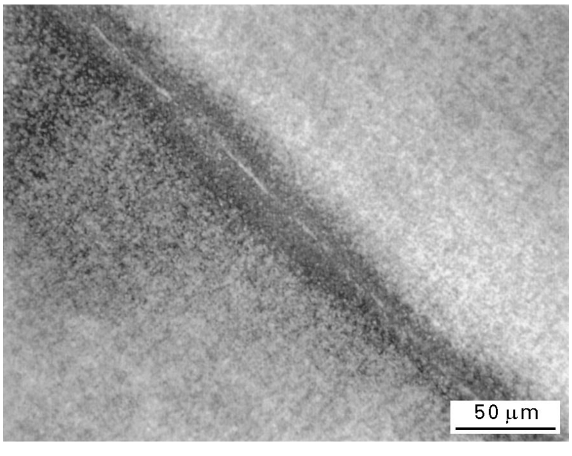

Figure 3 Optical micrograph of the weld line boundary of PE-HD2. Magnification 320×.

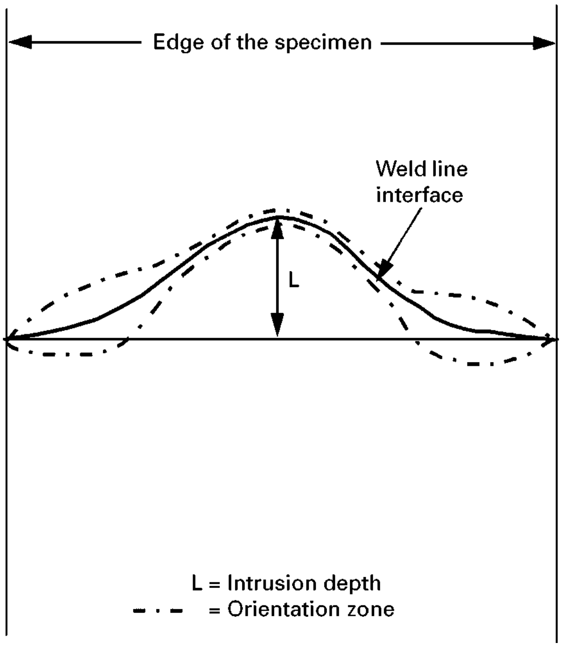

Figure 4 A schematic model of the weld line area (vertically cut sample).

