Metal Matrix Composites Reinforced with Fibre FP(<latex>$\alpha $</latex>-Al<latex>$_{2}$</latex>O<latex>$_{3}$</latex>)

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Metal matrix composites reinforced with Fibre FP(α-Al_2O_3)

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[Plate 1]

An experimental continuous aluminium oxide fibre designated Fibre FP is currently under development at the Du Pont Company. This fibre is well suited for the reinforcement of metals. A major problem limiting widespread usage of fibre reinforced metal matrix composites has been the lack of practical methods to fabricate composites. We have developed a versatile, potentially low cost, fabrication technique based on vacuum casting to incorporate Fibre FP into metal matrices. To date, fabrication of Fibre FP reinforced magnesium, aluminium, lead, copper and zinc composites have been demonstrated. A variety of FP/Al and FP/Mg composite components such as plates, rods, tubes, structural beams, billets and thin sheets containing volume loading 30–60 % FP have been prepared.

For a fibre volume loading of 60 %, undirectional FP/Al composites have an axial modulus of 262 GPa (38×10^6 lbf/in^2), tensile strength of about 690 MPa (10^5 lbf/in^2), compressive strength 3.4 GPa (5×10^5 lbf/in^2) and retain their mechanical properties to 316 °C. Transverse tensile strengths of 172–207 MPa (25–30×10^3 lbf/in^2) show that excellent fibre/matrix bonding is obtained.

INTRODUCTION

Du Pont is developing a new flexible inorganic fibre based on aluminium oxide. This experimental fibre is called Fibre FP and is a continuous filament polycrystalline α-Al_2O_3 yarn. 'Alumina Fibre FP' is discussed in a separate companion paper in these proceedings.

Fibre FP is well suited for metals reinforcement because of a combination of properties including high modulus and strength at elevated temperatures, compatibility with molten metals, composite fabricability and projected low cost. It lends itself to practical composite fabrication techniques involving molten metals and castings. A potentially low cost Fibre FP reinforced metal matrix composite fabrication technology based on vacuum casting has been demonstrated by the fabrication of Fibre FP reinforced magnesium, aluminium, lead, copper and zinc composite castings.

Requirements for composite casting

Fundamentally, the molten metal should wet Fibre FP to form a strong fibre/matrix bond at the interface. However, wetting alone is not sufficient to prepare high quality composites; the following combination of conditions must be satisfied to yield practical fibre reinforced composite casting systems.

(*a*) *Chemical fibre/matrix bonding*. The molten metal should wet Fibre FP to form a chemical bond at the interface which must be stable at the elevated temperatures. To achieve this critical fibre/matrix bonding a slight reaction with the fibre is required without fibre degradation.

(*b*) *Interface*. The fibre/matrix interface in composite must be free of brittle intermetallic phases to effectively transfer load from one fibre to another.

(*c*) *Matrix ductility*. Since Fibre FP is a brittle ceramic fibre, the reinforced composites fracture by a weak link mechanism. The matrix should be ductile to arrest micro-cracks initiated by the fracture of weaker fibres, thereby preventing premature composite failure.

(*d*) The composite fabrication process should be easy to scale up and have low cost potential.

I would now like to discuss composite casting of two different metal systems in order to illustrate Fibre FP reinforced metal matrix composite fabrication technology, one system in which the molten metal naturally wets Fibre FP, for example, FP/Mg, and the other system in which the molten metal does not wet Fibre FP such as FP/Al.

Fibre FP reinforced aluminium castings

As shown in table 1, the development of FP/Al composite casting systems may be seen from two aspects, one being Materials Science and the other Materials Engineering. The Materials Science problem arises because Fibre FP is not wetted by molten aluminium and commercial aluminium alloys even at high temperatures above m.p. of Al. The Materials Engineering problem arises because of the brittleness of the FP ceramic fibre and difficulty in handling required for composite fabrication.

Table 1. FP/Al composite development

1. *Material science problem*
    Molten Al does not wet FP (Al_2O_3) fibres.
    approach
        fibre coating – Co, Ni/Ti
        fibre doping
        matrix alloying (Ba, Be, Bi, La, Na, Si, Ti, Zr...did not wet FP)
    research breakthrough
        addition of Li (2 %) to Al forms alloy which shows
        chemical wetting ($3Li + 2Al_2O_3 \rightarrow 3LiAlO_2 + Al$)
        metallurgical compatibility
2. *Material engineering problem*
    Develop a practical method for the fabrication of FP reinforced Al composites.
        fibre handleability
    approach
        molten metal infiltration (casting)

1. Wetting between Fibre FP and aluminium

Three approaches were studied to obtain wetting between Fibre FP and molten aluminium: (1) fibre coating, (2) fibre doping, and (3) matrix alloying.

