Fracture Toughness of Vinyl Ester Composites Cured by Microwave Irradiation: Preliminary Results

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Abstract: The shrinkage of vinyl ester particulate composites has been reduced by curing the resins under microwave conditions. The reduction in the shrinkage of the resins by microwaves will enable the manufacture of large vinyl ester composite items possible (Ku et al., 2002a; 2002b; 2003a; 2003b). The impact strength of the vinyl ester composite components cured under microwave was reduced only by 1 percent when tested by drop weight impact tests. This project is to investigate the difference in fracture toughness between microwave cured vinyl ester particulate composites and those cured under ambient conditions. Short bar method of fracture toughness measurement was used to perform the tests. The results show that the difference in the fracture toughness is minimal between the ambient cured and microwaved-cured samples, provided the power level and duration of microwave irradiation are properly and optimally selected.

Introduction

Composite components made from vinyl ester resins by Fibre Composite Design and Development (FCDD) Centre of Excellence, University of Southern Queensland (USQ) suffer considerable shrinkage during hardening. This shrinkage is particularly serious if the fiber composite components are large. It can be more than ten percent, which is much higher than claimed by some researchers and resins' manufacturers (Clarke, 1996; Matthews and Rawlings, 1994). The main drawback of this shrinkage in a composite component is to have stresses set up internally. These stresses are usually tensile in the core of the component and compressive on the surface (Ossward and Menges, 1995). When these stresses act together with the applied loads during service they may cause premature failure of the composite components. Currently,

FCDD solves the shrinkage problem by breaking a large composite component into smaller composite parts because smaller parts tend to have less shrinkage. These smaller parts are then joined together to form the overall structure. By doing this, the manufacturing lead-time and costs of a composite component is significantly increased. Since the impact strength of the vinyl ester composites cured under microwave conditions had been proved to be as good as their counterparts, the fracture toughness of the two groups of composites are therefore compared. The vinyl ester composite used is thirty three percent (33%) by weight of fly ash particulate reinforced vinyl ester resins [VE/FLYASH (33%)], which is exactly the same type of material used in the previous relevant study (Ku et al., 2002a; 2002b; 2003a; 2003b).

Fracture toughness measures the ability of a material containing a flaw to withstand an applied load. Unlike the results of an impact test, fracture toughness is a quantitative property of the material (Askeland, 1998). Fracture toughness can be used to calculate the load which a structure can withstand without experiencing catastrophic failure due to fracture; hence it is an extremely important material property in many engineering designs. The short bar method is preferred to the E399 standard developed by the American Society of testing and Materials (ASMT) because it uses a real crack and reduces the size of the specimen. It does not require fatigue precracking. This is a low cost method with certain other advantages, such as eliminating residual stress effects as a source of error in the fracture toughness measurement (Barker, 1980). The method is also applicable to a wide range of materials, including metals, ceramics, polymers and rocks (Barker, 1981).

Fracture toughness

Fracture mechanics is the discipline concerned with the behavior of materials containing cracks or other small flaws. All materials, of course, contain some flaws. What one wishes to know is the maximum stress that a material can withstand if it contains flaw of a certain size and geometry. Unlike the result of an impact test, it is a quantity property of the material. A typical fracture toughness test may be performed by applying a tensile stress to a specimen prepared with a flaw of known geometry and size and is shown in Figure 1. The stress applied to the material is intensified at the flaw (Askeland, 1998). For a simple test the stress intensity factor,

$$K = f\sigma\sqrt{\pi a} \qquad (1)$$

where f is a geometry factor for the specimen and flaw. If the specimen is assumed to have 'infinite' width then f $\cong$ 1.0; for 'semi-infinite' width, f $\cong$ 1.1 (Askeland, 1998; Callister, 2003).

σ is the applied stress;

a is the flaw size.

By performing a test on a specimen with a known flaw size, the value of K that causes the flaw to grow and cause failure can be determined. The critical stress intensity factor is defined as fracture toughness, K_c is the K required for a crack to propagate and

$$K_c = f\sigma_c\sqrt{\pi a} \qquad (2)$$

K_c is a property that measures a material's resistance to brittle fracture when a crack is present and its unit is MPa$\sqrt{m}$.

For relatively thin specimens, the value of K_c will depend on specimen thickness but when the specimen thickness is much larger than the crack, it becomes independent of thickness. Under these conditions, a condition of plane strain exists. By plain strain it means that when a load operates on a crack in a manner represented in figure 1(b), there is no strain component perpendicular to the front and back faces. The value K_c for this thick-specimen situation is known as the plane strain fracture toughness $K_{I\,c}$; furthermore, it is also defines by (Callister, 2003).

$$K_{Ic} = f\sigma\sqrt{\pi a} \tag{3}$$

Brittle materials have low K_{Ic} values and are vulnerable to catastrophic failure. On the other hand, ductile materials have high K_{Ic} values. Fracture mechanics is especially useful in predicting catastrophic failure in materials having intermediate ductilities. Plane strain toughness fracture values for some polymeric materials are given in table 1 (Callister, 2003).

The plain strain fracture toughness K_{Ic} is a fundamental material property that depends on many factors, the most influential of which are temperature, strain rate and microstructure. The magnitude of K_{Ic} diminishes with increasing strain rate and decreasing temperature. Furthermore an enhancement in yield strength wrought by solid solution or dispersion addition or by strain hardening generally produces a corresponding decrease in K_{Ic}. Furthermore, K_{Ic} normally increases with reduction in grain size as composition and other microstructural variables are maintained constant.

Short Bar Geometry

Baker (1981) described the background, selection criteria and specimen geometry options for short rod and short bar methods. Figures 2 and 3 show the short rod and short bar specimens with straight chevron slots. The load line is the line along which the opening load is applied in the mouth of the specimen. The specimen parameter, B, is the specimen diameter (for short rod) or breath (for short bar). They also show two slot bottom geometries which result from two useful methods of machining the chevron slots. Figure 2 shows the straight slot geometry which results from feeding the saw or cutter through the specimen, while Figure 3 shows the curved slot geometry which is obtained from a plunge-type feed of the saw blade into the specimen. The modern way to produce the slot is to use electro discharge wire cutting (EDWC) (Baddeley and Ballard, 1991). Note that the section A-A of the rectangular short bars are identical with those of the round short rods. The height of the short bar is 0.87 B and was so selected to comply with the derivative with respect to crack length would be equal to that of the short rod. Thus the short bar and short rod calibrations should be equivalent, and Barker (1979) showed them to be equivalent by an experiment. The calibration of the straight-slotted specimens of Figure 2 was also shown to be equivalent to that of the curved-slotted specimens of Figure 3. The plan views of the two geometries were superimposed and the slot configurations adjusted until the straight and curved slot bottoms are tangent to each other at the critical crack length, a_c, where the peak load occurs in a linear elastic fracture mechanics test that is where the fracture toughness measurement is made (Figure 4). Thus, when the crack is near the position where the toughness measurement is taken, both geometries have essentially the same crack-front width,

rate of change of crack-front width with crack length, and compliance derivative, which causes their calibration to be essentially equivalent. The four specimen geometries (of Figures 2 and 3) are therefore equivalent and the user has the flexibility to choose the most convenient short rod or short bar specimen geometry (Barker, 1981).

The Composite Samples

The vinyl ester resin used is Hetron 922 PAS in summer and Hetron 922 PAW in winter. The vinyl ester is dissolved in 50% by weight of styrene. In this study, Hetron 922 PAW was used. It is based on the reaction between methacrylic acid and diglycidylether of bishphenol A. The resin hardener ratio used in the experiment was 98% resin by volume and 2% hardener by volume (Astrom, 1997). The reinforcer was fly ash (ceramic hollow spheres) particulate and they were made 44% by volume or 33 % by weight in the cured vinyl ester composite [VE/FLYASH (33%)]. Forty four percent by volume or 33 % by weight of flyash in the composite is considered optimum by the ECEFC because the composite will have a reasonable fluidity for casting combined with a good tensile strength in service.