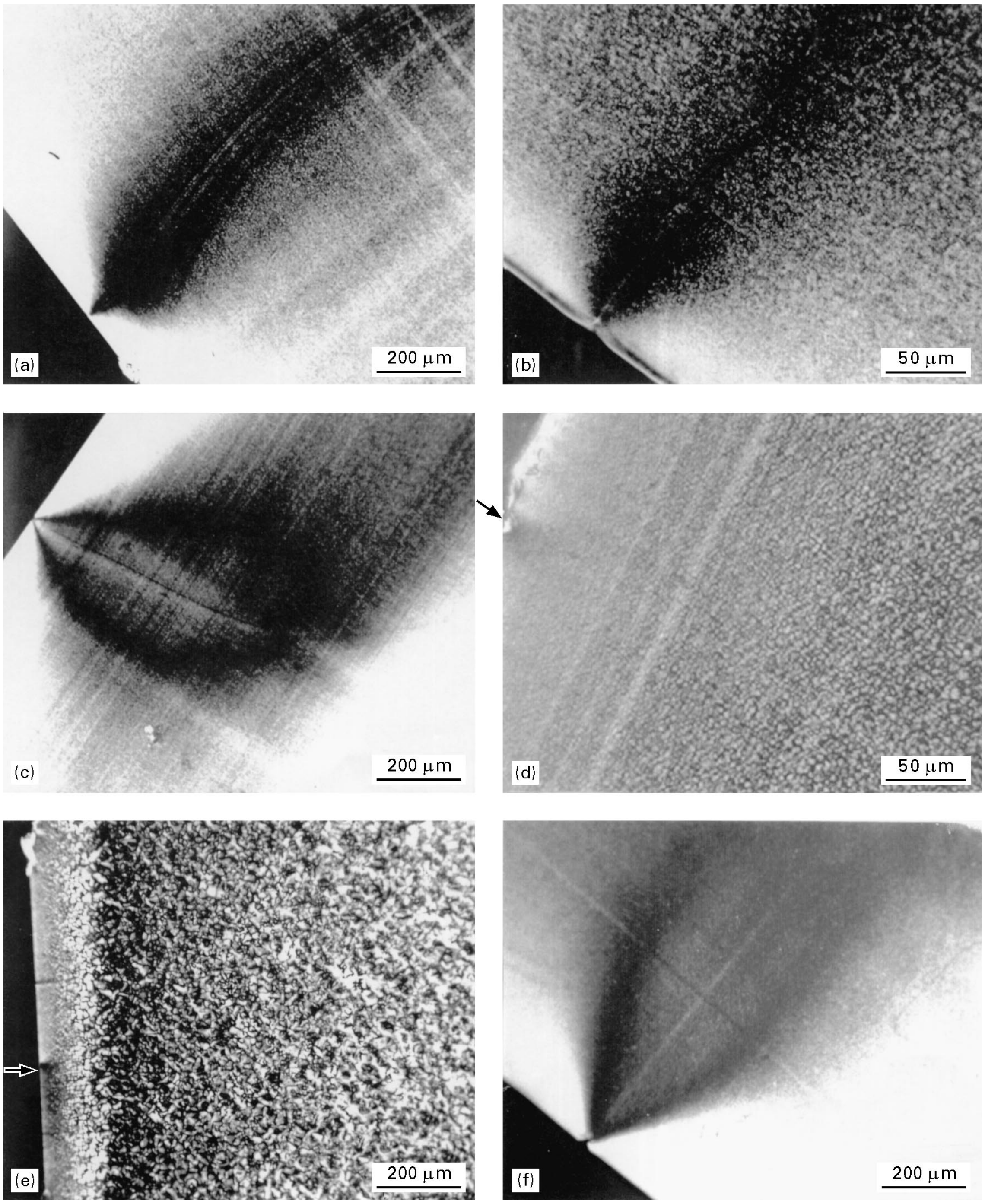

Figure 5 Optical micrographs of vertically cut samples: (a) PE-HD1, (b) PE-HD2, (c) PE-HD3, (d) PE-LLD, (e) PP1 and (f) PP2.

TABLE II The width of the orientation zone, *w*, as a function of the distance from the surface and intrusion depth, *L*

Depth (μm)	Width of orientation zone (μm)			
	PE-HD1	PE-HD2	PE-HD3	PP2
100	150	120	220	130
300	300	140	430	350
600	250	90	360	430
1000	260	80	30	450
Intrusion depth (μm)	120	390	1310	340

a homogenous spherulitic morphology was observed. In vertically cut samples well developed α spherulites were found. The size of the spherulites was smaller at weld line compared to that in the matrix.

Nucleated polypropylene, PP2, had a deeper V-notch on the surface compared to that of non-nucleated PP1. Around the V-notch, the lamellae were oriented to some extent parallel to weld line, but further away no significant orientation was seen. In regions below the V-notch no changes in the morphology could be detected. In the vertically cut samples, parallel and perpendicularly oriented lamella stacks and also cross-hatched structures were seen in the vicinity of the weld line.

In addition to the test specimens cut horizontally near the surface of the specimen, some specimens were also cut to depth of 700 μm, but neither a weld line interface nor any significant orientation were found at this depth in any of the samples.

