The Influence of Impurity Particles on the Mechanical Properties of Unreinforced and Short Fibre Reinforced Thermoplastic Mouldings

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ABSTRACT

Whatever may be the reason for the presence of impurity particles, they are likely to have some influence on the mechanical properties and it is not safe to assume that the data obtained on samples of the particle-free material can be used for design purposes. The type and amount of added particles, the shape and size of particles are also important in determining the failure behaviour. Based on the mechanical testing results and fractographic evidence presented in this work, several observations and conclusions about the influence of impurity particles on short and long term mechanical properties in short fibre reinforced thermoplastics may be noted.

Unreinforced materials are more prone to failure due to impurity particles than short fibre reinforced plastics (due to the mechanism of the reinforcement of fibres).

Key Words: impurity particles, injection moulding, mechanical properties, short fibre reinforced plastic mouldings

INTRODUCTION

Injection moulded parts may contain impurity particles arising from the following sources:

– polymer feedstock as gel particles and polymerization additives.

– compound additives as oversize particles and agglomerates, pigments, stabilizers, fillers, etc.

– material handling as paper fibres, metal fragments from materials handling equipment.

– processing machinery as detached metal parts from worn machinery, degraded polymer from processing dead spots.

Impurity particles arising from the last two sources are likely to arise in feedstock prepared from reground plastics.

The results of several literature searches during the course of work has failed to provide information covering the causes and types of impurity particles, and their influence on mechanical properties for short fibre reinforced thermoplastics moulding. However, few researchers have carried out some work on unreinforced materials. Studies carried out by Sandilands *et al.* [1], have been

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involved with the stress rupture lifetime of polyethylene pipes, which have been seen to fail in a brittle manner with fracture initiating from some inhomogeneity within the pipe wall, such as a metal particle. Such failure is associated with slow crack growth. It was concluded that the stress rupture lifetimes of polyethylene pipes failing in a brittle manner, depended upon the size of the adventitious flaw which initiated fracture. The work carried out by the author [2] has shown that contamination reduced the ductility of the plastic with the contaminated specimens tending to be more brittle than the virgin specimens.

Matushige *et al.*[3] have carried out work on the origin of parabolic markings on PMMA fracture surface. They have concluded that as *static factors* there exist several kinds of defects such as foreign materials and inhomogeneities inside of the polymer upon the crack propagation, strong stress waves are emitted in advance to a primary fracture front as *dynamic factor*, and cause locally a highly stress- concentrated region selectively at these defects, activating finally the secondary fracture.

In Haskell *et al.* [4] work on effects of flow on orientation of carbon short fibre reinforced polycarbonate, an interesting finding of the report was the appearance of a contaminant in the specimen. A glass fibre is believed to be the point where failure began. They concluded that contamination of the polymer may have harmful effects and care should be taken to prevent it.

Powders may be added to fibrous composites as cost-reducing fillers, as pigments or as nucleating agents for rapid processing. They may be intended to alter the mechanical properties, to reduce the thermal expansion or to improve the processability and surface finish. Some particles may be present in the received materials, in the form of contaminant particles for agglomerations of an insoluble additive.

The type and amount of added particles, the shape and size of the particles, are also important in determining the failure behaviour [1].

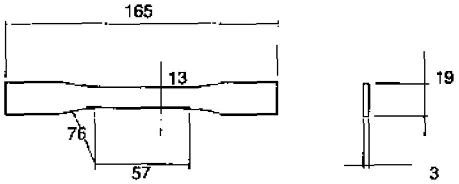


Figure 1. Specimen dimensions of D638 type bar in mm.

EXPERIMENTAL

In order to investigate the effects of added particles on mechanical properties, aluminium particles were deliberately added to the moulding materials, using a small quantity of oil as adhesive agent and mixing was carried out by hand before transfer to the injection moulder hopper. The following particle size ranges were used to observe their influence on the mechanical properties:

106–150 μ
180–250 μ
250–300 μ
300–425 μ
425–850 μ

Particle size range of 106–150 μ was used for carbon and glass fibre reinforced polyetheretherketone (PEEK) and the others were used for unreinforced and glass reinforced polypropylene. To show the effects of amount of added particles on the mechanical properties, four different formulations of polymer and aluminium particles were chosen with the following compositions:

- virgin material
- 0.05 w/w aluminium particles
- 0.1 w/w " "
- 0.2 w/w " "

Standard tensile test bars and 6 × 6 mm dumb-bell shaped bars were moulded. The dimensions of the specimen cavities are shown in Figures 1 and 2.

