Process monitoring of partially reinforced metal-matrix composite components by acoustic emission

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Partial reinforcement using a fibre bundle embedded in a part of a component has been investigated in the development of a composite piston for use in an internal combustion engine. A trial piston was fabricated by a casting operation in which molten aluminium was poured into a die containing an annular continuous fibre bundle. The most probable defects introduced during the manufacturing operation are (i) microcracks generated in the fibre bundle due to residual thermal stresses and (ii) imperfect impregnation of the molten aluminium into the fibre bundle. Acoustic emission measurements have been used as a technique to detect the presence of defects in the trial pistons. The acoustic emission was measured during cooling of the trial piston after casting. Microcracking in the fibre bundle during cooling could be detected. Imperfect impregnation of the aluminium into the fibre bundle could also be detected. The acoustic emission due to microcracking was found to be strongly dependent on the mechanical properties of the fibres, while the acoustic emission from incomplete impregnation was found to depend on process conditions. It is believed that acoustic emission measurements can not only be used for the detection of microcracks but can also be of value in the selection of fibre materials and in the adjustment of the process conditions.

1. Introduction

Continuous fibre reinforced metal-matrix composites are characterized by a high modulus, high strength and high heat resistance; hence they have been investigated extensively for application in structural metal components. Fabrication of the entire component from the composite material will also result in a significant weight reduction. However, often the increased costs involved in the fabrication of the composite components limit their use.

Partial reinforcement, a technique in which a continuous fibre bundle is embedded in only a portion of the component, can be an effective way to achieve many of the desired composite properties at a much lower cost. A composite piston for use in an internal combustion engine is an ideal candidate for the partial reinforcement technique [1]. The piston is normally made of aluminium for weight saving, but the cylinder wall in which it moves is made of steel. The difference in metals requires that the clearance between the piston and the cylinder wall must be great enough that the piston does not seize at the high operational temperatures. The large difference in the thermal expansion coefficients requires a rather large clearance. The excess clearance, however, causes excessive noise and a loss of acceleration in the initial operating period of the engine. A composite piston was conceived and developed in an attempt to solve these problems. The composite piston is a cylindrical casting of an aluminium alloy in which an annular continuous fibre bundle is embedded in its circumference. The fibre bundle acts as a reinforcement which suppresses the thermal expansion of the piston in the radial direction. The smaller radial expansion then allows for a smaller clearance between the piston and the cylinder wall, thus solving the problems of excessive noise and loss of acceleration.

There are difficulties, however, in the fabrication of a component with only partial fibre reinforcement. First, there will be a large residual thermal stress due to the large difference in the thermal expansion coefficients of the bulk metal and the reinforcing fibre. The stress may be of sufficient magnitude to cause microcracking within the fibre bundle. Second, it may be difficult to get total and complete impregnation of the molten metal matrix into the fibre bundle and maintain the bundle in the proper prescribed position. To be successful in the fabrication of a workable component it is necessary to obtain complete impregnation, and to select fibres of sufficient strength to eliminate microcracking. A method or technique to monitor the process which is sensitive to microcracking and imperfect impregnation is also required.

Recently, acoustic emission measurement has been used to detect the occurrence of microcracks in composite materials [2]. Most studies of composite mater-

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TABLE I Characteristics and mechanical properties of the different fibres used for reinforcement

No.	Type	Characteristics	Modulus (GPa)	Strength (GPa)	Thermal expansion coefficient ($\times 10^{-6}\,°C^{-1}$)
1	PAN–carbon fibre	High-modulus type (no surface treatment)	390	2.8	− 1.2
2	PAN–carbon fibre	High-modulus type (surface treatment)	390	2.8	− 1.2
3	PAN–carbon fibre	High-strength type	290	4.0	− 1.0
4	PAN–carbon fibre	Ultra-high strength type	290	5.7	− 1.0
5	Pitch–carbon fibre	High modulus type	540	2.8	− 1.2
6	Alumina fibre	Conventional type	360	1.5	6.8

ials by acoustic emission are concerned with the detection of microcracks as a result of an applied stress. Only a limited number of investigations have been carried out on the acoustic emission generated in composite materials during thermal treatment [3–10]. The previously reported work can be divided into two categories: (i) the study of acoustic emission generated by microcracks induced by thermal loading [3–6], and (ii) the study of acoustic emission due to the friction of crack surfaces due to thermal expansion [7–10]. The use of acoustic emission as a technique to monitor process control of composite materials has apparently been small [11]. The purpose of this paper is to report on the fabrication and process monitoring of a composite piston which has partial fibre reinforcement. Acoustic emission measurement was the monitoring technique used.