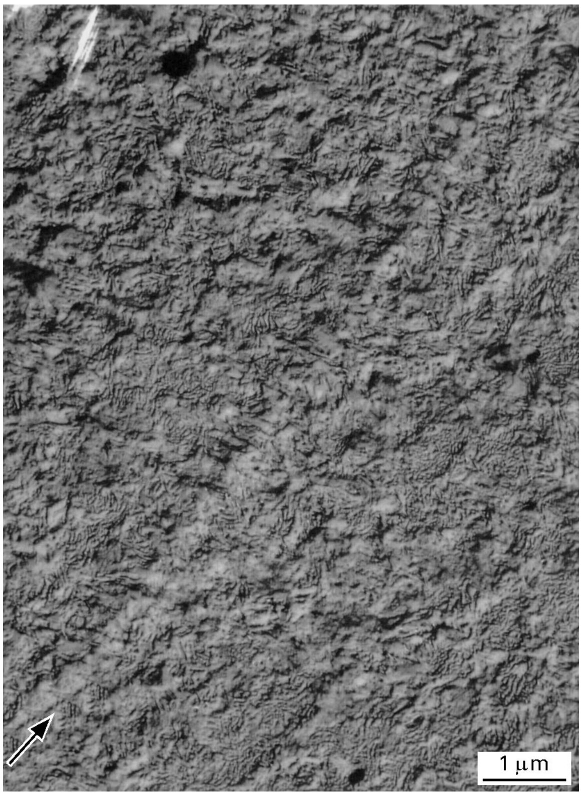

Figure 6 The weld line area of PE-HD2 (TEM, 7500×, tilt 25°).

Figure 8 Lamella stack oriented perpendicularly to weld line (PE-HD3) (TEM, 25 000×, tilt 0°).

Figure 7 The weld line area of PE-HD3 (TEM, 12 000×, tilt 0°).

TABLE III Tensile test results of the samples

Sample	Tensile modulus (MPa)	Tensile strength (MPa)	Maximum elongation (%)
PE-HD1, WL	837	24.2	43.5
PE-HD1, Ref	919	29.0	98.9
a_{w1}	0.91	0.83	0.44
PE-HD2, WL	899	24.6	116
PE-HD2, Ref	884	27.1	55.8
a_{w1}	1.02	0.91	2.08
PE-HD3, WL	822	23.6	23.2
PE-HD3, Ref	957	32.9	43.4
a_{w1}	0.86	0.72	0.53
PE-LLD, WL	224	12.8	>400
PE-LLD, Ref	232	18.6	>400
a_{w1}	0.97	0.69	1.00
PP1, WL	1327	31.8	>400
PP1, Ref	1335	31.8	>400
a_{w1}	0.99	1.00	1.00
PP2, WL	1690	36.3	8.2
PP2, Ref	1637	35.7	21.9
a_{w1}	1.03	1.02	0.37

3.3. Mechanical properties

The results from the tensile testing are summarized in Table III. The term a_{w1} is the weld line factor defined as the ratio of the result of the weld lined sample to that of the reference.

The impact results of notched test bars are presented in Table IV. The unnotched test bars broke either at the weld line, the matrix or the clamp. Due to the unreliability of the test results no numerical data are reported for unnotched samples.

The ESCR results are also included in Table IV.

TABLE IV Tensile impact strengths and ESCR results

Sample	Tensile impact strength (MPa)	ESCR (MPa)	
	Notched	V-notch	Milled samples
PE-HD1, WL	123	68[a]	
PE-HD1, Ref	144	> 1200[a]	
a_{w1}	0.85	0.06	
PE-HD2, WL	86	233[a]	> 2100[a]
PE-HD2, Ref	109	> 1200[a]	
a_{w1}	0.79	0.19	
PE-HE3, WL	164	259[a]	
PE-HD3, Ref	131	> 1200[a]	
a_{w1}	1.25	0.22	
PE-LLD, WL	154	(> 1200[b])	
PE-LLD, Ref	179	(2[b])	
a_{w1}	0.86	(400.0)	
PP1, WL	26	–	
PP1, Ref	31	–	
a_{w1}	0.84	–	
PP2, WL	22	–	
PP2, Ref	34	–	
a_{w1}	0.65	–	

ESCR: 60 °C, 10 vol.% Igepal, Stress [a] 5.0 MPa, [b] 2.0 MPa.

4. Discussion

4.1. Weld line morphology

In injection moulding, the laminar-like flow soon turns volcano-like as the polymer melt enters the mould cavity. At the front of the flow, melt spills from the centre towards the walls of the cavity. Shear forces parallel to the weld line are formed as the melt fronts unite. This forces the melt in the weld line area to flow perpendicular to the main flow [2]. In the optical micrographs of all the high density polyethylene samples and also the nucleated PP2 sample the weld line area is seen as a dark, curved orientation zone throughout the sample thickness. This is in contrast to the work of Bucknall who reported that the weld line of PE-HD was barely detectable [12]. These contradictory results are probably due to differences in the molar masses of the studied polyethylene samples. Bucknall studied an injection moulding grade polyethylene, whereas we studied blow moulding grades with a higher molar mass.