Although FP fibres coated with metals like Ni, Ti, Co or Cu wet molten Al, the resulting composites have poor mechanical properties due to the formation of brittle intermetallic phases at the interface. Dhingra (1970) found similar formation of brittle intermetallic phases and poor mechanical properties in cast metal-coated boron fibre reinforced aluminium matrix composites. Also, difficulties are encountered in making larger size composites owing to the reoxidation of metal-coated FP fibres at molten metal temperatures required for composite fabrication. This approach, therefore, is not considered practical to make low cost FP/Al composites. Doping of the FP fibre with elements such as Cr, Fe, Cu, Ni, Co, Si does not give satisfactory wetting. Al matrix alloying via Li additions is found to be highly promising to obtain chemical wetting between Fibre FP and Al. It was discovered that suitable additions of 2–3 % Li to Al caused chemical reaction with FP without embrittlement of the matrix or the interface and satisfies critical combination of chemical and metallurgical conditions required for practical fabrication and performance of FP/Al composites. Additions of other active elements, such as Ca, Na, Ba, Si and Ti, did not yield satisfactory composites either because of lack of proper wetting between the fibre and the matrix or formation of brittle interface or embrittlement of the matrix. Li appears to be unique in chemical and metallurgical compatibility with Al to give high quality FP/Al composites (Riewald *et al.* 1977).

2 (*a*) Al/Li *alloys*

Al/Li alloys are attractive as a matrix because of their light weight and excellent mechanical properties. Li-containing Al alloys are not new; they have been studied by various investigators (Drits *et al.* 1973; Noble & Thompson 1971). The high stability of Li in Al yield metallurgically compatible alloys which can be strengthened by heat treatment. In Al solid solutions, additions of Cu, Si and Zn reduce the Young modulus of Al, Mg has practically no effect and Li substantially increases it. Addition of 4 or 5 % Li to Al increases the modulus of pure aluminium by about 17 %. Because of the excellent specific properties of Al/Li alloys, aerospace companies are showing considerable interest in the development of these lightweight aluminium alloys in air frame and aerospace structural applications. Al/Li alloys have the potential of producing a 20 % improvement in strength and fatigue life, a 10–15 % reduction in density and improvements in crack and corrosion resistance as compared to current aerospace aluminium alloys (Aviation Week and Space Technology 1978).

2(*b*) *Composite casting process*

The major operations involved in the casting of Fibre FP reinforced aluminium composites are shown in table 2. Starting from the fibre, first a handleable flexible Fibre FP tape is prepared using about 5 % fugitive binder such as polyethyl acrylate. The tape is then converted into a pre-form with the fibre orientation and volume loading desired in the final product (Dhingra 1975). This pre-form is then packed into a casting mould, the fugitive binder burned off at about 600 °C and the mould vacuum infiltrated with molten metal at about 700 °C. The casting of a unidirectional 20 cm × 20 cm × 1.27 cm (8 in × 8 in × $\frac{1}{2}$ in) FP/Al plate with fibre volume loading of about 55 % using the above operations is illustrated in figure 1. The microstructure of the FP/Al composite showing complete wetting between the fibre and the matrix is shown in figure 2 (plate 1). The scanning electron micrograph of the fracture surface showing excellent fibre/matrix bonding without fibre pull-out is shown in figure 3 (plate 1).

TABLE 2. COMPOSITE FABRICATION TECHNIQUE

(i) prepare tape,
(ii) prepare pre-form,
(iii) load pre-form into mould,
(iv) burn off fugitive binder,
(v) infiltrate with molten metal.