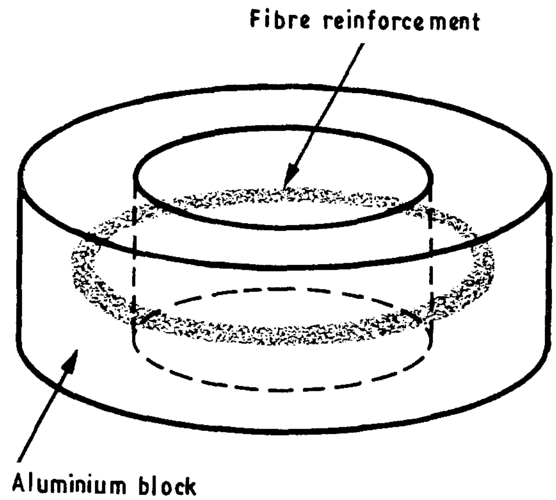

Figure 1 Schematic diagram of the cylindrical aluminium alloy test block, showing the annular continuous fibre bundle embedded in the circumference for reinforcement.

2. Experimental procedure

2.1. Manufacture of cylindrical aluminium piston with fibre reinforcement

A cylindrical aluminium alloy block containing an annular continuous fibre bundle embedded in its circumference for reinforcement was fabricated using a casting operation. A schematic diagram of the part is shown in Fig. 1. The process of fabrication was as follows: (i) the annular fibre bundle was preheated to 600 °C and placed at the prescribed position in the casting die, (ii) molten aluminium alloy (JIS AS8A) was immediately introduced into the die, and (iii) a solidification pressure of approximately 100 MPa was applied. The dimensions of the cylindrical block were 92 mm outside diameter, 76 mm inside diameter and 18 mm height. The dimensions of the fibre bundle were 86 mm outside diameter, 82 mm inside diameter and 5 mm height. In the area of the fibre bundle, the volume fraction of fibre was found to be 65%.

Six different types of fibre bundle were investigated. They are listed, along with important characteristics, in Table I. Test blocks were fabricated using each of the six different fibre types as well as a control (block 7) with no fibres.

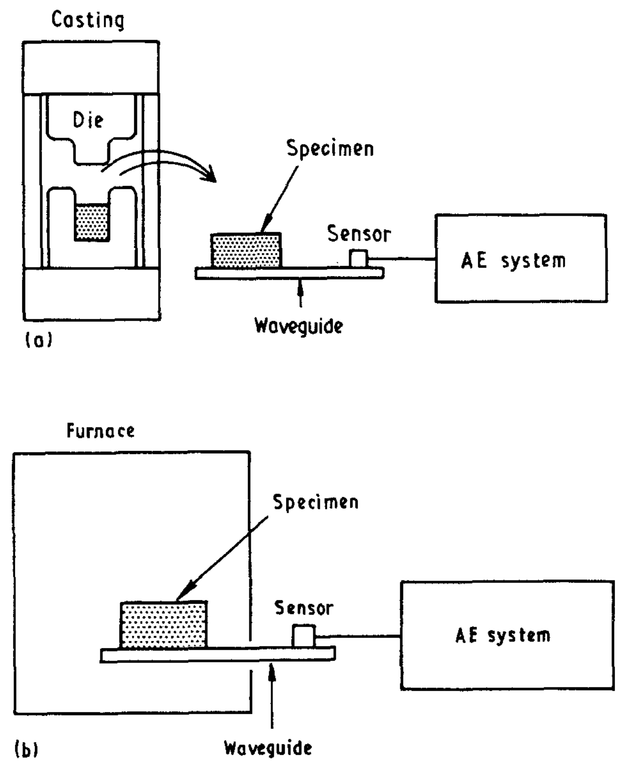

Figure 2 Block diagram of the experimental measurement systems used for (a) acoustic emission measurements during cooling after casting and (b) acoustic emission measurements during thermal cycling.