The Figures 3 and 4 are photographs produced from radiographs of selected samples, and illustrate the presence of aluminium particles in the mouldings.

A series of mouldings were produced for each formulation, and before the production of

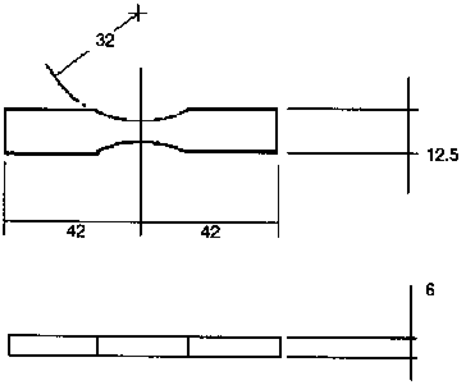


Figure 2. Specimen dimensions of the bar used for tensile and flexural fatigue testing in mm.

mouldings at each stage, the following procedures were carried out to avoid contamination from the previous formulation:

1- Removal of all arising polymer from the hopper and then empty the barrel.

2- Uncontaminated virgin polymer is introduced to purge and about 10 mouldings produced.

3- Stage (1) is repeated and then polymer with new formulation is introduced and moulding continued.

The first ten mouldings in each run were discarded to ensure machine-equilibrium conditions had been attained. The sprue and runners on each specimen were removed and the specimens numbered.

Materials

Natural and GFR PP

Natural polypropylene (GXM43), 20% glass fibre reinforced (HW60 GR20) and 30% glass fibre reinforced (HW60 GR30) polypropylene were supplied by Imperial Chemical Industries (ICI) in granular form.

Polypropylene (PP) belongs to the polyolefin class of polymers and is polymerizing propylene ($[CH_2-CH(CH_3)]_n$), its density is among the lowest of all plastics. Properties of the polymer vary widely according to molecular weight and method of preparation. The grades used for

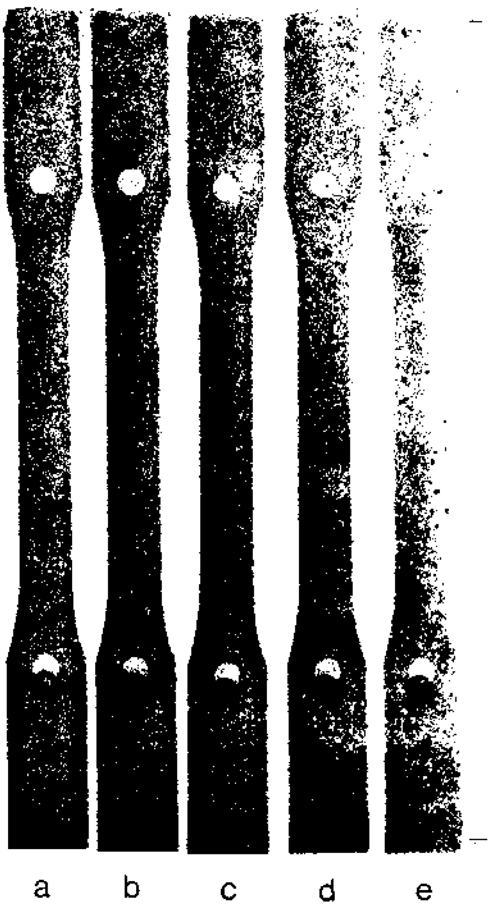


Figure 3. Photographs produced from radiographs of 3 mm moulded bars made from 30% GFR polypropylene, (a) particle-free and containing 0.2 w/w aluminium particles of size range (b) 180−250 μ (c) 250−300 μ (d) 300−425 μ (e) 425−850 μ.

moulding plastics have molecular weight of 40,000 or more , they are usually highly crystalline, have good resistance to heat and chemicals, and good electrical properties. PP can be modified to gain improved properties by incorporation of short glass

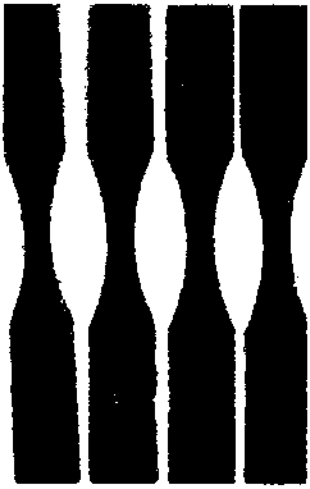
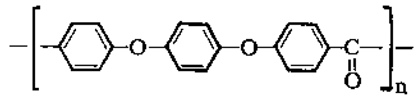


Figure 4. Radiograph photographs of 6 mm moulded bar made from 30% GFR polypropylene, containing 0.2 w/w aluminium particles of size range 350−425 μ.

fibres into the matrix. The physical properties are represented in Table 1 [5].