As the raw materials of the composites are liquid and ceramic hollow spheres, the short bar specimens were cast to shape. The resin is a colourless liquid and is first mixed with the colourless accelerator. After that the fly ash is added to the mixture and they are then mixed to give the uncured composite. Table 2 shows the mass in grams of resin, accelerator and flyash required respectively to make a volume of 1000 millilitres of uncured composite (of 44% by volume of flyash or of 33 % by weight).

The uncured composite was then poured into the moulds for curing in ambient or microwaved conditions (Ku et al., 2003a). The mould was made from hard cartoon with six pieces of short bar specimen each. This is depicted in Figure 5. The slots were made by inserting plastic sheets of suitable thickness. Figure 6 shows some of the VE/FLYASH (33%) short bar specimens ready for the tests.

Microwaves/Material interactions

Microwaves form part of a continuous electromagnetic spectrum that extends from low-frequency alternating currents to cosmic rays. These microwaves propagate through empty space at the velocity of light and their frequencies range from 300 MHz to 300 GHz. Industrial microwaves are generated by a variety of devices such as magnetrons, power grid tubes, klystrons, klystrodes, crossed-field amplifiers, travelling wave tubes, and gyrotrons (NRC, 1994).

Frequency bands reserved for industrial applications are 915 MHz, 2.45 GHz, 5.8 GHz and 24.124 GHz. At the customary domestic microwave frequency of 2.45 GHz, the magnetrons are the workhorse. Material processing falls into this category (NRC, 1994). Huge sums of money and effort have been spent in developing microwave-processing systems for a wide range of product applications. Most applicators are multimode, where different field patterns are excited simultaneously.

The material properties of greatest importance in microwave processing of a dielectric are the complex relative permittivity $\varepsilon = \varepsilon' - j\varepsilon''$ and the loss tangent, $\tan \delta = \varepsilon''/ \varepsilon'$ (Pritchard, 1999). The real part of the permittivity, ε', sometimes called the dielectric

constant, mostly determines how much of the incident energy is reflected at the air-sample interface, and how much enters the sample. The most important property in microwave processing is the loss tangent, tan δ or dielectric loss, which predicts the ability of the material to convert the incoming energy into heat. For optimum microwave energy coupling, a moderate value of ε′, to enable adequate penetration, should be combined with high values of ε″ and tan δ, to convert microwave energy into thermal energy.

Microwaves heat materials internally and the depth of penetration of the energy varies in different materials. The depth is controlled by the dielectric properties. Penetration depth is defined as the depth at which approximately $\frac{1}{e}$ (36.79%) of the energy has been absorbed. It is also approximately given by (Bows, 1999):

$$D_p = \left(\frac{4.8}{f}\right)\frac{\sqrt{\varepsilon'}}{\varepsilon''} \tag{4}$$

where D_p is in cm, f is in GHz and ε′ is the dielectric constant.

Note that ε′ and ε″ can be dependent on both temperature and frequency, the extent of which depends on the materials. The results of microwaves/materials interactions are shown in Figure 7 (Sheppard, 1988).

Interaction of Microwaves with VE/FLYASH (33%)

Whether a material will absorb microwave energy and convert it into heat depends on its relative complex permittivity and loss tangent. Ku et al. (2001) showed that liquid

rapid Araldite (epoxy resin) has a dielectric constant of 2.81 and a loss tangent of 0.244 at 2.45 GHz at room temperature. The loss tangent is quite high and it is expected that Araldite will absorb microwaves readily and convert it into heat. Vinyl ester resin is produced from modified epoxy resin and methacrylic acid and epoxy resin absorbs microwave irradiation readily, it is therefore expected that it will also absorb microwaves readily (Peters, 1998; Ku et al., 1999a; 1999b). A possible risk in applying microwave energy to the vinyl ester composite is the interaction of the styrene in the resin with the high voltage (HV) transformer in the oven. The oven cavity is spot welded together and is not necessarily water/air/steam proof. Styrene is a highly flammable vapour and will be given off during the curing process of the composite. High vapour concentrations of styrene may cause explosions. The gas may explode if it is ignited by an electric arc or the heat of the HV components. The oven does not have an exhaust fan. A blower motor inside sucks air through the air filter at the front and cools the HV transformer as the air passes. The air from the fan is blown into a duct and cools the magnetrons. Some air is forced into the cavity at the back and then out of the steam exhaust outlet at the back. This is where the styrene containing air will interact with HV transformer and ignition or explosion may result. Due to this, the oven was modified to ensure that ignition or explosion would not happen. Details of the modifications have been mentioned in another paper (Ku, 2002b). The microwave facility used in this project is shown in Figure 8.

Short Bar Method Test and Sample Size

A MTS 810 Material Testing Systems was used for the test. The rate of extension was made 1 mm per minute. The specimens were tested in the manner shown in Figures 9 and 10. In this project, VE/FLYASH (33%) was exposed to microwave irradiation of 180 and 360 W. The duration of exposure for both power levels was 60 and 80 seconds respectively. With the above varying parameters of power levels and exposure of duration in mind, sample size for each set of parameters can be determined. One mould or six uncured short bar specimens was exposed to microwaves each time. At the same time, one mould of each type of composites was cured under ambient conditions and their fracture toughness values will be used a benchmark for comparison.

The short bar tests involve an opening load being applied near the mouth of the specimen, causing a crack to initiate at the point of the chevron slot. Ideally, the opening load should be less than the load that will be required to further advance the crack. A continually increasing load must be supplied until the crack length reaches the critical crack length, a_c. Beyond a_c, the load should decrease, as shown in Figure 11

The equation for fracture toughness in a short bar test can be derived from basic fracture mechanics using the assumptions of linear elastic fracture mechanics (LEFM).). The equation for the material plane strain critical stress intensity factor, K_{ICSR} (Munz, D, 1981):

$$K_{ICSB} = \frac{(F_{max} Y_m^*)}{B\sqrt{W}} \quad (5)$$

where F_{max} = Peak load

Y_m^*=16.5013

Y_m^* is the compliance calibration according to ASTM E-399-78 and

Y_m^* =

$$\{- 0.36 + 5.48\omega + 0.08\omega^2$$

$$+ (30.65 - 27.49\omega + 7.46\omega)\,\alpha_0$$

$$+ (65.90 + 18.44\omega - 9.76\omega)\alpha_0^2\} \left\{\frac{\alpha_1 - \alpha_0}{1 - \alpha_0}\right\}^{\frac{1}{2}} = 16.5013$$

and

$$\omega = \frac{W}{H} = \frac{73.7}{44.2} = 1.667$$

$$\alpha_0 = \frac{a_0}{W} = \frac{24.4}{73.7} = 0.331$$

$$\alpha_1 = \frac{a_1}{W} = \frac{63.8}{73.7} = 0.866$$

B and W (see figure 2a)

a_1 (see figure 12).

Results and Discussion

Figure 12 shows the change of load versus crack length of a sample cured under microwave condition (180 Watt power level and 60-second exposure time) when tested for fracture toughness in the MTS Universal Testing Machine. Figure 13 illustrates a similar plot of a sample cured under ambient condition. It is found that

there is no significance difference between the two figures. Plots of other samples, except one, are also similar. Table 3 shows the different test results of samples cured under microwave condition (180 Watt power level and 60-second exposure time). The mean ($\bar{\mu}$) of its fracture toughness is 52.72 J/mm^2 and the calculations for it are as follows (Munz, D, 1981):

$$K_{ICSB} = \frac{(F_{max} Y_m^*)}{B\sqrt{W}}$$

If B = 50.8 (by design), W = 73.3 (not 1.5B used but see Figure 14), F_{max} = 1389.67 N and Y_m =16.5013

$$K_{ICSB} = \frac{(1389.67x16.5013)}{50.8\sqrt{73.3}} = 52.72 \text{ MPa}\sqrt{m}$$

Considering Latin Square (Denes and Keedwell, 1974; University of Denver, 2003) and assign the following symbols for the different treatments of the VE/FLYASH (33%):

x: 180(60)$^{\#}$, y: 180(80), z: 360(60), u: 360(80), v: ambient cured

$^{\#}$power level (duration of exposure)