2.2. Acoustic emission measurements

Acoustic emission measurement was carried out during cooling of the test blocks after their removal from the casting die. Fig. 2a gives a schematic illustration of the measurements. The test block was removed from the die immediately upon solidification and placed upon a stainless steel plate. The stainless steel acted as a waveguide for emission to the acoustic emission transducer. The acoustic emission transducer was a resonant piezoelectric type with a resonant frequency of approximately 140 kHz. The signals detected by the transducer were amplified by 93 dB (preamplifier of 40 dB and main amplifier of 53 dB, with highpass filter of 100 kHz) and were counted (threshold value of 1 V) using a conventional commercial acoustic emission system. The acoustic emission data will be reported as the rate of ring-down counts per second. The acoustic emission data will be given as a function of surface temperature of the test block detected by a thermocouple.

Acoustic emission measurement were also carried out during thermal treatment cycles of the test blocks. Fig. 2b shows the system used to detect the acoustic emission during heating. The test blocks were heated to 300 °C at a rate of 5 °C min^{-1}, held at 300 °C for 1 h and then furnace-cooled to room temperature. Acoustic emission measurements as described above were carried out during the total thermal cycle.

2.3. Microscopy

Optical microscopy was carried out to detect the presence of microcracking in the as-cast test blocks after cooling. Cross-sections parallel to the fibre reinforcement were prepared to determine whether microcracking had occurred during cooling.

2.4. Mechanical properties of the test material

In order to estimate the mechanical properties of the test blocks, similar materials were prepared with unidirectional fibre bundles. A rectangular die was used to produce unidirectional fibre samples having the same metal-matrix material, the same types of fibre and the same fibre volume fraction. A plain aluminium alloy sample was also fabricated. The compressive modulus, compressive strength and thermal expansion coefficients as determined from these samples using conventional methods and samples of 5 mm × 5 mm × 20 mm (length) are given in Table II.

3. Results and discussion

3.1. Acoustic emission during cooling

The surface temperature of the test blocks upon removal from the casting die was approximately 300 °C; cooling to room temperature occurred in about 45 min. Fig. 3 shows the measured acoustic emission during cooling of each of the test blocks. The differences in the acoustic emission from different test blocks are obvious. Acoustic emission was detected from block 7, which is the pure aluminium alloy sample containing no reinforcement fibres. The acoustic emission from block 7, however, was minimal and is believed to be due to recrystallization of the aluminium alloy. Large amounts of acoustic emission were generated in blocks 1 and 2 as the blocks were cooled beow 200 °C. The acoustic emission is believed to be a result of microcracking generated by differences in thermal expansion. By comparison, only a small amount of acoustic emission was observed during the cooling of blocks 3, 4, 5 and 6. The acoustic emission measured during the cooling of these test blocks was slightly greater than that observed for the aluminium alloy test block. The acoustic emission clearly depends upon the type of fibre used and can thus be used as a technique for the selection of fibres suitable for partial reinforcement.

TABLE II Mechanical properties of unidirectional fibre-reinforced composite samples

Name	Modulus (GPa)	Compressive strength (GPa)	Thermal expansion coefficient ($\times 10^{-6}$ °C^{-1})
UD 1	235	0.69	2.2
UD 2	235	1.15	2.2
UD 3	191	1.69	2.3
UD 4	191	1.75	2.3
UD 5	343	1.67	2.2
UD 6	157	2.04	8.3
UD 7	76	0.35 (yield)	20.0

3.2. Acoustic emission during a thermal cycle

The acoustic emission was measured while subjecting the test blocks to a complete thermal cycle (as described earlier) after casting. Fig. 4 shows the acoustic emission generated during the thermal cycles for each of the test blocks. The results in general are very similar to those found on cooling after casting, i.e. significant acoustic emission from test blocks 1 and 2 with slight acoustic emission from test blocks 3, 4, 5, 6 and 7. Test block 1, however, was the only test block to generate acoustic emission during cooling. From approximately 150 °C to room temperature, a large amount of acoustic emission was measured for test block 1. As mentioned earlier, it is believed that the origin of emissions generated during cooling is the occurrence of microcracks due to residual thermal stress. The acoustic emission during heating of the test blocks is most likely due to friction and rubbing of microcracks which were previously formed during the initial cool-down [7, 8]. The measured results on heating are consistent with that explanation, since only those test blocks which were believed to have microcracked during cool-down showed any acoustic emission on reheating. The heat-up results indicate that if it is impossible to obtain data during the initial cool-down, the occurrence of microcracking can still be determined by measuring the acoustic emission during a thermal cycle.