The weld line areas of the PE-LLD and PP1 samples were only seen in the outermost 80 μm layer adjacent to the surface. These samples had a well developed spherulitic structure and the weld line area was seen as a triangular non-spherulitic feature similar to the studies of Bucknall. The weld line area of the non-nucleated PP1 sample was outlined in the matrix of monoclinic α spherulites by many well developed hexagonal β spherulites. At a distance of 500 μm or more from the weld line the same spherulitic features were seen except that the β spherulites were present in lower numbers and they were much smaller in size. The higher abundance of β spherulites at the weld line may be caused by the shear forces that the polymer melt experiences when the flow fronts join. Hobbs has stated that for crystallizable polymers, the weld line interface is often outlined by row-nucleated spherulites [13]. Contrary to our findings in this work, Kunz *et al.* have reported that in the weld line of PP no β spherulites occurred [14].

The intrusion depth, *L*, illustrated in Fig. 4, was only affected by material properties since the injection conditions were kept constant. For the polyethylene samples the intrusion depth increased with molar mass, but the molar mass distribution had a remarkably more pronounced effect on the intrusion. This was clearly demonstrated by comparing the high molar mass polyethylene grades. The broad MWD polyethylene, PE-HD2, had only one third of the intrusion depth of that of the PE-HD3 sample which had a narrower MWD. These results clearly indicate that the intrusion depth is dependent on the viscosity of the polymer melt. The broader MWD materials have a more pronounced shear thinning behaviour compared to the narrower ones. Similarly polypropylene has a more pronounced shear thinning behaviour as compared to polyethylene.

The orientation zone at the weld line of all the PE samples broadened as a function of depth. However, at a depth of about 300 μm the zone suddenly became narrower. The broadest orientation zone, and the highest variation in the width of that boundary throughout the sample thickness was found in the PE-HD3 sample. The high molar mass of this material lowers the molecular mobility there by inhibiting the relaxation of the polymer chains. Thus the orientation within the object produced in the injection moulding is frozen in. In the case of the nucleated PP2 sample the oriented boundary systematically broadened throughout the sample thickness.

Despite the findings of the optical microscopy analyses, no changes in the morphology were found in TEM studies underneath the skin and shear layers for the low molar mass material, PE-HD1, and both PP grades. For the high molar mass polyethylene PE-HD2 (broad MWD) and PE-HD3, the effect of the weld line was found down to the shear layer or possibly even into the outermost regions of the core layer. The weld line interface of PE-HD3, Fig. 7, was outlined by flat-on lamellae, whereas PE-HD2, Fig. 6, had a flat-on structure accompanied by some edge-on lamellae growing through the interface. In the vicinity of the weld line, the orientation of the PE-HD3 sample was mostly perpendicular to the weld line and that of the PE-HD2 sample was parallel to it. Short chain branched PE had a rather homogenous morphology below the skin layer. Only the relative abundance of non-spherulitic areas was higher in the vicinity of the weld line.

4.2. Effect of material characteristics on the weld line morphology

The effect of molar mass on the weld line morphology was obvious. The weld line area was structurally more visible for polyethylene grades with a high molar mass. TEM micrographs showed that the higher the molar mass of the PE, the stronger the structural changes seen at the weld line. In addition in OM studies the weld line of the high molar mass PE was the most distinct one. The molar mass distribution had an even more pronounced effect. A broad MWD gave improved melt flow properties in injection moulding due to shear thinning phenomenon and thus the intrusion depth and the thickness of the orientation region observed in OM studies were smaller. Also diffusion of lamellae across the weld line interface was higher for the broad MWD material.

Parameters that slow the crystallization speed, such as short chain branching in PE-LLD or methyl-groups in PP, made the polymer less sensitive to the parameters that affect the formation of the weld line area during injection moulding. The weld line was only seen down to the outermost regions of the shear layer in both the OM and TEM studies. A clear weld line was found for nucleated PP2.

4.3. Mechanical properties

The presence of weld lines has been observed to reduce the mechanical properties and surface appearance of injection moulded products. The V-notch forms when the air in the mould compresses against the mould walls as the flow fronts of a polymer melt meet. In a mechanical test the V-notch acts as a crack initiator and thus along with the morphological effects it deteriorates the mechanical properties [2, 3]. In our investigations the V-notch also seemed to initiate all of the breaks except those of non-nucleated PP1 samples, which had a scarcely perceptible V-notch. It initiated breaks randomly along the tensile bar. Thus the molecular parameters had only a minor effect on the mechanical properties of the weld line samples.