If all variables are taken into account when establishing the Latin Square, the matrix will be a 5 x 5 matrix (Table 4). From Table 5, it is found that the F Distribution value for the treatments is 1.31which is smaller than that, 3.26 (5%) found on the F Distribution Table with v_1 = (n-1) = 4, and v_2 = (n-1) (n-2) = 12 (Murdoch and Barnes, 1975). This means that some of the fracture toughness values have an error of more than 5 percent. Therefore, not all treatments are acceptable. Treatment y sample, 180-W and 80-second exposure seems to be the most acceptable as its fracture toughness mean (51.41) is closest to the sample of ambient cured mean

(51.65). The shrinkage of treatment y was also found to be least. Other fracture toughness values of the composites cured under different conditions are summarized in Table 6, which shows that the value of the fracture toughness of the 180W and 60s microwaved cured sample is higher than the ambient cured one by 2%. While that of 180W and 80s microwaved cured one is lower than the ambient cured one by 0.5%. These figures illustrate that the exposure of the samples by microwave irradiation did reduce the shrinkage of the vinyl ester composite but at the same time the toughness of the material was retained. At higher power level (360 W), the one exposed to microwaves for 60 seconds has very close fracture toughness (-0.3%) to that of the ambient cured one. The toughness value of the sample exposed to 80 second of microwave irradiation is lower than the ambient cured one by 6 %, which is considered to be significance. Visual inspection on the surface of the fracture sample show that there are a lot of blow holes in it. Preliminary scanning electron microscope study showed that there was very little void (bubble) found in the fractured surface of 180-W and 60-second treated sample as illustrated in Figure 15; while, bubbles could be spotted in the fracture surface of 360-W and 80-second treated sample as shown in Figure 16. This implies that microwaves do help in reducing the shrinkage of the vinyl ester composites during curing provided that the power level and exposure time are within certain limits. Beyond these limits, the advantage will be offset by the reduction in fracture toughness of the samples.

Figure 17 shows the change of load versus crack length of a sample. The first maximum load dropped significantly before rising back to the second maximum load. This was repeated the second time. Visual inspection illustrates that bubbles/holes are found just after the regions of the first and second maximum loads. This phenomenon

was brought about by crack jumping in the sample during testing; it was considered as the outlier and was excluded from mean and standard deviation calculations.

Acknowledgement

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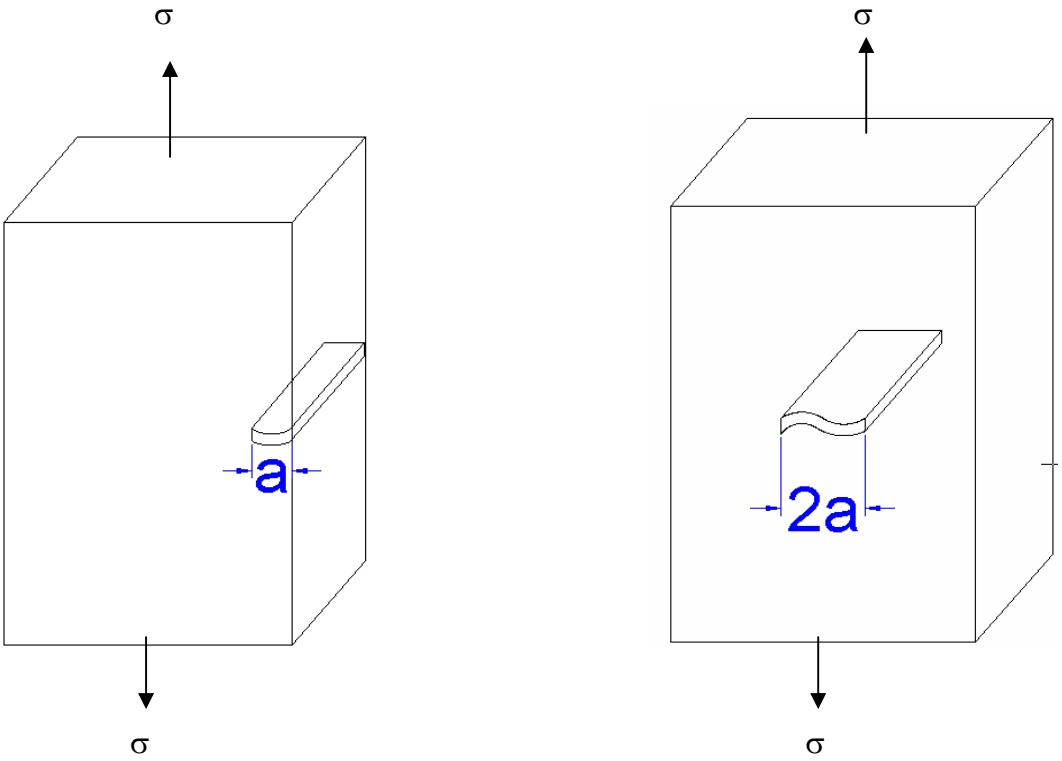
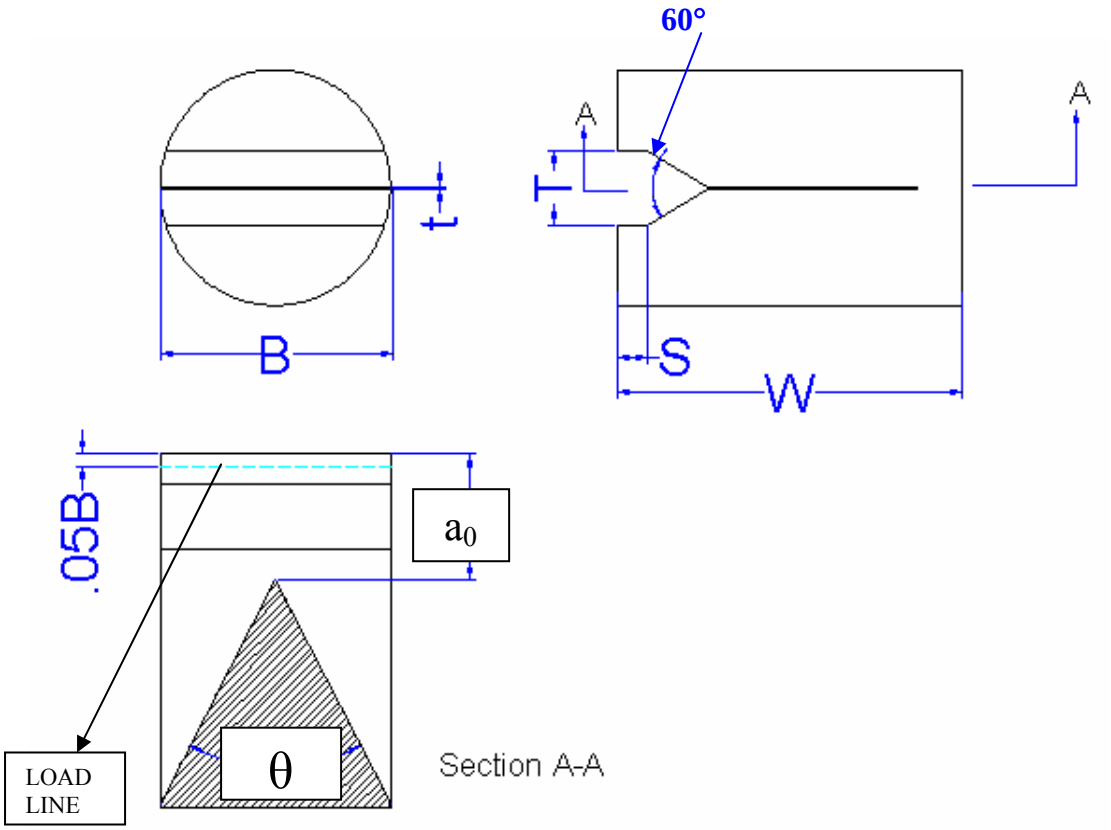