3.3. Acoustic emission used to detect poor castings

The most common defect in the casting process used to fabricate the test blocks is the incomplete impregnation of the molten aluminium into the fibre bundle.

With improper casting conditions, i.e. insufficient preheating of the fibre bundle or inadequate pressure, incomplete impregnation will occur. Test blocks using fibres 3 and 4 were fabricated using a fibre bundle preheat of 200 °C and a casting pressure of 60 MPa, intentionally using improper casting conditions. When properly fabricated, test blocks fabricated with fibres 3 and 4 showed essentially no acoustic emission on cooling from the casting operation. Fig. 5 shows the acoustic emission data measured on cooling for the test blocks fabricated intentionally with improper conditions; clearly, significant acoustic emission is measured. Fig. 6 shows the acoustic emission data for the same blocks during a complete thermal cycle. From these data it appears that acoustic emission is sensitive to the casting conditions and could be used to establish and determine whether proper casting conditions were used.

3.4. Acoustic emission from repeated thermal cycles

The acoustic emission was also measured for test blocks that were subjected to repeated thermal cycles. Test blocks with fibres 1 and 4 were chosen. Test block 1 produced a large amount of acoustic emission upon cooling from the casting operation, while test block 4 generated very little acoustic emission while cooling. Acoustic emission data measured over three complete thermal cycles is given in Fig. 7. In both cases the acoustic emission decreases with the number of thermal cycles. The results for test block 4 clearly indicate that interaction between the aluminium matrix and the fibre bundle remains stable for subsequent thermal cycles.

3.5. Observation of microcracks

Microscopy was used to determine whether microcracks had been formed in the test blocks upon cooling from the casting operation. Microcracks were easily found in test blocks 1 and 2. The microcracks in these test blocks were observed to propagate across the reinforcement fibres at an angle of approximately 45° from the fibre direction and to stop at a boundary (see for example Fig. 8a and b). It is believed that the observed microcracks are a result of buckling failure of the reinforcement fibres due to the residual thermal stresses. Microcracks of this type are believed to be the source of the acoustic emission measured for test blocks 1 and 2. For test blocks 3 to 6 no microcracks due to buckling of the reinforcement fibres could be found. Fig. 8c shows a typical micrograph of the reinforcement fibres for test blocks 3 to 6. In some cases, however, a small number of microcracks along the fibre, probably due to debonding between the fibre