30% CFR and 30% GFR PEEK

PEEK is a linear aromatic polymer which can be chemically described as a poly(arylether ketone) based on the following repeat unit:



The combination of a high continuous service temperature of 260 °C, excellent wear, abrasion, and fatigue resistance, outstanding mechanical properties and excellent chemical resistance make PEEK an ideal material for an extremely wide range of applications.

Glass and carbon fibre reinforced PEEK offer all the properties associated with the unreinforced material and also greatly improved mechanical properties, heat distortion temperature and wear behaviour.

The 30% glass fibre (450 GL30) and 30% carbon fibre (450 CA30) reinforced PEEK were used, supplied from ICI (Table 2) [6].

Table 1. The physical properties of natural and GFR PP.

Properties	Natural	20% GFR*	30% GFR*
Melt flow index at 230 °C and 2.16 kg, g/10min	9.0	4.0	3.0
Density (mean), gcm^{-3}	0.905	1.04	1.12
Tensile yield stress, MPa	34.5	72.4	86.2
Flexural modulus, GPa	1.72	4.96	6.5
Izod impact strength at 23 °C, J/m	40	70	100
Moulding shrinkage at 20 °C, %	1−2	0.2−1.0	0.2−1.0

*These materials are anisotropic and therefore the values given depend on the orientation of the glass fibres in the moulding.

Sample Preparation

Moulding 3 mm Tensile Bar (30% GFR and 30% CFR PEEK)

The reciprocating injection moulder used in this part of the work was a Sandretto 6GV/50 tonne model. Although the machine could be manually operated, but it had a fully automated micro-

Table 2. The physical properties of natural and reinforced PEEK.

Properties	Natural	30% GFR	30% CFR
Density, gcm^{-3}	1.32	1.49	1.44
Typical level of crystallinity, %	35	35	35
Mould shrinkage, %	1.1	0.5	0.1−1.4[a]
Flexural modulus at 23 °C, GPa	3.66	10.31	13.0
Flexural strength at 23 °C, MPa	170*	233	318*
Tensile strength at 23 °C, MPa	92[y]	157[b]	208[b]
Elongation at break, %	50	2.2	1.3

*Yield value at >5% strain are estimated values.

a: Anisotropic, b: Break, y: Yield.

processor control accessory.

A double cavity single gated standard tensile test bar (ASTM D 638 type 2) mould was used for the production of test specimens. The test materials were dried in a vacuum oven overnight at 150 °C. In order to investigate the effects of added particles on mechanical properties, the following compositions were chosen:

– virgin polymer

– adding 0.2w/w aluminium powders (doubly sieved) with a 106–150 μ particle size range.

A Dynisco FT 444 1000 psi (6.89×10^6 N/m^2), strain gauge transducer was located behind a dummy ejector pin, and the changes in cavity pressure during mould filling were continuously monitored to ensure good reproducibility and optimum mould filling. Suitable processing parameters were carefully chosen.

Moulding 3 mm Tensile Bar (20% GFR and 30% GFR PP)

The reciprocating injection moulder used for this part of work was a Negri Bossi (NB85-240-85). The machine could be manually operated, but had a fully automated microprocessor control accessory. Procedure above was repeated using the following formulation:

– virgin polymer, 20% GFR and 30% GFR polypropylene.

– adding aluminium powder in three concentrations of 0.05w/w, 0.1w/w and 0.2w/w.

This part was repeated for aluminium powders (doubly sieved) having the following particle size ranges:

180–250 μ
250–300 μ
300–425 μ
425–850 μ

Similar procedure was used for producing 6 mm bars.

RESULTS AND DISCUSSION

Tensile tests were carried out on the complete range of mouldings. Restrictions, due to geometry of some mouldings, cost and time resulted in the limitation of impact and fatigue tests to selected specimens.

The results of mechanical tests are presented in tables, accompanied by a statement of testing conditions. In order to encourage brittle failure a high crosshead speed of 500 mm/min was used.

Unreinforced and Glass Fibre Reinforced Polypropylene

20% GFR PP

The results for specimens containing included aluminium particles with different size-ranges and in different concentrations are presented in Tables 3 and 4.

Table 5 presents Charpy impact test results gained from 3 mm bars containing aluminium particles.