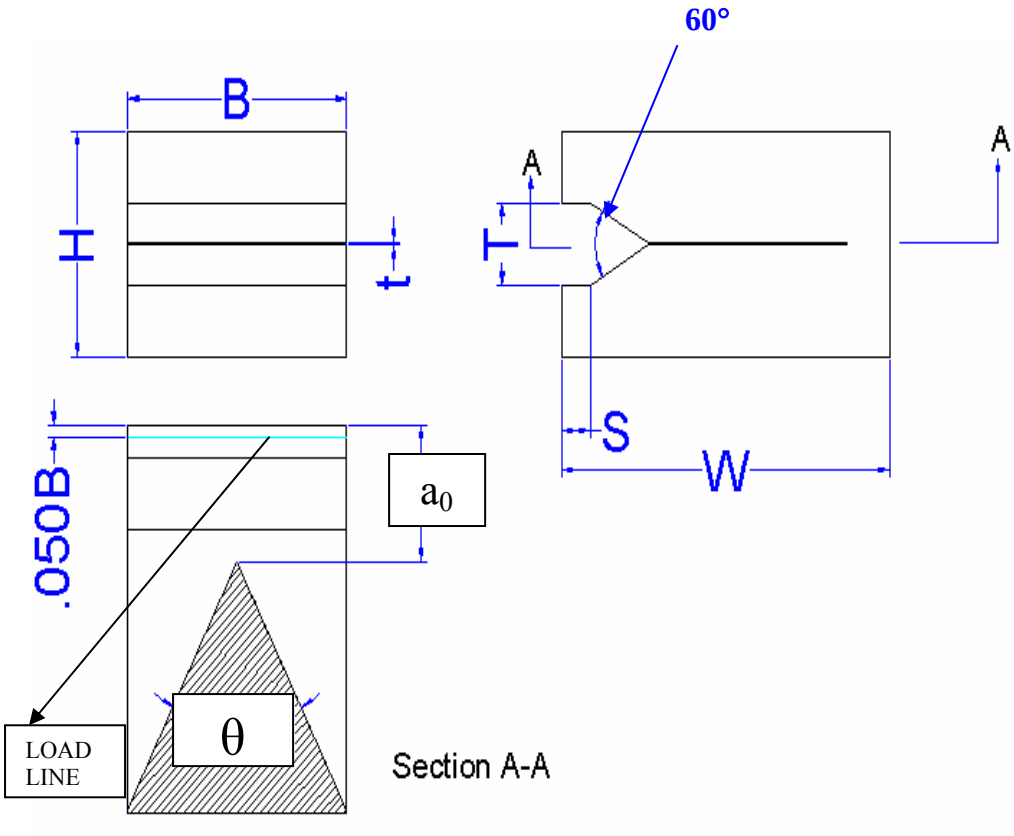
(a) **(b)**

Figure 1: Schematic Drawing of Fracture Toughness Specimens with Edge and Internal Flaws



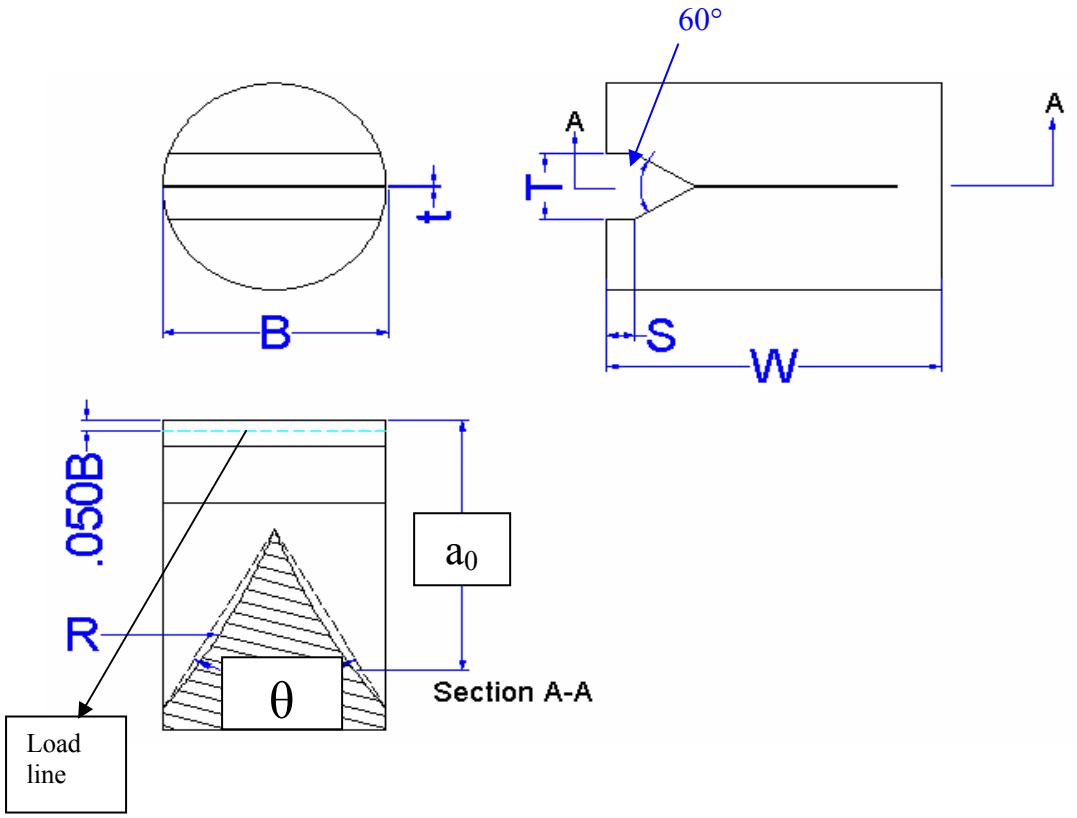
SYMBOL	DEFINITION	VALUE	TOLERANCE
B	DIAMETER	B	
W	LENGTH	1.5B	± .010B
a_0	INITIAL CRACK LENGTH	0.513B	± .005B
θ	SLOT ANGLE	55.2°	± 1/2°
T	SLOT THICKNESS	SEE TABLE III (of Barker, 1981)	
S	GRIP GROOVE DEPTH	.130B	± .010B
T	GRIP GROOVE WIDTH	.313B	± .005B
R	RADIUS OF SLOT CUT	SEE FIGURE 4 (of Barker, 1981)	± 2.5

Figure 2a: Short Rod Specimen with Straight Chevron Slots. The LOAD LINE is the line along which the opening load is applied in the mouth of the specimen.



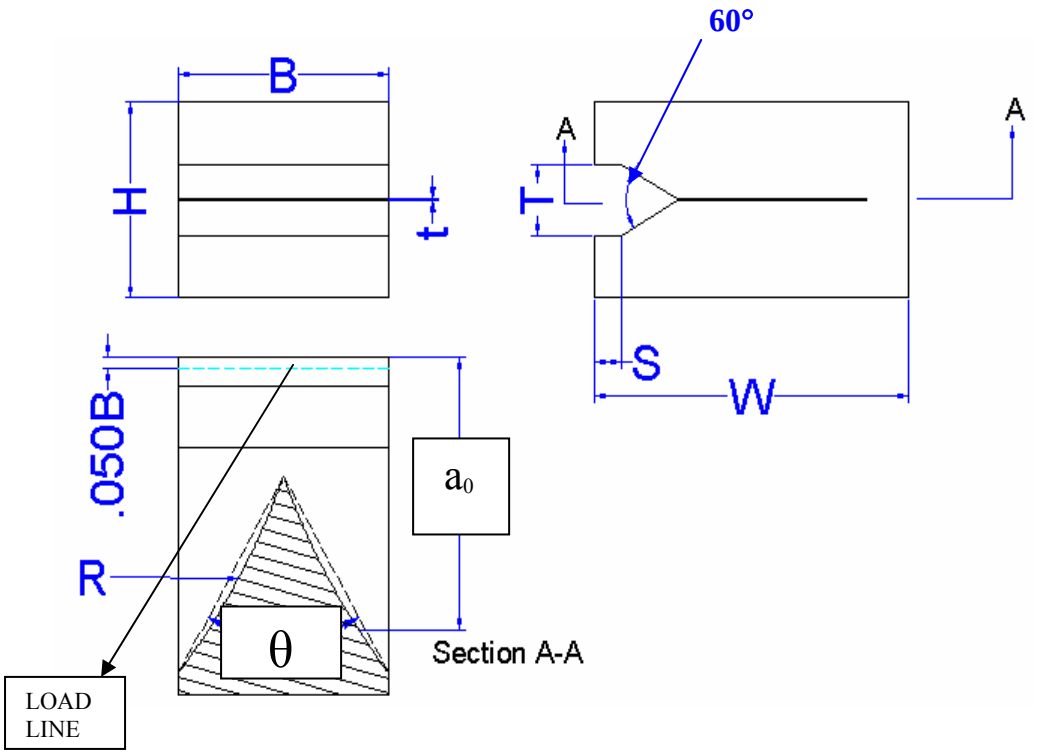
SYMBOL	DEFINITION	VALUE	TOLERANCE
B	BREADT	B	
W	LENGTH	1.5B	± .010B
H	HEIGHT	.870B	± .005B
a_0	INITIAL CRACK LENGTH	.513B	± .005B
θ	SLOT ANGLE	55.2°	± 1/2°
T	SLOT THICKNESS	SEE TABLE III (of Barker, 1981)	
S	GRIP GROOVE DEPTH	.130B	± .010B
T	GRIP GROOVE WIDTH	.313B	± .005B
R	RADIUS OF SLOT CUT	SEE FIG 4 (of Barker, 1981)	±2.5B