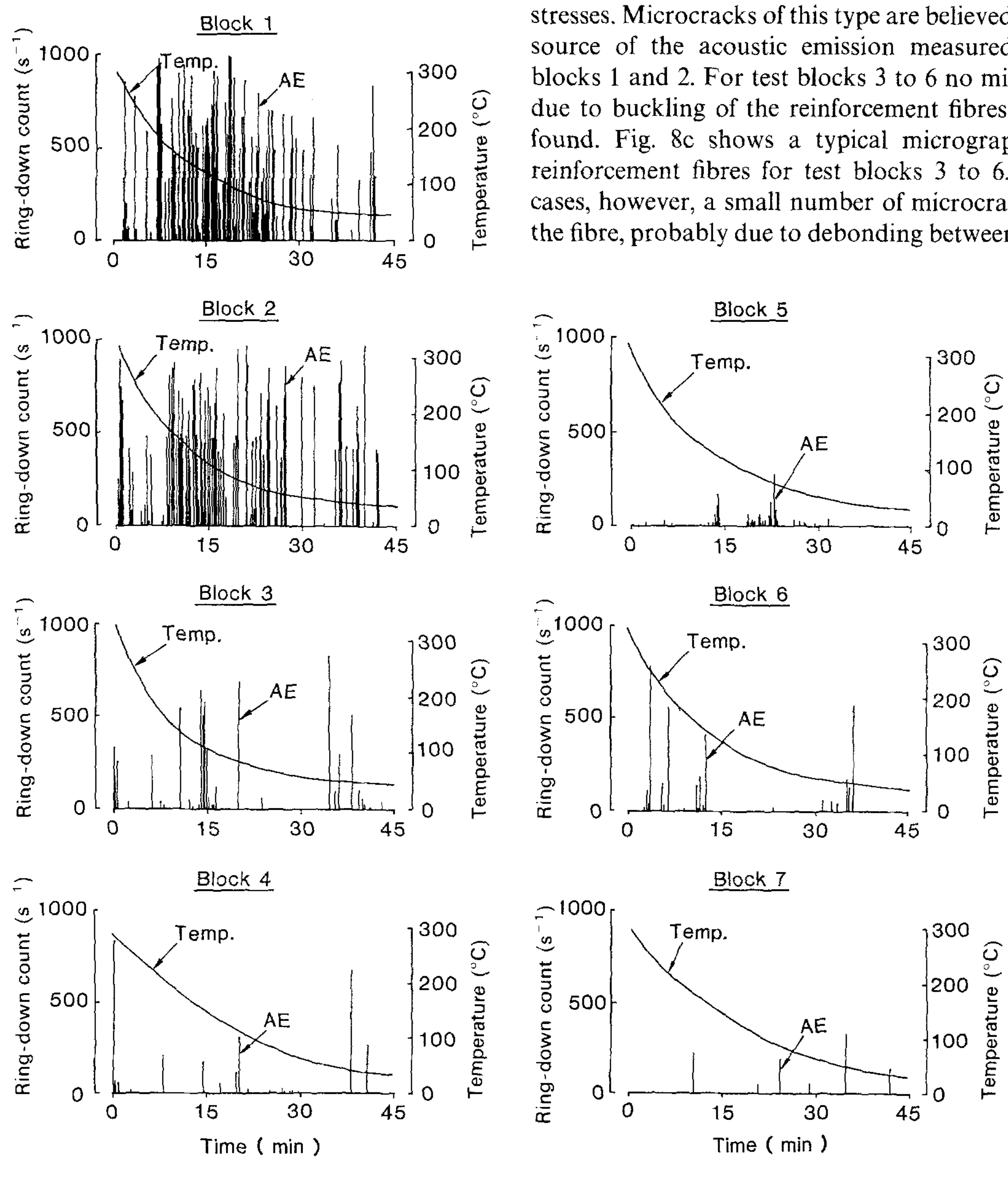

Figure 3 Acoustic emission behaviour of test blocks 1 to 7 during cooling after casting.

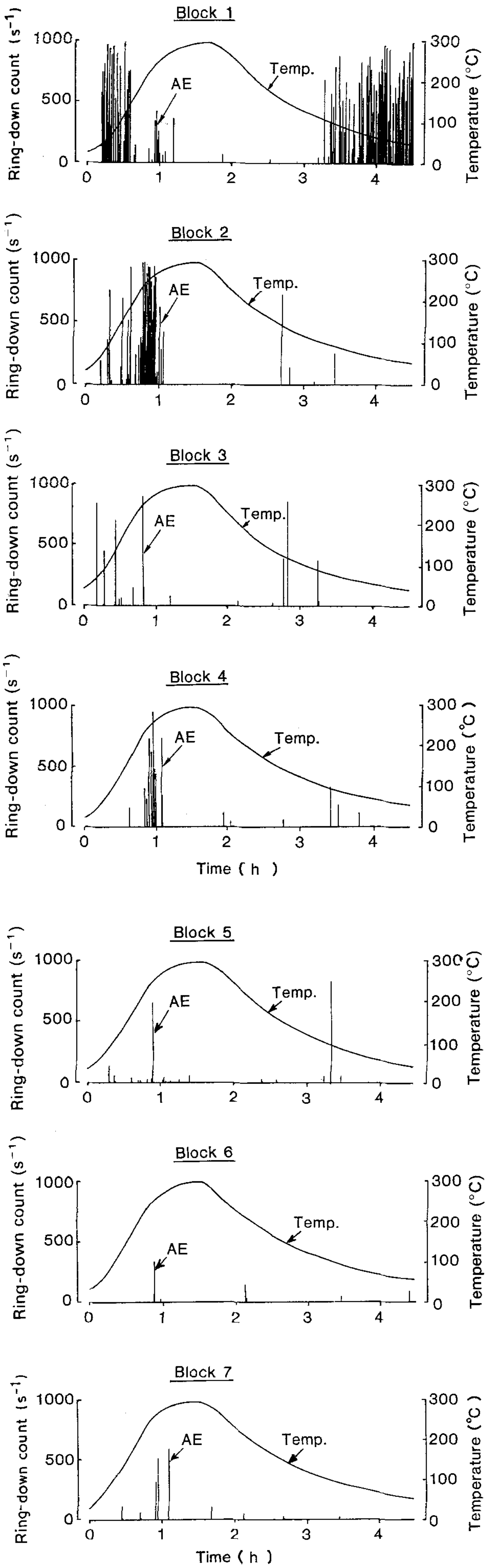

Figure 4 Acoustic emission behaviour of test blocks 1 to 7 during thermal cycling.