By suitably combining fibre reinforced resin composite technology to prepare pre-forms and

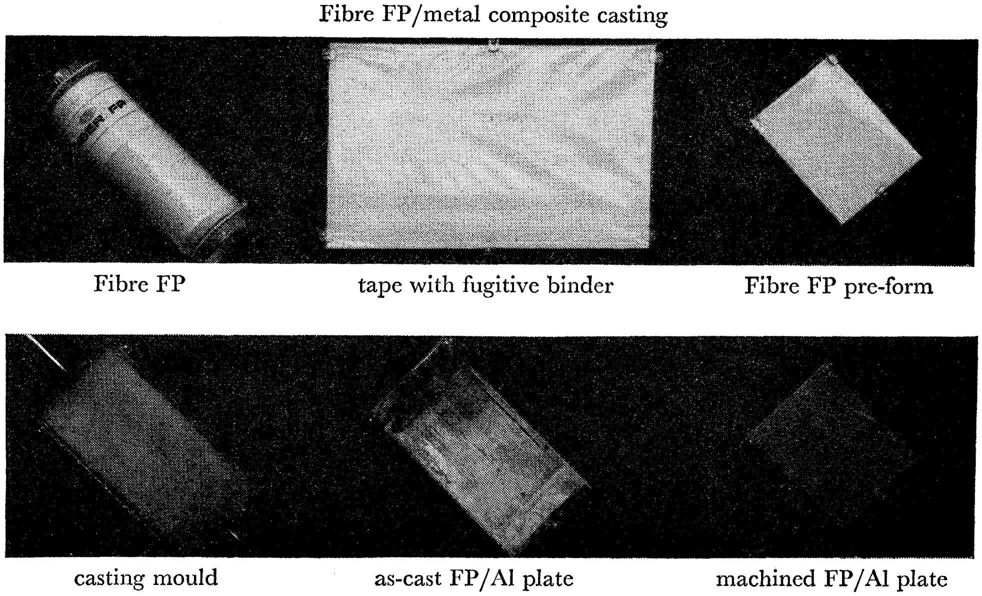

FIGURE 1

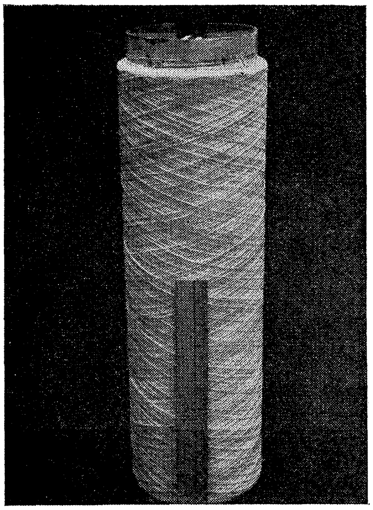

FIGURE 4

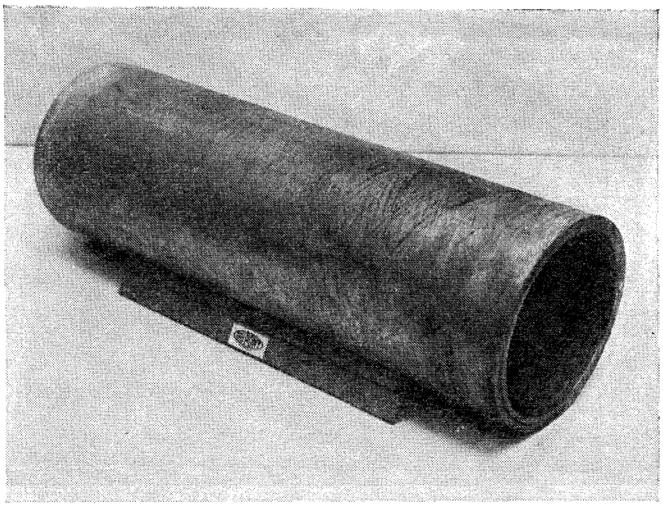

FIGURE 5

FIGURE 4. Filament wound Fibre FP pre-form for casting FP/Al hollow cylinder.

FIGURE 5. Filament wound Fibre FP/Al hollow cylinder. Fibre FP orientation: $\pm 70^\circ/0^\circ/\pm 70^\circ/0^\circ/\pm 70^\circ$.

the vacuum casting process described above, a variety of composite components such as rods, tubes, structural beams, billets, plates, thin sheets containing fibre volume loading of up to 60 % have been demonstrated. For example, figure 4 shows the Fibre FP pre-form prepared by filament winding techniques used for resin composites. This pre-form was cast into an FP/Al hollow cylinder as shown in figure 5.