Boukhili *et al.* [15] have reported that weld line samples were more notch sensitive than non-weld samples due to the inability of the weld line region to develop a plastic deformation zone at the crack tip. Thus under stress the weld region may behave more as a surface crack rather than as a macroscopic defect.

The decrease in the tensile strength due to the weld line was less significant than expected for both the PE and PP samples. The tensile strength of the polyethylene samples decreased about 20% for weld line samples whereas polypropylene samples retained their strength in spite of the weld line. For PP2 samples, the orientation in the vicinity of the weld line seen in TEM analysis, may have increased the effect of the V-notch. Non-nucleated PP1 had a hardly visible V-notch on the surface and thus the notch effect was minimized.

A high molar mass or short chain branching did not improve the tensile strength of polyethylene, but the bimodal molar mass distribution made the weld line stronger. The TEM studies strengthened this interpretation since bimodal PE was the only grade, in which the diffusion of molecular chains across the interface was observed.

The elongation properties were highly sensitive to the presence of a weld line. The elongation at break was reduced by about 50% for most of the samples. The PE-LLD and PP1 samples had such high elongations that the effect of the weld line could not be studied. The drop in elongation can be explained by the unfavourable orientation caused by the volcano-like flow. For polyethylene, the maximum elongation increased with molar mass. A higher molecular mobility of the low M_w material makes the orientation of the chains easier and thus the bonding in the interface is more incomplete. The bimodal PE-HD2 specimen with a weld line had twice the maximum elongation of the reference specimen. This behaviour can be explained by the favourable molecular orientation and its weld line morphology.

The weld line sample of nucleated PP2 had the lowest elongation at break; only 37% of that of the reference. The weld line sample broke without yielding whereas the reference sample yielded. In the case of non-nucleated PP1, both samples yielded to very high elongations.

The tensile impact test was as sensitive on structural differences at the weld line as the elongation properties were in the tensile test. A reduction in strength of about 25% was observed in the notched tensile impact test for all materials except the high molar mass material, PE-HD3. Polypropylene samples experienced the highest losses in impact properties due to their inherent rigidity which led to catastrophic brittle fractures.

Also notable is the point that the fractures did not initiate at the milled notch, but at the V-notch produced in the injection moulding process.

PE-HD3 with the weld line had a 25% higher impact strength than the reference. This might be due to the favourable orientation at the weld line as seen in Fig. 9. The intrusion depth in the PE-HD3 sample was remarkably higher than that in the other PE grades. Thus the interface is not situated between the notches, but about 1000 μm away from it. The area, where the impact energy is directed to, has an orientation parallel to the impact direction. This was also shown in the TEM analyses, where regions oriented parallel to the weld line were found in the vicinity of it.

The bimodal material, PE-HD2, that had tensile properties of the weld line superior to the other polyethylene grades, had the worst impact properties. PE-HD2 was the only polyethylene grade, in which the

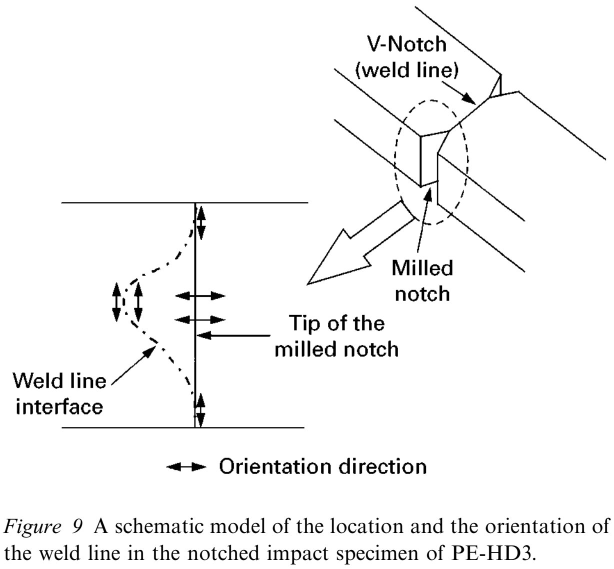

Figure 9 A schematic model of the location and the orientation of the weld line in the notched impact specimen of PE-HD3.