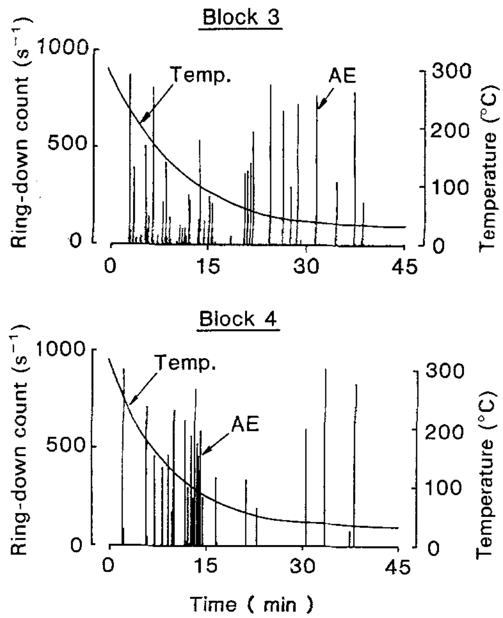

Figure 5 Acoustic emission behaviour during cooling after casting for test blocks 3 and 4 which were prepared using improper process conditions.

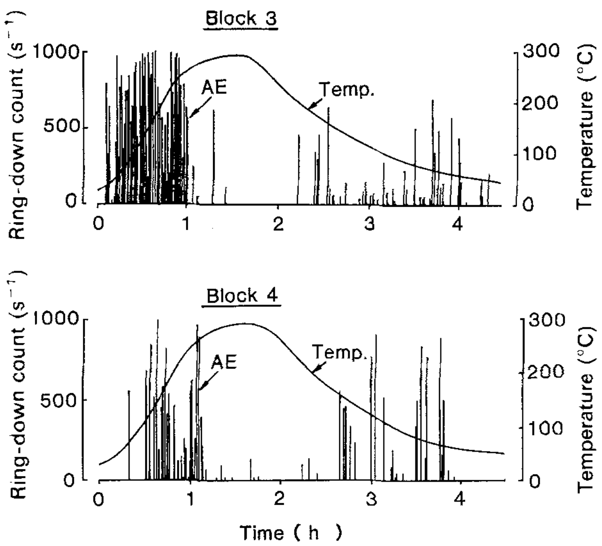

Figure 6 Acoustic emission behaviour during thermal cycling for test blocks 3 and 4 which were prepared using improper process conditions.

and the matrix, were observed. Fig. 8d provides an example of this type of microcrack. It is probable that the limited acoustic emission observed from test blocks 3 to 6 could be from this type of microcrack. The relationship between the amount of acoustic emission measured during the cool-down period after casting and the number of microcracks observed in a whole cross-section of the annular fibre bundle parallel to the fibre reinforcement is given in Fig. 9. A good correlation between the acoustic emission and the amount of microcracking is clearly indicated.

3.6. Residual thermal stress analysis

It has been postulated earlier in this paper that microcracks have been produced as a result of residual stresses in the reinforcement fibre bundle as a result of the difference in thermal expansion of the aluminium alloy matrix and the fibre reinforcement bundle. To determine the feasibility of the postulate a stress analysis was performed to estimate the residual thermal stress. These values were then compared with the experimental compressive strength of unidirectional composite samples described earlier. The residual thermal stress within the composite after cooling should be given by

$$\sigma_C = \frac{S_a E_c(\alpha_a - \alpha_c)\Delta T}{S_a E_a + S_c E_c} \quad (1)$$

where E, α, S and ΔT are the modulus, thermal

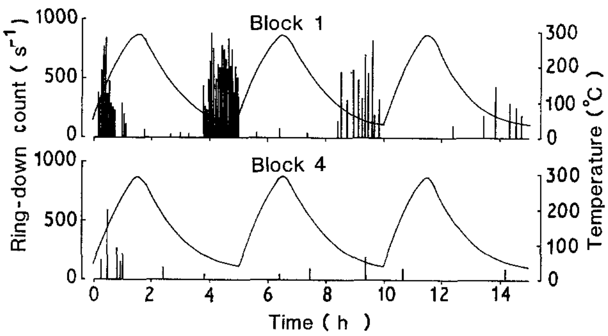

Figure 7 Acoustic emission behaviour of test blocks 1 and 4 during repeated thermal cycling.

expansion coefficient, cross-sectional area and temperature change from solidification to room temperature, respectively. The subscripts a and c indicate the aluminium alloy and the composite material, respectively. The values used in Equation 1 were determined experimentally at room temperature and are listed in Table II. The temperature change from solidification to room temperature was approximately $-600\,^\circ$C; however, in the evaluation of Equation 1 a value of $-300\,^\circ$C was used because of the gradual increase of the modulus of the alloy during cooling.