2 (*c*) *Properties of* FP/Al *composites*

The coupons cut from unidirectional plates such as those shown in figure 1 were used to determine the mechanical properties of FP/Al composites. The fibre tensile strength was 1380

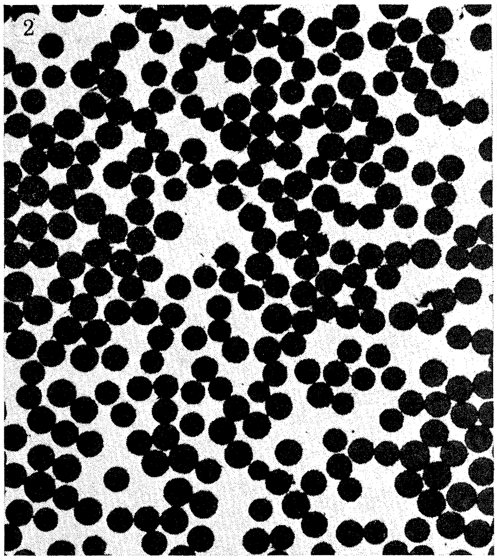

FIGURE 2. Polished cross section of FP/Al composite.

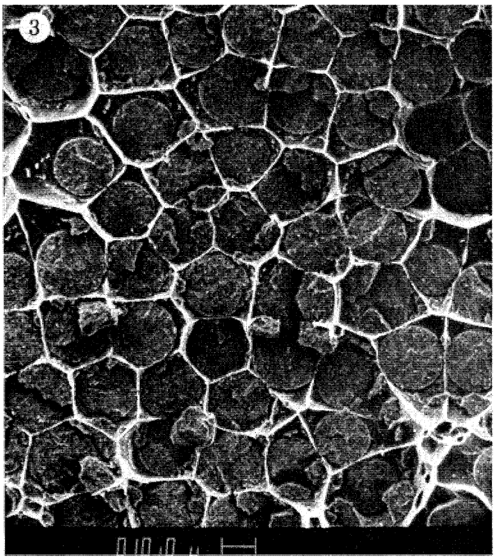

FIGURE 3. Scanning electron micrograph of FP/Al composite fracture surface.

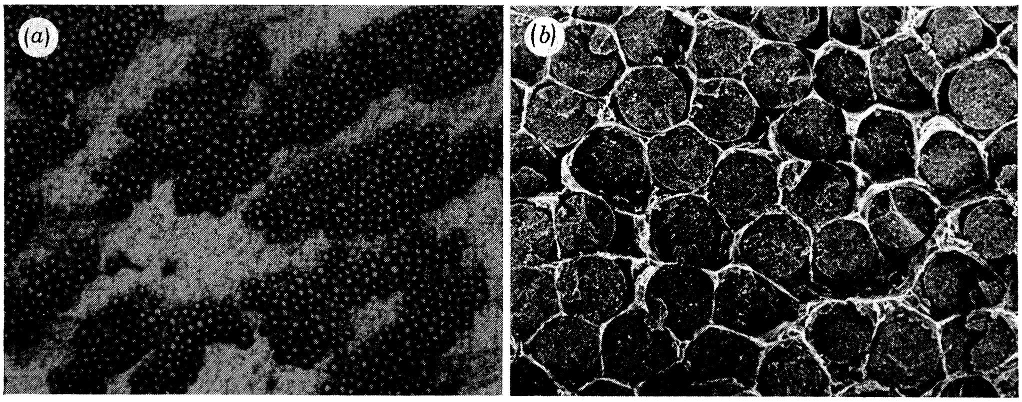

FIGURE 7. (*a*) Microstructure of FP/Mg tube (matrix commercially pure Mg). (*b*) Scanning electron micrograph of FP/Mg composite fracture surface (matrix ZE41 magnesium alloy).

MPa (2×10^5 lbf/in^2) and the alloy used was Al–2 %Li. The key properties of FP/Al composites are given in table 3. FP/Al composites containing 60 % volume loading of Fibre FP have a modulus greater than that of steel; they have very high compressive strength; they have moderate tensile strength and excellent fatigue behaviour. Fibre FP/Al composites have a use temperature twice as high as aluminium. For example, the axial properties of FP/Al composites are unchanged from room temperature to 316 °C. Composites have good corrosion resistance comparable with aircraft aluminium alloys. Since alumina is one of the hardest materials, FP/Al composites have excellent wear resistance.