Figure 2b: Short Bar Specimen with Straight Chevron Slots. The LOAD LINE is the line along which the opening load is applied in the mouth of the specimen.



SYMBOL	DEFINITION	VALUE	TOLERANCE
B	DIAMETER	B	
W	LENGTH	1.5B	± .010B
a_0	INITIAL CRACK LENGTH	.513B	± .005B
θ	SLOT ANGLE	55.2°	± 1/2°
T	SLOT THICKNESS	SEE TABLE III (of Barker, 1981)	
S	GRIP GROOVE DEPTH	.130B	± .010B
T	GRIP GROOVE WIDTH	.313B	± .005B
R	RADIUS OF SLOT CUT	SEE FIG 4 (of Barker, 1981)	

Figure 3a: Short Rod Specimen with Curved Chevron Slots. The LOAD LINE is the line along which the opening load is applied in the mouth of the specimen.



SYMBOL	DEFINITION	VALUE	TOLERANCE
B	BREADT	B	
W	LENGTH	1.5B	± .010B
H	HEIGHT	.870B	± .005B
a_0	INITIAL CRACK LENGTH	.513B	± .005B
ANG	SLOT ANGLE	55.2°	± 1/2°
T	SLOT THICKNESS	SEE TABLE III (of Barker, 1981)	
S	GRIP GROOVE DEPTH	.130B	± .010B
T	GRIP GROOVE WIDTH	.313B	± .005B
R	RADIUS OF SLOT CUT	SEE FIG 4 (of Barker, 1981)	

Figure 3b: Short Bar Specimen with Curved Chevron Slots. The LOAD LINE is the line along which the opening load is applied in the mouth of the specimen.

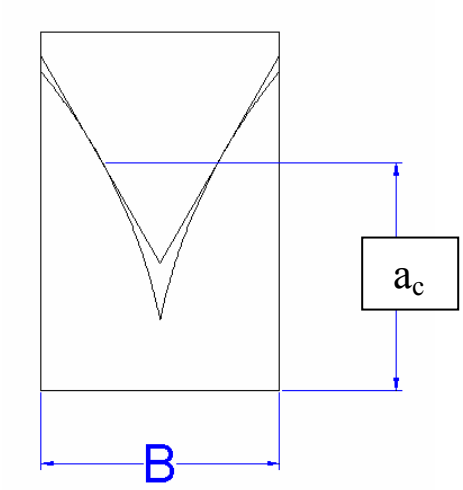


Figure 4: Curved and Straight Slots Tangent at a_c = 0.85B, in the short rod specimen geometries