fracture clearly started in a brittle way. Thus the plastized zone must be localized in the immediate vicinity of the notch tip and the stress concentration effect dominated (notch sensitivity). In addition the TEM analysis showed lamellae in the vicinity of the weld line oriented parallel to it (i.e., perpendicular to the impact direction). Thus in the case of PE-HD2, the orientation had an opposite effect to that for PE-HD3. Another interesting observation was that the unnotched specimens of PE-HD2 never broke at the weld line. Thus the weld line itself is actually strong, but due to its notch sensitivity and the unfavourable orientation, the impact energy led to a highly catastrophic brittle fracture in the notched test specimen and the impact strength of the material was reduced. The other polyethylene grades experienced a ductile fracture (a larger plastized area around the notch). The low molar mass material, PE-HD1, had slightly better tensile impact properties than the bimodal PE-HD2 sample.

The short chain branching in PE-LLD did not lead to an improved impact strength for the weld line.

Nucleated PP2 specimens had worse impact properties for the weld line than did non-nucleated PP1 specimens due to the very shallow V-notch in PP1 which made its weld line mechanically stronger. Polypropylene is very sensitive to surface defects such as a V-notch.

The ESCR properties of the samples with a weld line were very poor being only approximately 20% of the strength of the corresponding reference materials. The notch sensitivity of the material dominated the ESCR behaviour over the weld line morphology. As the V-notch was milled away, the ESCR properties of the material became similar to the reference.

The environmental stress cracking resistance increased with molar mass as expected. The ESCR properties of the LLDPE samples could not be compared, because no stress level could be found that would lead to controlled failure of both the weld line and reference samples within the time of the experiment. (The reference specimen would have needed a very low stress (<2 MPa) in order to avoid yielding, whereas by using a stress of 2.5 MPa the weld-PE-LLD had a high ESCR value of >1200 h.)

Because the tensile and tensile impact tests already indicated the notch sensitivity of the samples, in the ESCR test the V-notch was milled away for one sample (PE-HD2 with a weld line) in order to see the effect of the V-notch on the ESC-properties. The weld line strength of milled PE-HD2 was similar to that of the unmilled reference, which proves the earlier assumption to be correct. For the PE-HD2 sample the weld line itself is mechanically quite strong, and in most cases the weakness of the weld lined sample is caused by the surface notch.

4.4. Mechanical properties versus weld line morphology

The orientation zone found in the OM analysis was broad and dark, and the intrusion depth was high for the high M_w polyethylene, PE-HD3. The broad MWD of PE-HD2 produced a much narrower orientation zone and shallower intrusion compared to the PE-HD3 sample which had practically the same molar mass. The mechanical properties measured in the tensile tests were also worse for high molar mass polyethylene, whereas the broad MWD of PE-HD2 improved the tensile properties compared to other PE grades. Short chain branched polyethylene, PE-LLD, that had a visible weld line only in the skin layer of the material in OM and TEM studies, retained most of its tensile properties.

The depth of the V-notch dominated the mechanical behaviour of polypropylene rather than the morphology that, in TEM analysis, was shown to be homogeneous below the shear layer. Nucleated PP2 had both a deeper V-notch and worse tensile properties than PP1, which experienced no reduction at all in the tensile test due to the weld line. In addition, the weld line area of PP2 in OM micrographs was more visible than that of PP1, which may have boosted the effect of the deeper V-notch.

The behaviour of the polyethylene grades in the impact tests was opposite to that observed in the tensile tests. The high molar mass material, PE-HD3, had the best impact properties. This can be explained by its high intrusion that moved the unfavourable orientation area further away from the notch area. On the other hand, the broad MWD material, PE-HD2, had surprisingly poor impact properties. Its intrusion depth was found to be much smaller than that of PE-HD3, and thus the unfavourable orientation perpendicular to the impact direction was located in the notch area. However, the unnotched PE-HD2 impact specimens never broke at the weld line. Thus it is possible that the weld line itself was strong, but due to the notch sensitivity and unfavourable orientation around the weld line, a catastrophic fracture took place even at a low impact level. The low molar mass material PE-HD1 that had lower intrusion depth, but a stronger orientation zone, had better impact properties than the PE-HD2 sample. Despite the homogenous weld line structure in short chain branched PE-LLD specimen, its impact properties were no better than those of high density polyethylene. This is due to the V-notch that lowered the impact strength compared to the reference sample value.