Table 3. Properties of FP/Al composites

(60 % volume loading of fibre)

density/(gm cm^{-3})	3.45 (0.125 lbf/in^3)
tensile and compressive modulus/GPa	262 (38×10^6 lbf/in^2)
tensile strength/MPa	690 (100×10^3 lbf/in^2)
compressive strength/GPa	3.4 (500×10^3 lbf/in^2)
transverse modulus/GPa	152 (22×10^6 lbf/in^2)
transverse tensile strength/MPa	172–207 ($25\text{–}30 \times 10^3$ lbf/in^2)
transverse compressive strength/MPa	380 (55×10^3 lbf/in^2)
flex modulus/GPa	269 (39×10^6 lbf/in^2)
flex strength/GPa	1.03 (150×10^3 lbf/in^2)
shear strength/MPa	117 (17×10^3 lbf/in^2)

By using the Materials Science Corporation composite laminate (CLAM) computer code which incorporates the results of Hashin & Rosen (1964), the composite constituent properties were used to calculate elastic properties for a unidirectional lamina when the fibre content is 50 % by volume. The theoretical values of lamina properties are listed in table 4 along with the corresponding experimental values showing good translation of fibre properties in the composites.

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Table 4. Theoretical and experimental moduli and Poisson ratio of FP/Al composites

(50 % fibre volume loading)

property	theoretical value	experimental value
longitudinal modulus/GPa (10^6 lbf/in^2) (0° orientation)	207 (30.0)	212 (30.8)
transverse modulus/GPa (10^6 lbf/in^2) (90° orientation)	141 (20.4)	140 (20.3)
tensile modulus/GPa (10^6 lbf/in^2) (±45° orientation)	145 (21.0)	126 (18.3)
shear modulus/GPa (10^6 lbf/in^2)	54.5 (7.9)	50 (7.2)
Poisson ratios		
$\nu_{l,t}$	0.244	0.244
$\nu_{t,l}$	0.166	0.170
$\nu \pm 45°$	0.33	0.31

FP REINFORCED MAGNESIUM COMPOSITES

Commercially pure magnesium and magnesium alloys naturally wet Fibre FP, forming a strong bond at the interface. Also, Fibre FP is not degraded by molten magnesium even when in contact for prolonged periods of time. Therefore, FP/Mg composite castings can be made by the process described in 2(*b*). FP/Mg structural beams, tubes and rods up to 1.5 m (5 ft) long shown in figure 6 were fabricated by using commercially pure magnesium and magnesium alloys with fibre volume loadings of up to 65% (Dhingra 1974). The microstructure of the tube and scanning electron micrograph of the fracture surface is also shown in figure 7 (plate 1). FP/Mg composites show expected theoretical properties like FP/Al and are reported by Dhingra *et al.* 1975).

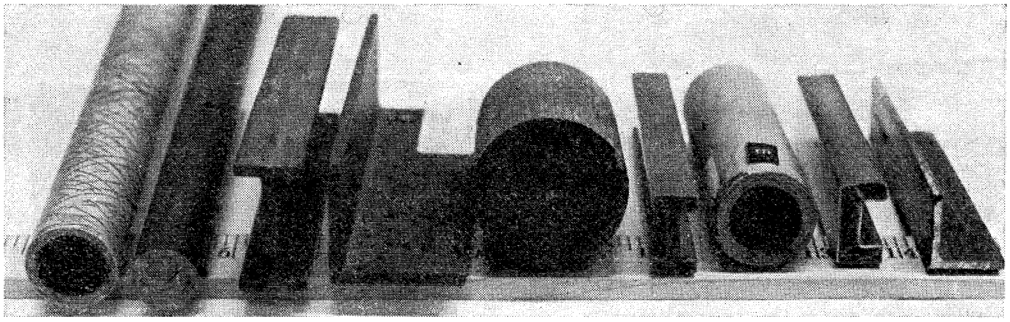

FIGURE 6. Unidirectional FP/Mg composite structural beams, tubes and rods with fibre volume loadings of up to 65%.

CONCLUDING REMARKS

Fibre FP reinforced metal matrix composite materials represent a new class of future engineering structural materials. They have potential for low cost composite fabrication based on molten metal infiltration and casting techniques. However, they are at an early stage of development and considerable effort is required in many areas of technology including fabrication, joining, machining, non-destructive testing, design and testing before these new materials become a reality.