The residual thermal stress using a ΔT of $-300\,^\circ$C is given in Table III for the different reinforcement fibres used. It is instructive to compare the data in Table III with the experimental compressive strengths of the unidirectional composite as given in Table II. Notice that for test materials 1 and 2 the calculated residual thermal stress is greater than the experimental compressive stress. On the basis of these data one would expect buckling and microcracking of the reinforcement in materials 1 and 2 during cooling, as was observed by microscopy and acoustic emission. In a similar manner no microcracking or acoustic emission during cooling would be expected from materials 3 to 6, since the residual thermal stress is lower than the compressive stress of the material. This is in agreement with the observed data.

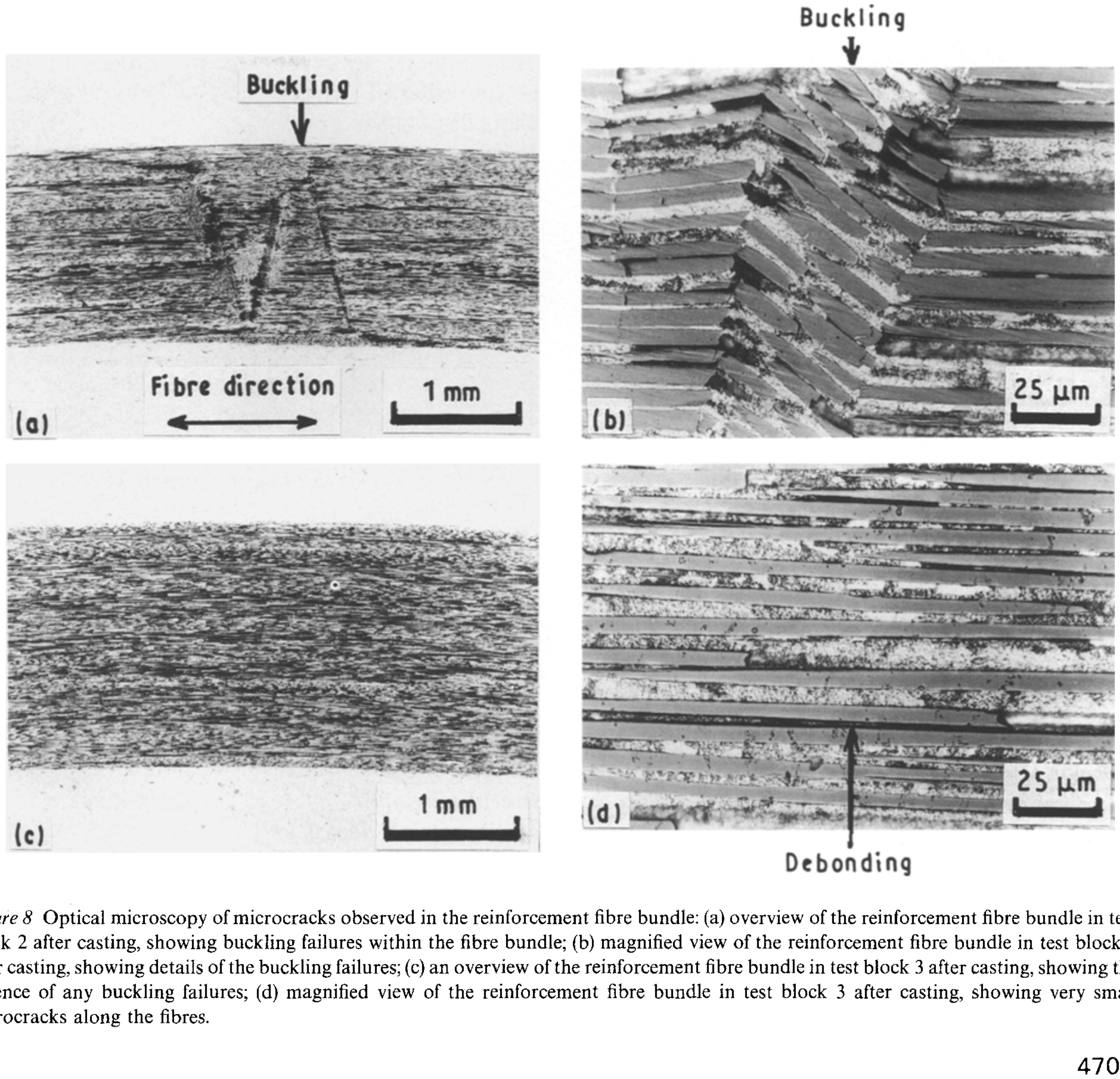

Figure 8 Optical microscopy of microcracks observed in the reinforcement fibre bundle: (a) overview of the reinforcement fibre bundle in test block 2 after casting, showing buckling failures within the fibre bundle; (b) magnified view of the reinforcement fibre bundle in test block 2 after casting, showing details of the buckling failures; (c) an overview of the reinforcement fibre bundle in test block 3 after casting, showing the absence of any buckling failures; (d) magnified view of the reinforcement fibre bundle in test block 3 after casting, showing very small microcracks along the fibres.

TABLE III Calculated values of the residual thermal stress in reinforcement fibre bundles after cooling to room temperature from casting

Name of cast block	Block 1	Block 2	Block 3	Block 4	Block 5	Block 6
Calculated stress value (GPa)	1.20	1.20	1.01	1.01	1.60	0.60

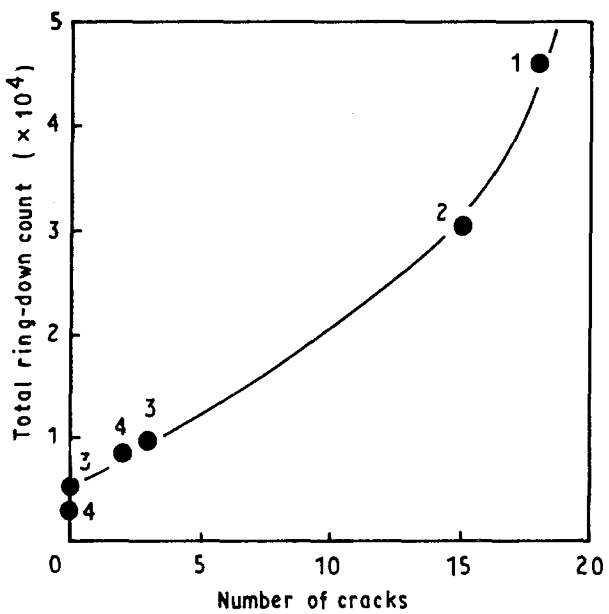

Figure 9 Relationship between the total amount of acoustic emission measured during cooling after casting and the number of microcracks observed in a cross-section of the reinforcement fibre bundle. The numbers refer to specific test blocks.

