Impact fracture toughness of high-density polyethylene – Effects of material parameters and moulding conditions

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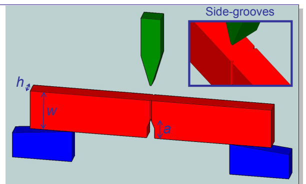
INTRODUCTION

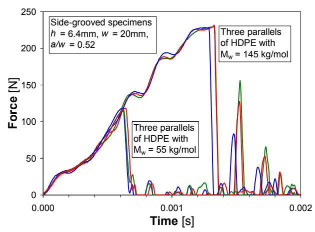
- There is a demand for better models describing the mechanical response of polymers subjected to impact loading. Fracture, in particular, is not well understood.
- This poster presents results on the plane-strain impact fracture toughness of high-density polyethylene (HDPE) materials. These toughness parameters characterise the **resistance to initiation of semi-brittle fracture**, and crazing is the main contributing mechanism.

EXPERIMENTAL



- Testing according to ISO 17281.
- 'Single-edge-notch-bend' specimens with cross-section (h x w) 4 x 10 mm^2 and 8 x 20 mm^2.
  - ▶ Sidegrooves on the large specimens to avoid shear lips. Force oscillations dampened by 0.25 mm silicone grease on specimens.
- Most tests were performed with loading rate 1 m/s at 23 °C.
- HDPE materials: Six commercial grades for injection moulding and five materials made in lab reactors.
  - ▶ Relatively low molecular weight: M_w = 55-145 kg/mol.
  - ▶ Nominal density: 953-963 kg/m^3 (copolymerisation with butene).

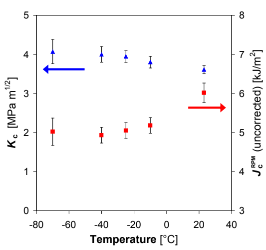
FRACTURE MECHANICS (FM) PARAMETERS



- **Linear-elastic** FM toughness parameters (K_c and G_c) were determined according to ISO 17281.
  - ▶ Only the most brittle materials (low M_w and high density) satisfied the size criteria of ISO 17281, and some of these materials still failed to satisfy the load curve criteria (fluctuations, linearity).
- **Elastic-plastic** FM parameters were calculated from the same data: Critical *J* integral values (J_c) using the expressions of *Rice, Paris and Merkle* (RPM), *Sumpter and Turner* (ST), and *Merkle and Corten* (MC).
  - ▶ RPM assumes a linear-elastic ideal-plastic material. ST and MC consider elastic and plastic energies separately, but this may introduce uncertainties and errors.
  - ▶ The J_c values satisfied the most common size criterion, except for injection-moulded specimens of the toughest material (showing stable crack growth and ductility)

LOWER-BOUND GEOMETRY-INDEPENDENT PLANE-STRAIN IMPACT TOUGHNESS?

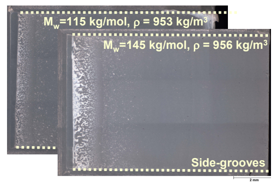
The HDPE literature has reported energy-based fracture toughness of HDPE to decrease towards a plateau at high loading rates and/or low temperatures, although some have also observed an increase with decreasing temperature. Recent approaches based on the essential work of fracture concept (not impact) claim to obtain plane-strain toughness independent of specimen thickness.



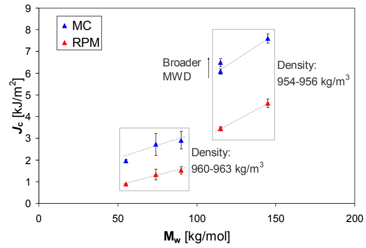
- Depending on the material and the specimen geometry, we observed either increasing or decreasing J_c with decreasing temperature. K_c values increased in all cases.
- Large specimens gave ~30% higher toughness values than small specimens (dimensions scaled down by a factor 2). This is in line with the *thermal decohesion* model.
- Size/rate/temperature effects need to be studied further. Crack tip geometry at the initiation of unstable crack growth?

IMPACT FRACTURE TOUGHNESS OF COMMERCIAL GRADES

- The toughness increased with increasing **molecular weight** (M_w).
  - ▶ This is usually attributed to increasing craze fibril strength due to higher density of chain entanglements and interlamellar tie-chains. The fracture surfaces show that the craze zone length increases with increasing M_w.

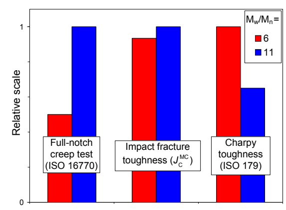


Fracture surfaces of compression-moulded specimens with large cross-section.



- Most toughness parameters indicated an increase in toughness with decreasing **density** (higher comonomer content, i.e. more short-chain branches and hence more entanglements and tie-chains).
  - ▶ Our J_c^{ST} values did not discern between the two density groups. The literature is not in unison regarding the effect of density.
- Some toughness parameters were sensitive to the **molecular weight distribution** (MWD), other were not (see graph).

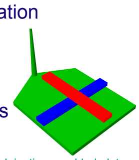
IMPACT FRACTURE TOUGHNESS vs. RESISTANCE TO RAPID AND SLOW CRACK GROWTH



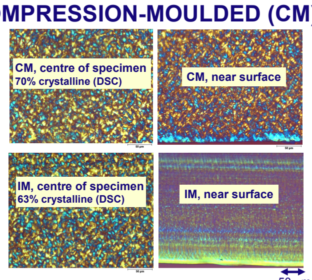
- **Slow crack growth resistance** (e.g. FNCT, ISO 16770):
  - ▶ Related to craze fibril strength, favoured by high comonomer content, broad MWD and HMW fraction.
- Standard Charpy impact toughness (ISO 179):
  - ▶ The Charpy toughness includes the crack propagation energy. **Rapid crack propagation resistance**, dominated by shear yielding, is reported to increase with decreasing comonomer content and narrower MWD.
- Our J_c data seem to follow the former trend (comonomer effect), or fall between the two trends (MWD effect in bar diagram above).

INJECTION-MOULDED (IM) vs. COMPRESSION-MOULDED (CM) SPECIMENS

- IM specimens had higher J_c values (but lower K_c), and higher energy absorption after peak force.
  - ▶ This is probably due to the higher cooling rate in the IM process, giving more entanglements and tie-chains.
  - ▶ Flow-induced orientation during IM had no significant effect. This was checked by testing specimens machined parallel and perpendicular to the flow.



Injection-moulded plate (green) and test specimens machined from the plate.



Above: Optical microscopy of microtomed sections of untested specimens. Below: Selected data. All results for M_w = 90 kg/mol, h x w = 4 x 10 mm^2.

	J_c^{RPM} [kJ/m^2]	E_d [GPa]	ρ [kg/m^3]
CM	1.5	1.5	962
IM	1.9	1.0	953

E_d = dynamic modulus, ρ = density at the centre of the specimen

EFFECTS OF MOULDING CONDITIONS

- Effect of IM parameters: Changing mould temperature (25-80 °C) or melt front speed (0.1-0.9 m/s) had no effect on the toughness (a/w=0.5).
  - ▶ With the high mould temperature, the initial crack propagation was less unstable (more arrest lines)
- Effect of CM cooling rate (below and above 15 K/min): Fracture toughness increased with increasing cooling rate.
  - ▶ Crack propagation resistance also increased.

BOREALIS

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