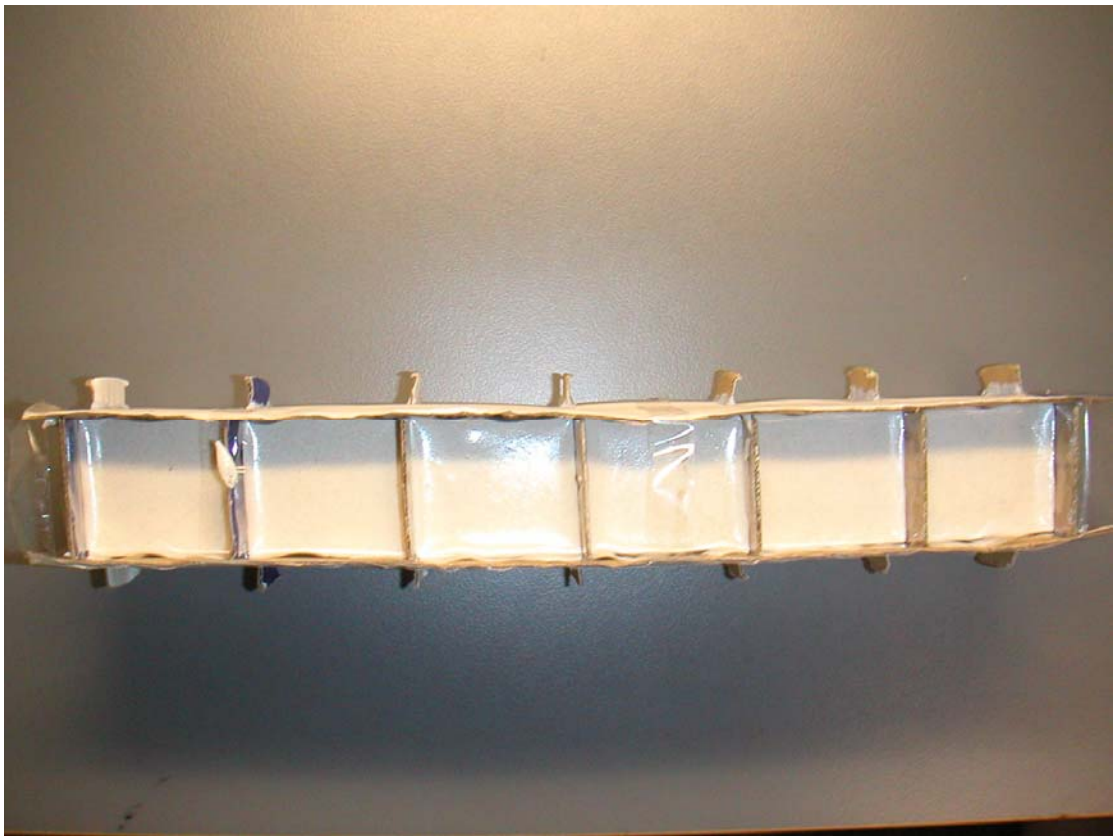


Figure 5: The mould for short bar specimens

Figure 6: The short bar specimens

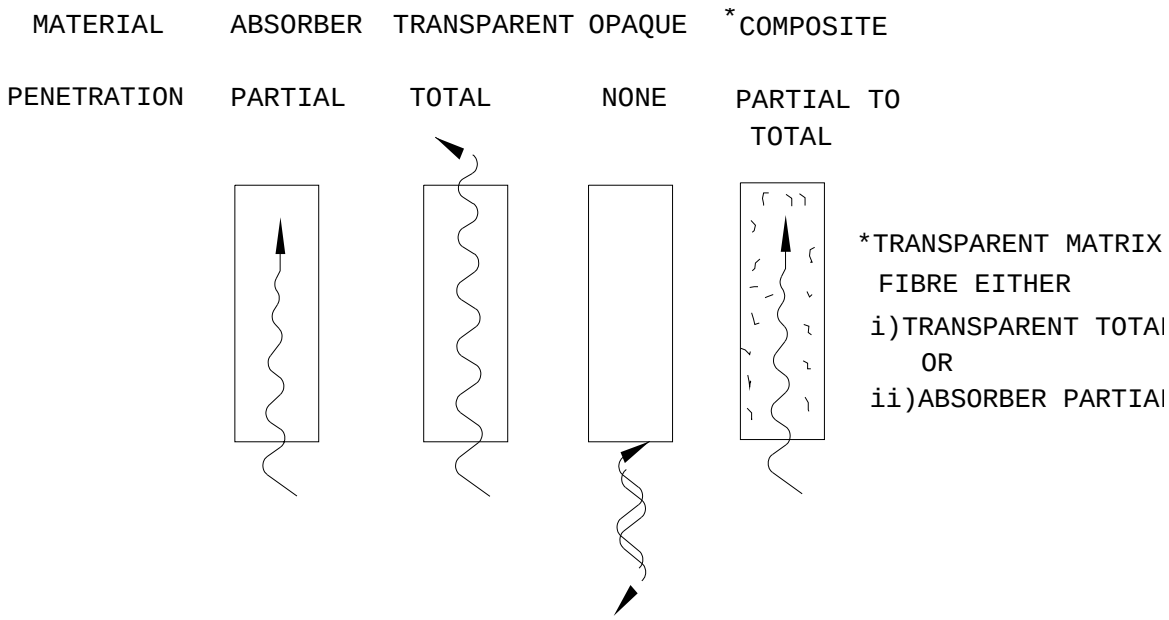


Figure 7: Interaction of Microwaves with Materials

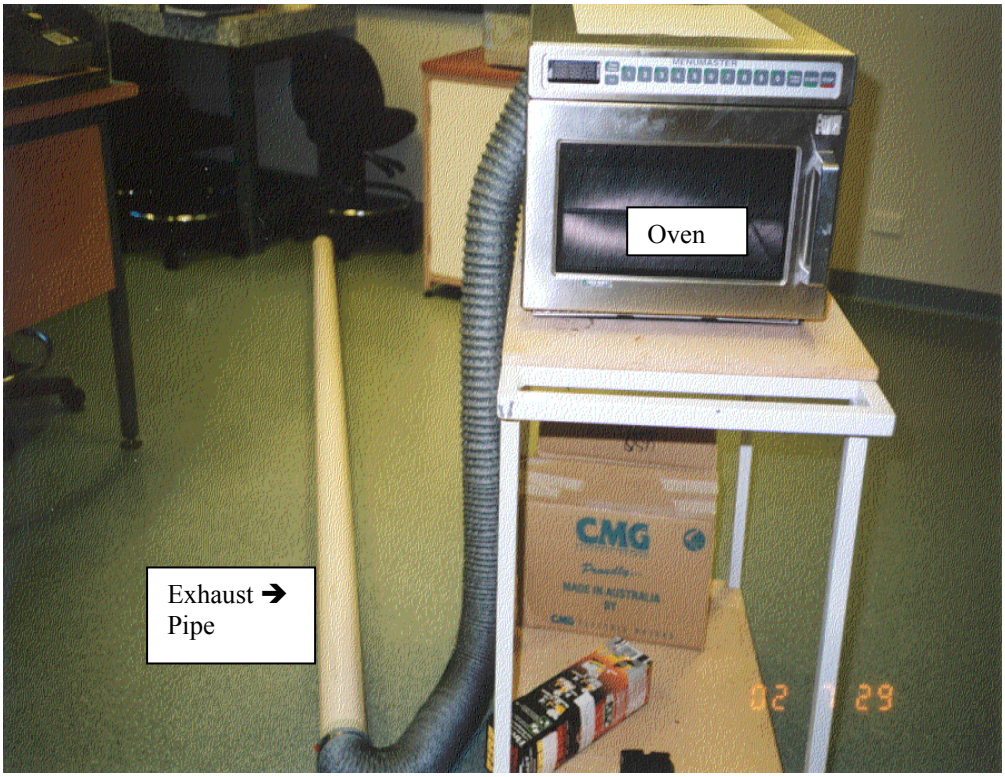


Figure 8: The Microwave Facility Configuration

Figure 9: Fracture toughness test in process

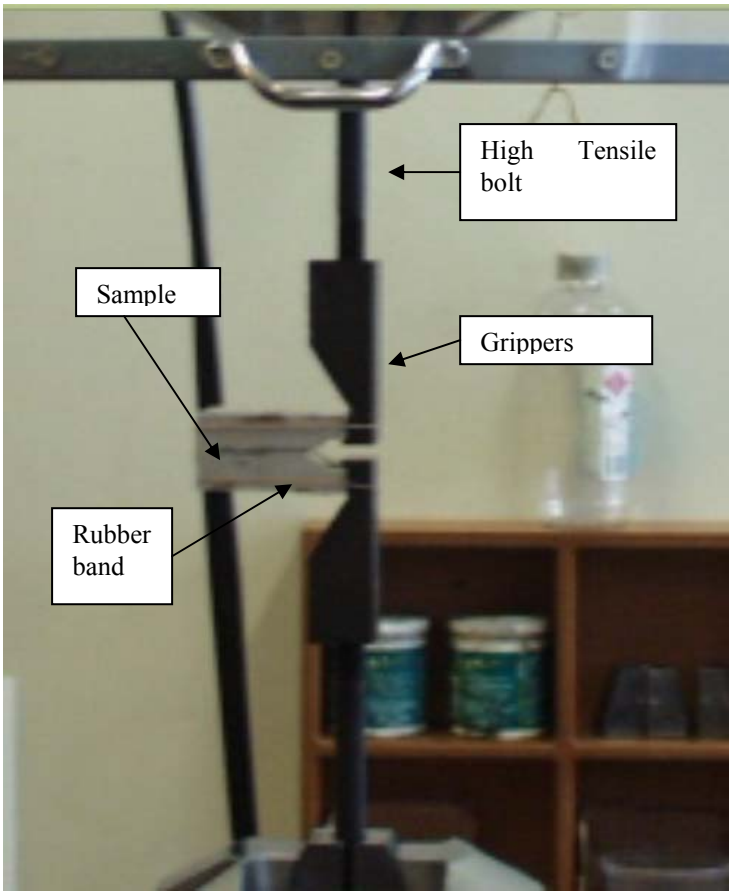


Figure 10: Test rig with specimen in position.

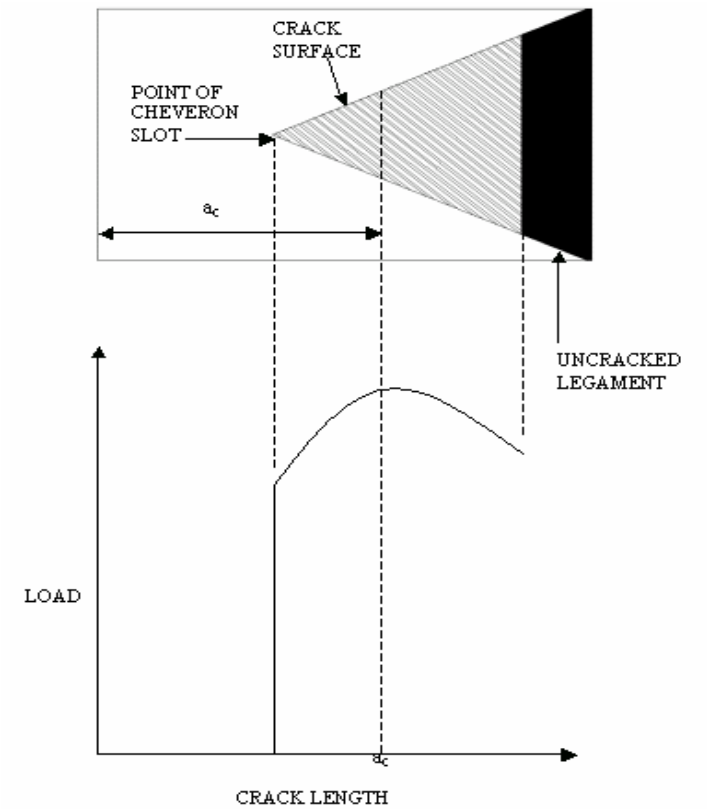
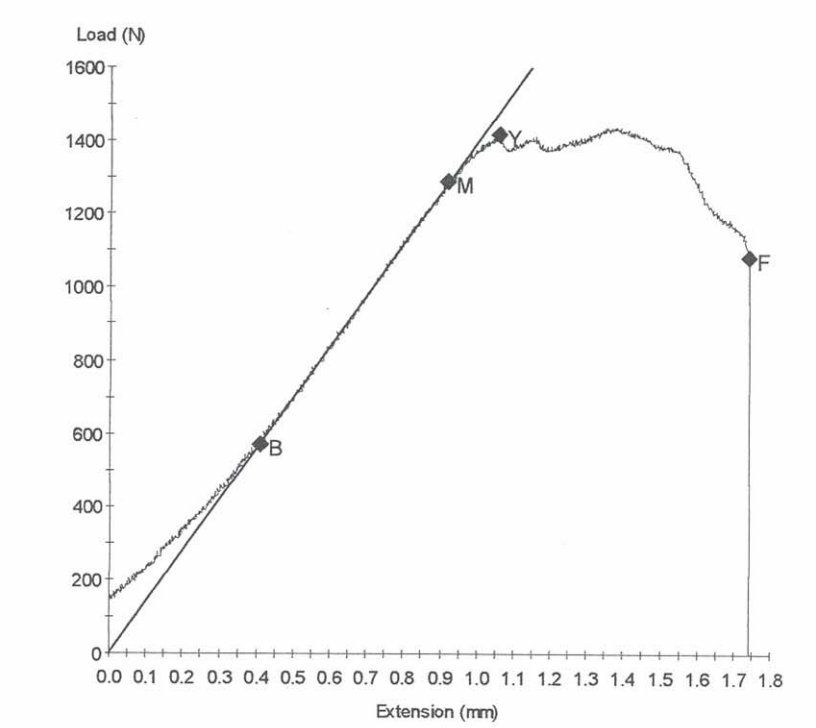