The tensile impact properties of PP samples decreased due to the V-notch. The morphology, on the other hand, was rather homogeneous for both samples. PP2 had a deep V-notch and also a larger reduction in impact strength than PP1 that had a just barely visible V-notch.

The impact fracture surfaces of PE-HD1 and PP2 were investigated by scanning electron microscopy (SEM). The unnotched PE-HD1 samples (that broke at the weld line) were observed to have yielded only at the centre of the specimen. Thus it is possible that slow crack growth took place to a certain extent at the weld line before yielding but that the stored energy was insufficient to cause a catastrophic fracture. Those unnotched specimens that failed outside the weld line region yielded on the whole fracture surface. The notched PE-HD1 specimens yielded on the whole

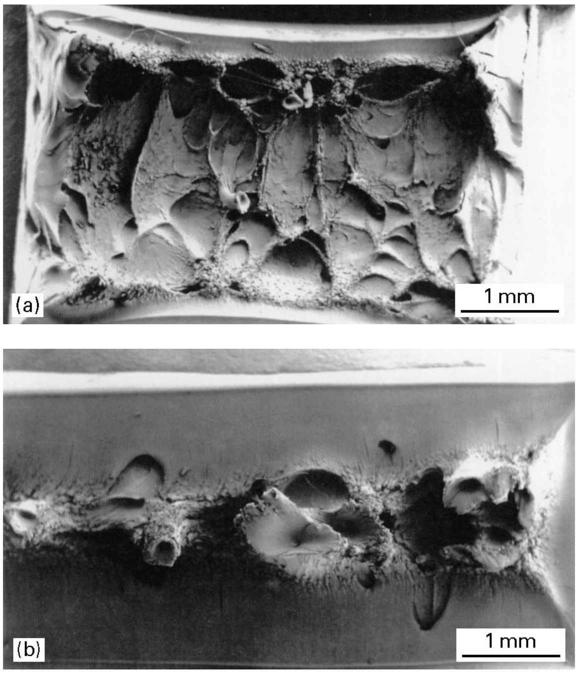

Figure 10 Fracture surfaces of (a) notched and (b) unnotched PE-HD1 (SEM, 20×).

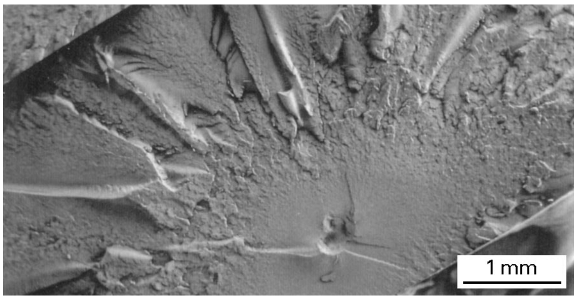

Figure 11 Fracture surface of unnotched PP2 (SEM, 20×).

fracture surface except the edges. The fractures were initiated by the weld line instead of the notch. The fracture surfaces of unnotched (break at weld line) and notched PE-HD1 are presented in Fig. 10 (a and b).

The PP2 sample fractured in a brittle way. SEM micrographs revealed that the fractures of unnotched specimens (that were observed to never break at the weld line) were initiated by a defect, Fig. 11. That was a stronger initiator than the weld line itself.

5. Conclusion

The observed loss of strength in the mechanical tests due to the weld line was in fact due to the V-notch on the surface rather than a morphological change at the weld line. However, the structural parameters were often in accordance with the mechanical properties.

The polyethylene grades showed stronger structural changes at the weld line than did the polypropylene grades. The shape and intensity of the weld line were related to the flow properties of the material during injection moulding and thus into its molecular structure. The morphological changes at the weld line were induced by low melt flowability in the mould cavity.

Short chain branching in PE-LLD and methyl groups in polypropylene reduce their crystallization rate compared to that of linear polyethylene. During the slow crystallization process the molecular chains were allowed to relax longer leading to a quite homogeneous weld line morphology. This did not improve their mechanical behaviour, as the V-notch effect dominated the crack initiation process.

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