Examination of the tensile modulus (E), tensile stress (σ) and strain to failure ($\%\varepsilon$) data from tensile tests, failure energy (F_E) and failure deflection (F_D) from impact tests, show that there is no significant dependence on the presence of aluminium particles.

The tensile strengths obtained are similar to the strength data provided by the materials supplier (ICI).

30% GFR PP (Tensile Test Bar of 3 mm thickness)

Using two crosshead speeds of 200 and 500 mm/min tensile test results gained are presented in Tables 6 and 7. The full range of particle-free and bars containing aluminium particles were used in the tests.

The tensile strength obtained are identical to the tensile strength data provided by the manufacturer (ICI). Figures 5 and 6 are scanning electron micrographs of typical tensile fracture surfaces. Comparison of these fracture surfaces indicates there are no readily apparent differences in fracture surface morphology which can be attributed to the presence of aluminium particles.

30% GFR PP (Tensile Test Bar of 6 mm thickness)

The results of tensile tests of representative specimens are presented in Table 8. Fatigue test results for the same range of specimens are shown

Table 3. Tensile test results for 20% GFR polypropylene ASTM tensile bars of 3 mm thickness, free from and containing aluminium particles (Crosshead speed: 200 mm/min, Gauge length: 100 mm, Temperature: 23 °C).

Parameters	Particle-free			Added particles								
				0.05 w/w			0.1 w/w			0.2 w/w		
	σ (MPa)	ε (%)	E (GPa)	σ (MPa)	ε (%)	E (GPa)	σ (MPa)	ε (%)	E (GPa)	σ (MPa)	ε (%)	E (GPa)
Mean*	70.6	4.1	2.6	71.1	4.1	2.5	71.7	4.1	2.5	70.7	4.0	2.6
SD*	0.402	0.045	0.130	0.408	0.158	0.141	0.334	0.230	0.151	2.118	0.241	0.130
Mean●	70.6	4.1	2.6	69.6	4.0	2.6	71.5	4.0	2.8	71.6	4.0	2.7
SD●	0.402	0.045	0.130	1.868	0.164	0.217	0.200	0.179	0.148	0.559	0.219	0.100
Mean○	70.6	4.1	2.6	72.0	3.9	2.9	72.0	3.9	2.8	71.5	3.9	2.8
SD○	0.402	0.045	0.130	0.505	0.158	0.100	0.505	0.148	0.130	0.219	0.071	0.109
Mean+	70.6	4.1	2.6	70.7	3.7	3.1	71.4	3.9	2.7	71.0	3.8	2.8
SD+	0.402	0.045	0.130	0.297	0.264	0.400	0.962	0.084	0.100	0.720	0.152	0.109

NB: Five tests per quoted result.

SD: Standard deviation.

Size range: * 180–250 μ, ● 250–300 μ, ○ 300–425 μ, + 425–850 μ.

Table 4. Tensile test results for 20% GFR polypropylene ASTM tensile bars of 3 mm thickness, free from and containing aluminium particles (Crosshead speed: 500 mm/min, Gauge length: 110 mm, Temperature: 23 °C).

Parameters	Particle-free			Added particles								
				0.05 w/w			0.1 w/w			0.2 w/w		
	σ (MPa)	ε (%)	E (GPa)	σ (MPa)	ε (%)	E (GPa)	σ (MPa)	ε (%)	E (GPa)	σ (MPa)	ε (%)	E (GPa)
Mean*	72.7	3.4	2.8	73.1	3.5	2.7	72.3	3.5	2.6	70.0	3.2	2.6
SD*	2.427	0.148	0.083	0.913	0.055	0.109	1.080	0.109	0.045	2.442	0.151	0.071
Mean●	72.7	3.4	2.8	71.6	3.6	2.5	71.7	3.7	2.5	72.8	3.6	2.5
SD●	2.427	0.148	0.083	0.693	0.158	0.083	1.259	0.164	0.044	0.862	0.187	0.083
Mean○	72.7	3.4	2.8	72.6	3.8	2.5	71.7	3.6	2.5	71.4	3.4	2.6
SD○	2.427	0.148	0.083	0.493	0.148	0.114	2.797	0.249	0.045	1.194	0.045	0.089
Mean+	72.7	3.4	2.8	70.6	3.5	2.5	71.5	3.5	2.5	71.6	3.4	2.5
SD+	2.427	0.148	0.083	2.210	0.192	0.071	2.180	0.151	0.083	1.436	0.100	0.089

NB: Five tests per quoted result.

SD: Standard deviation.

Size range: * 180–250 μ, ● 250–300 μ, ○ 300–425 μ, + 425–850 μ.