Figure 11: Variation of load versus crack length

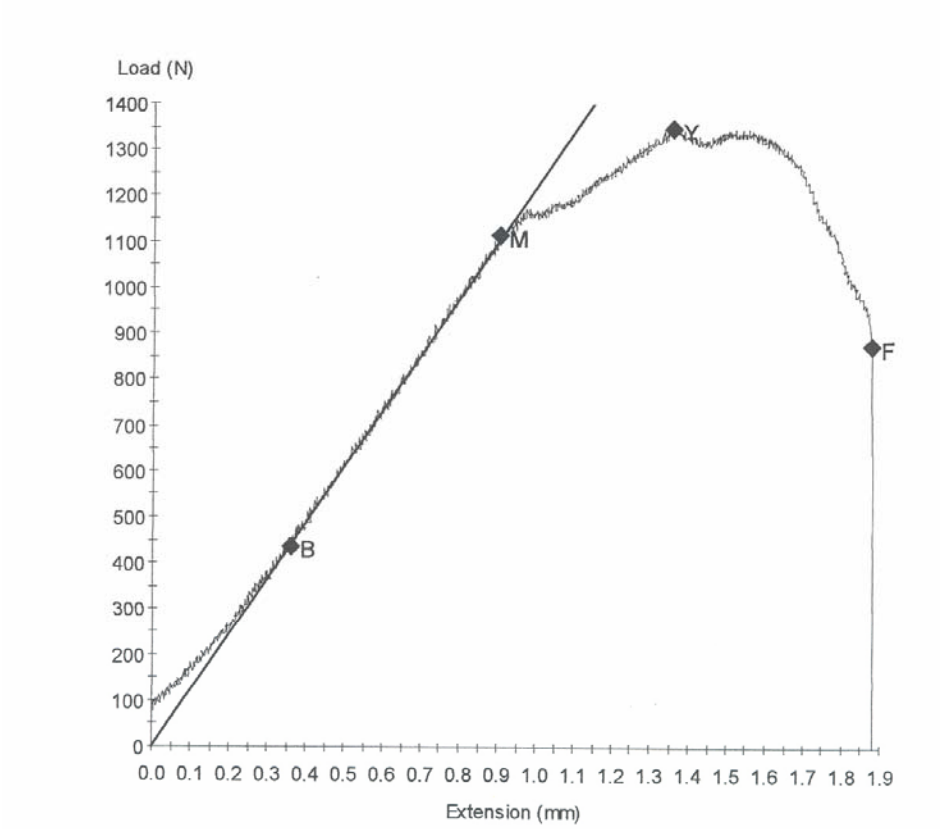


Specimen Results:

Name	Value	Units
Width	8.000	mm
Area	406	mm^2
Peak Load	1438	N
Peak Stress	3.54	MPa
Elongation at Peak	1.374	mm
Break Load	1084	N
Break Stress	2.67	MPa
Elongation At Break	1.743	mm
Stress At Offset Yield	3.389	MPa
Load At Offset Yield	1377.132	N

Specimen Comment:

Figure 12: The change of load versus crack length of a sample cured under microwave condition (180 Watt power level and 60-second exposure time)



Specimen Results:

Name	Value	Units
Width	12.000	mm
Area	609	mm^2
Peak Load	1349	N
Peak Stress	2.21	MPa
Elongation at Peak	1.359	mm
Break Load	876	N
Break Stress	1.44	MPa
Elongation At Break	1.877	mm
Stress At Offset Yield	1.926	MPa
Load At Offset Yield	1174.069	N

Figure 13: The change of load versus crack length of a sample cured under ambient condition

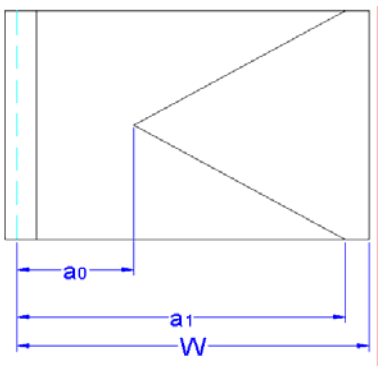


Figure 14: Cross-section dimension of short bar specimen showing a_1

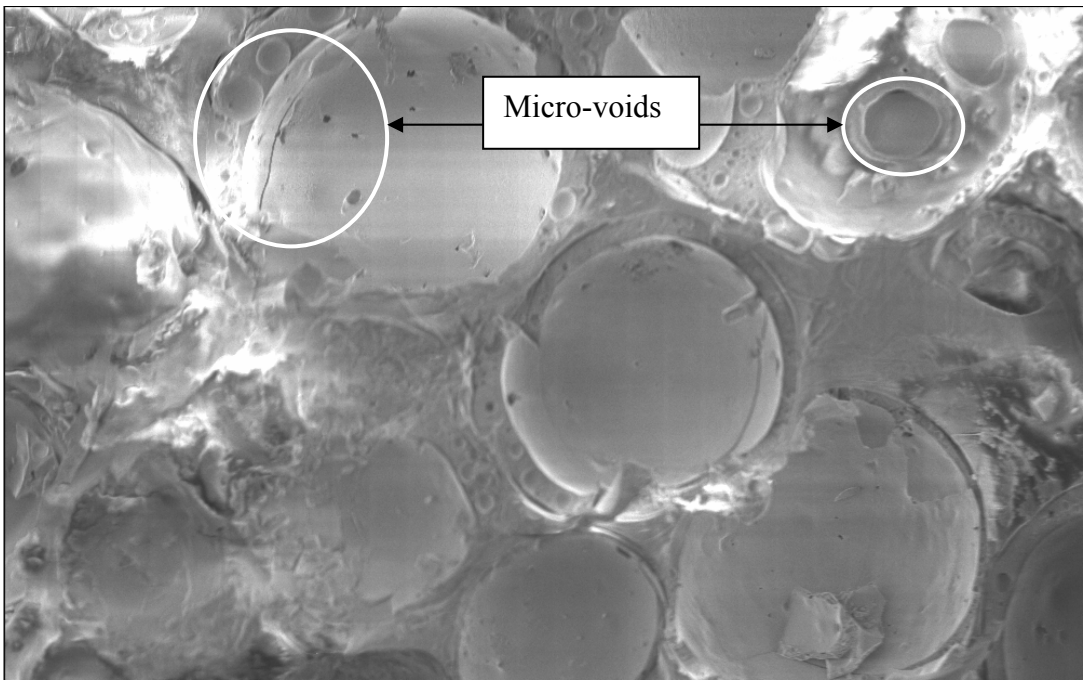


Figure 15: Some micro-voids (bubbles) existed in the composite cured under 360-watt and 80-second microwave irradiation.