4. Conclusions

The acoustic emission was measured during cooling from casting of partially reinforced aluminium alloy cylindrical test blocks. The test blocks were partially reinforced with an annular fibre bundle. Measurements were also carried out during thermal cycling after cooling. Microscopy was carried out to detect microcracking and the residual thermal stress was estimated and compared with the experimental compressive stress of unidirectional composites of similar materials. From the data generated in the investigation it is possible to reach the following conclusions:

1. The development of microcracks in the reinforcement fibre bundle during cooling from the casting operation could be detected by acoustic emission measurements.

2. The occurrence of additional microcracking during thermal cycling could also be detected by acoustic emission measurements. The acoustic emission during heating was related to frictional noise from the microcrack interfaces of cracks that had been previously formed during the initial cool-down. The acoustic emission during cooling is believed to be due to the formation of new microcracks.

3. Incomplete impregnation of the aluminium alloy could also be detected by acoustic emission measurements.

4. The estimated residual thermal stress from a simple calculation when compared to the experimental compressive strength, provided additional proof that the acoustic emission during cooling was from the formation of microcracks within the fibre bundle.

5. Optical microscopy confirmed the presence or lack of microcracks in the test materials as predicted by their acoustic emission behaviour.

6. The acoustic emission data were not only found to be useful for the detection of microcracking, but were also shown to be useful in the selection of the appropriate fibre material and the determination of the proper processing conditions.

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