Table 5. Impact test results for 20% GFR polypropylene tensile bars of 3 mm thickness free from and containing 0.2 w/w aluminium particles (F_E = Failure energy in Nm and F_D= Failure deflection in mm).

Parameters	Particle-free		Added particles					
			180–250 μ		250–300 μ		300–425 μ	
Mean SD	0.994 0.084	6.60 0.210	1.075 0.075	6.88 0.202	1.065 0.074	7.06 0.221	1.050 0.031	7.38 0.238

NB: Five tests per quoted result.

Velocity: 2 ms^{-1}

Weight: 27 kg

in Table 9. Only one specimen for each formulation was tested, using six stress levels.

Within the experimental errors the tensile test results do not reveal any significant reduction in properties due to the presence of the added particles.

However, the tensile strengths of all specimens were 25% below the strength values specified by the materials supplier. Fatigue test results based on one specimen of each type fail to show any consistent reduction in endurance due to the presence of added-particles.

Natural Polypropylene

Table 10 presents the tensile test results using 200 and 500 mm/min crosshead speeds. The Charpy impact test results are shown in Table 11.

All of the specimens containing included-particles which were tested at 200 mm/min failed in a brittle manner and all of the virgin specimens

Table 6. Tensile test results for 30% GFR polypropylene ASTM tensile bars of 3mm thickness, free from and containing aluminium particles (Crosshead speed: 200 mm/min, Gauge length: 100 mm, Temperature: 23 °C).

Parameters	Particle-free			Added particles								
				0.05 w/w			0.1 w/w			0.2 w/w		
	σ (MPa)	ε (%)	E (GPa)	σ (MPa)	ε (%)	E (GPa)	σ (MPa)	ε (%)	E (GPa)	σ (MPa)	ε (%)	E (GPa)
Mean*	85.3	3.7	3.6	79.5	3.5	3.2	81.5	3.8	3.2	81.0	3.9	3.2
SD*	1.053	0.083	0.181	2.335	0.055	0.219	0.784	0.109	0.130	0.313	0.045	0.164
Mean●	85.3	3.7	3.6	79.3	3.8	3.1	81.0	3.8	3.4	77.1	3.8	3.0
SD●	1.053	0.083	0.181	0.743	0.071	0.100	0.522	0.114	0.217	0.761	0.084	0.217
Mean○	85.3	3.7	3.6	81.4	3.8	3.1	80.2	4.0	3.2	79.5	3.9	3.2
SD○	1.053	0.083	0.181	0.672	0.114	0.219	1.499	0.084	0.084	1.631	0.114	0.084
Mean+	85.3	3.7	3.6	78.6	3.7	3.2	79.2	3.9	3.2	79.1	3.6	3.2
SD+	1.053	0.083	0.181	2.442	0.192	0.114	0.479	0.084	0.100	1.492	0.321	0.130

NB: Five tests per quoted result.

SD: Standard deviation.

Size range: * 180–250 μ, ● 250–300 μ, ○ 300–425 μ, + 425–850 μ.

Table 7. Tensile test results for 30% GFR polypropylene of 3 mm ASTM tensile bars, free from and containing aluminium particles (Crosshead speed: 500 mm/min, Gauge length: 110 mm, Temperature: 23 °C).

Parameters	Particle-free			Added particles								
				0.05 w/w			0.1 w/w			0.2 w/w		
	σ (MPa)	ε (%)	E (GPa)	σ (MPa)	ε (%)	E (GPa)	σ (MPa)	ε (%)	E (GPa)	σ (MPa)	ε (%)	E (GPa)
Mean*	85.6	3.1	3.56	86.2	3.2	3.3	85.6	3.2	3.2	85.3	3.3	3.1
SD*	1.106	0.071	0.089	0.455	0.114	0.130	0.559	0.045	0.158	0.559	0.151	0.089
Mean●	85.6	3.1	3.6	84.9	3.4	3.0	84.1	3.3	3.1	85.0	3.4	3.0
SD●	1.106	0.071	0.089	1.165	0.122	0.084	1.561	0.130	0.249	0.999	0.122	0.084
Mean○	85.6	3.1	3.6	85.7	3.4	3.1	85.3	3.3	3.1	84.6	3.3	3.0
SD○	1.106	0.071	0.089	0.829	0.179	0.089	0.756	0.122	0.109	1.984	0.179	0.089
Mean+	85.6	3.1	3.6	84.0	3.3	3.0	83.5	3.3	3.0	84.4	3.2	3.1
SD+	1.106	0.071	0.089	2.631	0.192	0.114	2.291	0.100	0.045	1.474	0.134	0.130

NB: Five tests per quoted result.