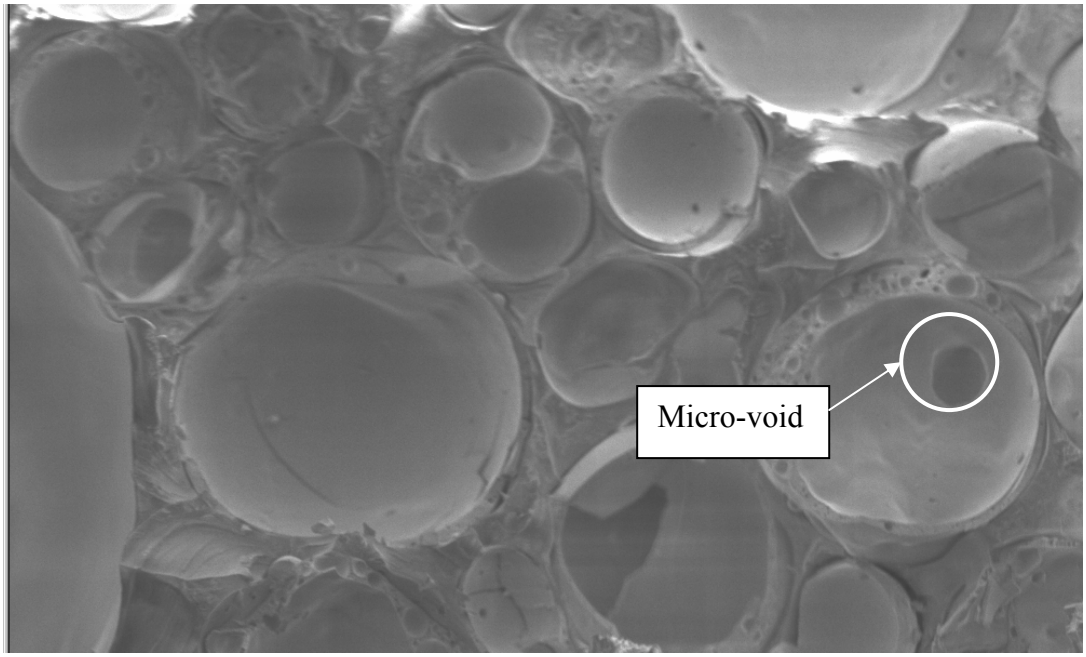
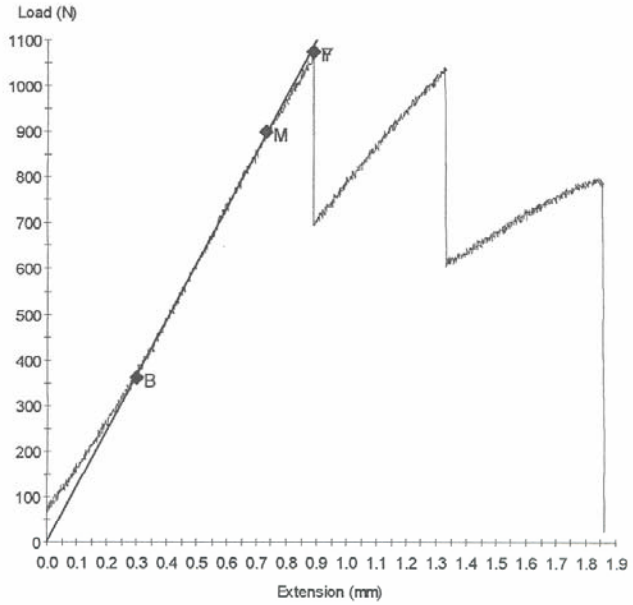


Figure 16: The micro-void (bubble) is less in the composite cured under 180-watt and 60-second microwave irradiation.



Specimen Results:

Name	Value	Units
Width	8.000	mm
Area	406	mm^2
Peak Load	1074	N
Peak Stress	2.64	MPa
Elongation at Peak	0.890	mm
Break Load	1074	N
Break Stress	2.64	MPa
Elongation At Break	0.890	mm
Stress At Offset Yield	1.736	MPa
Load At Offset Yield	705.651	N

Specimen Comment:

Figure 17: The change of load versus crack length of a sample cured under microwave condition (360 Watt power level and 60-second exposure time)

Table 1: Room temperature plane strain fracture toughness and strength values for polymers

Polymeric Materials	Fracture toughness, K_{Ic} MPa $\sqrt{m}$	Strength MPa
Epoxy	0.6	-
Nylon 6, 6	2.5-3.0	44.8-58.6
Polycarbonate	2.2	62.1
Polyethylene terephthalate (PET)	5	59.3
Polymethyl methacrylate (PMMA)	0.7-1.6	53.8-73.1
Polypropylene (PP)	3.0-4.5	31.0-37.2
Polystyrene (PS)	0.7-1.1	-
Polyvinyl chloride (PVC)	2.0-4.0	40.7-44.8
Polyester (thermoset)	0.6	-
Steel alloy 1040 (metal)	54	260 (Yield)
VE/FLYASH (33%)	**51.65**	**0.27**

Table 2: Weight of materials required to make 500 ml of VE/FLYASH (33%)

Parameters / Materials	Resin	Accelerator	Fly ash	Composite
Relative density	1.1	1.0	0.7	---
Percentage by volume	56	---	44	100
Percentage by weight	67	---	33	100
Weight for 500 ml of composite	603.6 (g)	11.2 (g)	308 (g)	---

Table 3: Test results of 180-Watt power and 60-second exposure

Specimens	Elongation at Peak (mm)	Peak load (N)	Elongation at Break (mm)	Break Load (N)	Fracture Toughness (MPa $\sqrt{m}$)
1	1.062	1344	1.479	1011	50.85
2	1.340	1426	1.635	1070	54.10
3	1.240	1304	1.240	1304	49.47
4	1.149	1344	1.592	994	50.85
5	1.439	1499	1.676	1383	56.87
6	1.296	1421	1.722	953	53.91
Mean	1.254	1389.67	1.557	1119.17	52.72
Standard Deviation	0.135	71.78	0.176	179.54	2.567

Table 4: Latin Square for the Project

x (50.85)	y (48.81)	z (48.96)	u (47.52)	v (51.04)
y (51.84)	z (48.62)	u (48.09)	v (48.20)	x (54.10)
z (48.39)	u (48.55)	v (50.74)	x (50.85)	y (51.72)
u (53.91)	v (52.97)	x (50.85)	y (49.47)	z (48.49)
v (51.88)	x (49.47)	y (48.47)	z (51.04)	u (46.99)

Table 5: Results of Statistical Calculations

Source	**D.F.**	**Sum Sq.**[##]	**Estimate**[#]	**F** [!]
Columns	4	8.75	2.19	0.55
Rows	4	13.45	3.36	0.84
Treatments	4	21.00	5.25	1.31*
Error	12	48.72	4.00	-------
Total	24	91.92	---------	-------

[##] Sum of Square due to rows is n (here = 5) times the sum of the squares of the deviations of the row averages from the grand average, and similarly for the column and treatment averages.

$$^{\#}\text{Estimate} = \frac{Sum\ \ of\ \ Square}{DF}$$

$$^{!}\text{F} = \frac{Estimate}{Error}$$

Table 6: Results of the fracture toughness and other parameters for VE/FLYASH (33%) cured under different conditions

Condition	Ambient	180 Watt		360 Watt	
Time	Nil	60s	80s	60s	80s
Elongation at Peak (mm)	1.214	1.254	1.162	1.234	1.121
Peak Load (N)	1365.33	1389.67	1358.67	1264.17	1281.67
Elongation at Break (mm)	1.520	1.557	1.518	1.478	1.445
Break Load (N)	1090.33	1119.17	897.33	1054.83	907.33
Fracture toughness (MPa$\sqrt{m}$)	51.65	52.72	51.41	47.85	48.49