SD: Standard deviation.

Size range: * 180–250 μ, ● 250–300 μ, ○ 300–425 μ, + 425–850 μ.

failed in a ductile manner.

This demonstrates that the presence of aluminium particles has reduced the ductility of the material and is reflected in a sharp decrease of about 44% in strain to failure.

However the tensile strength and modulus were not influenced by the presence of aluminium particles. The effect of embrittlement associated with the presence of aluminium particles was less pronounced at the 500 mm/min crosshead speed tests.

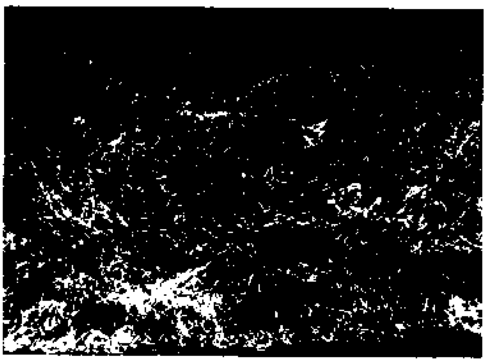


Figure 5. Scanning electron micrographs of fracture surface of 30% GFR polypropylene ASTM test bars (1/2 cross section of the bar).

The scanning electron microscopy observations combined with elemental analysis showed that aluminium particles initiated failure in the polypropylene containing aluminium. Some typical examples are shown in Figure 7. The fracture surface of the included-particles specimen shown in (b) exhibits a typical fast crack growth region.

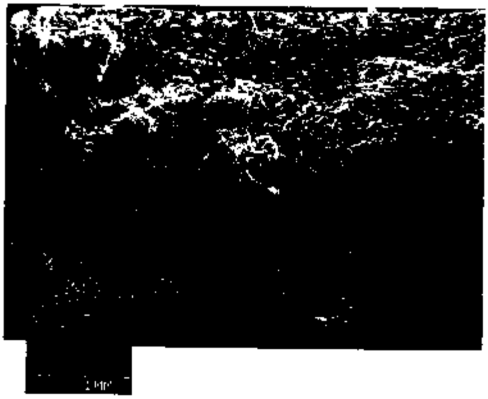
The results gained from the impact testing reflect the results gained by tensile testing. The measured failure energy and deflection decrease when aluminium particles are added.

30% CFR and 30% GFR Polyetheretherketone

30% CFR PEEK

Table 12 presents tensile test results for test bar specimens of 3mm thickness.

Within the experimental errors, the tensile test results combined with scanning electron



(a)

(b)

Figure 6. Scanning electron micrographs of fracture surfaces of 30% GFR polypropylene ASTM tensile test bar containing 0.2 w/w aluminium particles. (a) Typical fracture surface of 1/2 cross section of the bar. (b) Detail showing the presence of an aluminium particle.

microscopy observations reveal no significant differences in the trends of tensile properties for particle-free and mouldings containing included-particles.

In order to gain some understanding of fatigue behaviour of the specimens, some limited experimental tests were caried out at various

Table 8. The results for tensile test for 6 mm tensile bar (dumb-bell) made from 30% GFR PP, particle-free and containing 0.2 w/w aluminium particles with size range 300−425 μ (Crosshead speed: 2 mm/min, Gauge length: 50 mm, Temperature: 23 °C).

Sample	Particle-free			Added-particles		
	σ (MPa)	ε (%)	E (GPa)	σ (MPa)	ε (%)	E (GPa)
1	64.0	4.7	3.4	61.8	5.8	2.7
2	62.0	4.2	3.3	65.4	5.10	3.6
3	63.4	4.6	3.1	62.8	3.8	3.5
4	63.0	4.2	3.5	63.2	4.2	3.0
5	65.7	4.3	3.3	64.8	5.0	3.2
Average	64.0	4.4	3.3	63.6	4.8	3.2

temperatures and stress levels. These results are given in Table 13.

There is an evidence in Table 13 that the influence of aluminium particles on the long term properties is much more significant than the short term properties. Thus there appears to be a substantial reduction (60%) in the number of cycles to failure due to the presence of aluminium particles.

30% GFR PEEK

The tensile test results for particle-free and mouldings containing aluminium particles are presented in Table 12.

The results follow the same trends as for

Table 9. The fatigue test results for fatigue test based on one specimen for 6mm bar (dumb-bell) made from 30% GFR PP, particle-free and containing 0.2 w/w aluminium particles (Environment: air, Temperature: 23 °C, Frequency: 1 Hz, Mode: tension/compression, Waveform: square).

Stress (MPa)	Endurance (cycles)	
	Particle-free	Added-particles
36	475	2,200
34	450	1,550
32	2,200	1,550
30	4,250	13,500
28	25,000	105,000
26	650,000	150,000

Table 10. Tensile test results at 23 °C for ASTM natural polypropylene tensile bars of 3 mm thickness, free from and containing 0.2 w/w aluminium particles.

Parameters	Particle-free			Size range											
				180–250 μ			250–300 μ			300–425 μ			425–850 μ		
	σ (MPa)	ε (%)	E (GPa)	σ (MPa)	ε (%)	E (GPa)	σ (MPa)	ε (%)	E (GPa)	σ (MPa)	ε (%)	E (GPa)	σ (MPa)	ε (%)	E (GPa)
Mean*	36.5	27	1.3	36.7	16	1.5	36.6	17	1.4	36.5	15	1.4	36.2	15	1.4
SD*	0.109	2.949	0.109	0.223	0.447	0.109	0.148	0.707	0.200	0.616	0.447	0.089	0.917	1.140	0.109
Mean○	37.7	18	1.2	37.6	14	1.1	36.7	14	1.0	37.7	13	1.0	37.4	14	1.0
SD○	0.00	1.140	0.071	0.296	1.341	0.100	0.961	0.548	0.187	0.316	0.836	0.148	0.311	0.837	0.045

NB: Five tests per quoted result.

SD: Standard deviation.

* Crosshead speed: 200 mm/min, Gauge length: 100mm.

○ Crosshead speed: 500 mm/min, Gauge length: 110 mm.

30% CFR PEEK, and reflect no notable differences due to the presence of the aluminium particles.

The tensile strengths obtained are similar to the value of 157 MPa referred to by the manufacturer.

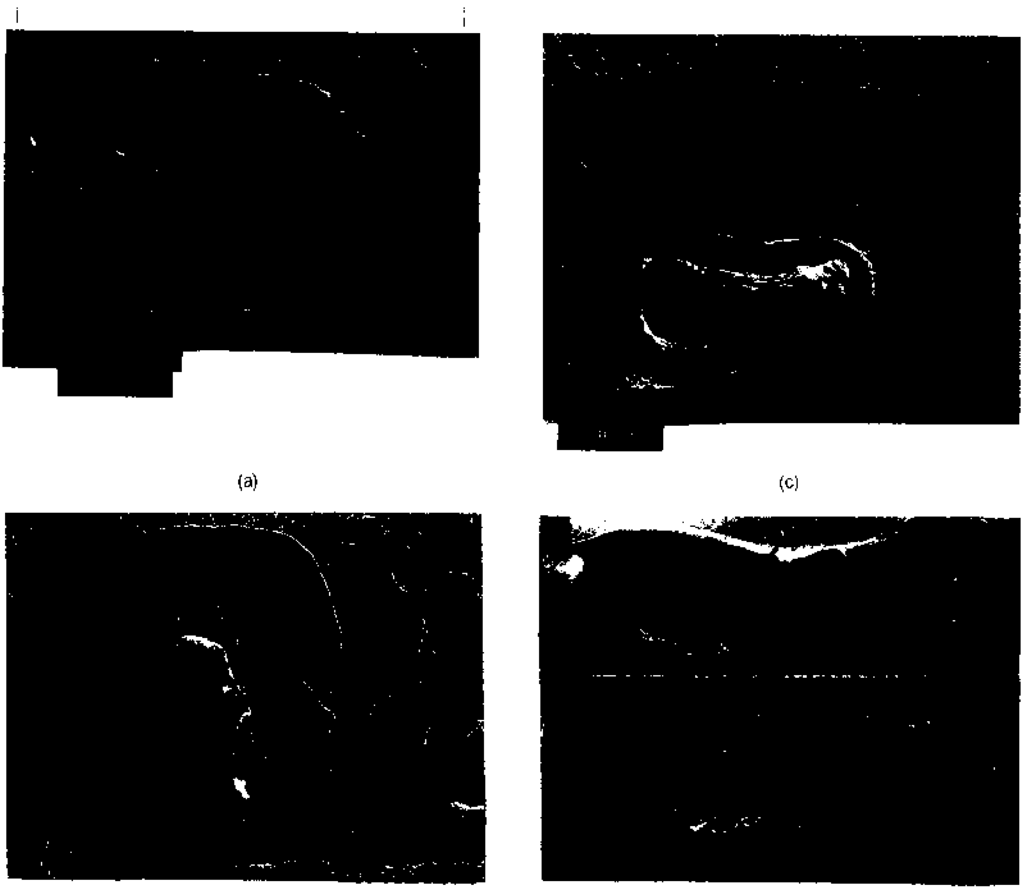
CONCLUSION

The tensile and impact test results and fracture mechanisms, as interpreted by scanning electron microscopical fractography reported in this work for 3 mm bars made of 20% GFR PP, 30% GFR PP, 30% GFR PEEK and 30% CFR PEEK, indicate there are no readily apparent differences in mechanical properties or fracture surface morphology which can be attributed to the presence of aluminium particles. The tensile strengths obtained for particle-free test bars and bars containing aluminium particles are identical to the tensile strength data provided by the manufacturers. The amount and type of fibre as well as different crosshead speeds used for the samples

Table 11. Impact test (Charpy) results for 3 mm natural polypropylene bars, free from and containing added aluminium particles 2.2 w/w (Velocity: 2 ms^{-1}, Weight: 27 kg, Span: 50 mm, Temperature 23 °C).

Particle-free			Size range								
			180–250 μ			250–300 μ			300–425 μ		
Failure energy (Nm)	Failure deflection (mm)	Type of failure	Failure energy (Nm)	Failure deflection (mm)	Type of failure	Failure energy (Nm)	Failure deflection (mm)	Type of failure	Failure energy (Nm)	Failure deflection (mm)	Type of failure
3.18	31.7	ductile	2.24	17.9	brittle	1.97	16.3	brittle	2.04	17.0	brittle

NB: Failure mode was selected by the computer program based on force-deflection records.



(a) (c) (b) (d)

Figure 7. Scanning electron micrographs of fracture surfaces of natural polypropylene tensile tested specimens. (a)aluminium fracture initiating particles, (b) Fractured cross-section of the bar containing 0.2 w/w aluminium particles showing brittle fracture, (c) similar as (a), (d) fractured cross-section of a bar free from aluminium particles showing ductile fracture.

investigated did not make any significant changes.

Within the aluminium particle size range investigated, a larger number of small particles is not more effective than a small number of large particles in influencing the mechanical properties.

However, the results gained for unreinforced PP show that all of the specimens containing included-particles failed in a brittle manner and all of the virgin specimens failed in a ductile manner.

This demonstrates that the presence of aluminium particles has reduced the ductility of the material, and is reflected in sharp decrease of about 44% in strain to failure. However, the tensile strength and modulus are not influenced by the presence of aluminium particles.

The presence of aluminium particles appear to have significant degrading effect on the fatigue properties of 30% CFR PEEK bars. This demonstrates that long term mechanical properties are strongly influenced by the added particles.

Table 12. The 30% GFR PEEK and 30% CFR PEEK tensile test results for 3 mm ASTM tensile bar, particle-free, and 0.2 w/w added aluminium particles (Crosshead speed: 2 mm/min, Gauge length: 110 mm, Temperature: 23 °C).

Sample	Particle-free			Added-particles		
	σ (MPa)	ε (%)	E (GPa)	σ (MPa)	ε (%)	E (GPa)
30% CFR PEEK	213.5	3.2	7.5	204.3	2.8	7.6
30% GFR PEEK	142.4	2.8	4.9	149.3	3.0	5.0

Similar observations were gained for 6 mm (dumb-bell) bar mouldings. However, the tensile strength of all the specimens were 20% below the strength values specified by the materials supplier. This is due to the anisotropic nature of these materials, the strength values specified by the materials supplier is based on 3 mm bars. Fatigue test results based on one specimen of each type failed to show any consistent reduction in endurance due to the presence of aluminium particles.

Presence of added particles were not critical in determining tensile properties of short fibre reinforced thermoplastics. This supports the contention that strength in these materials is predominantly orientation- controlled.

Fatigue results indicate that fatigue loading has a more damaging effect on the interface and that cyclic damage starts as localized debonding.

Table 13. Fatigue test results for 30% CFR PEEK 3 mm tensile bars for particle-free, and containing 0.2 w/w aluminium powder with size range 106–150μ (Environment: air, Frequency: 5 Hz, Cyclic stress: 75±75 MN/m^2, Mean stress: 75 MN/m^2, Temperature: 23 °C, Mode: repeated tensile, Waveform: sinusoidal).

Sample	Endurance (cycles)	
	Particle-free	Added-particle 0.2 w/w
1	36,000	14,523
2	44,344	15,200
3	47,912	18,056
4	53,940	22,180
5	55,900	27,100
Ave	47,620	19,411

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