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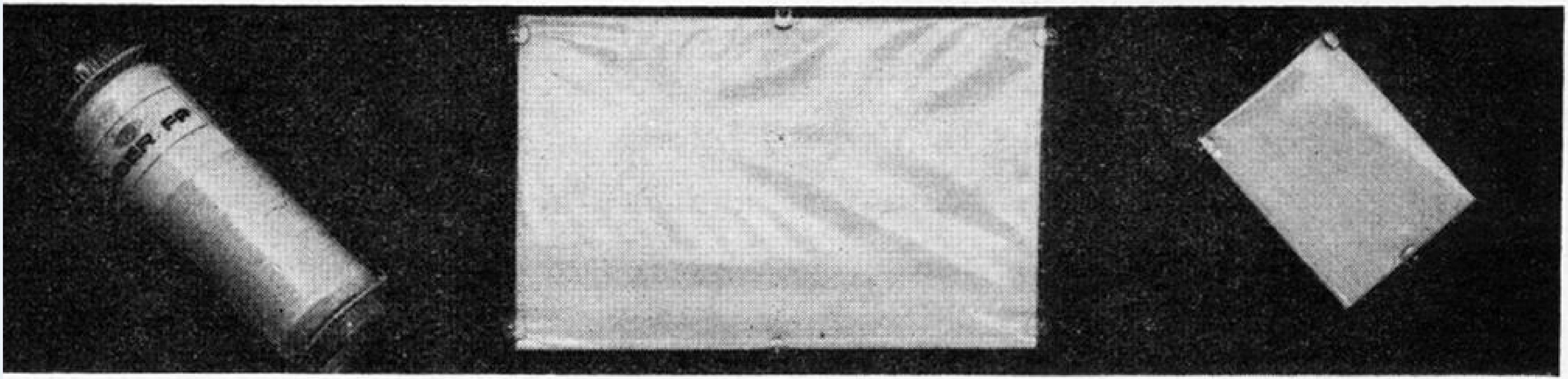
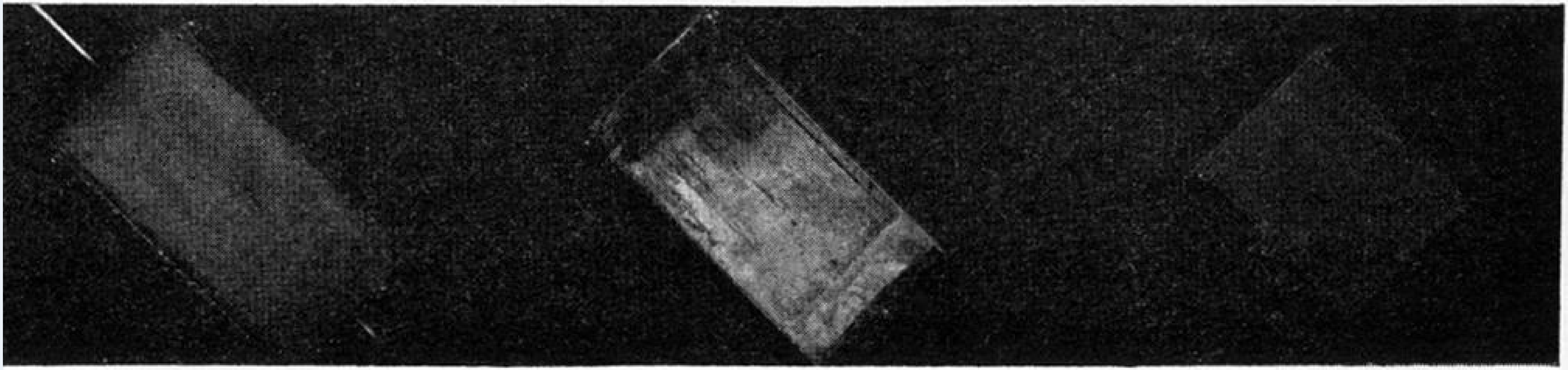
Fibre FP/metal composite casting



Fibre FP tape with fugitive binder Fibre FP pre-form



casting mould as-cast FP/Al plate machined FP/Al plate

FIGURE 1

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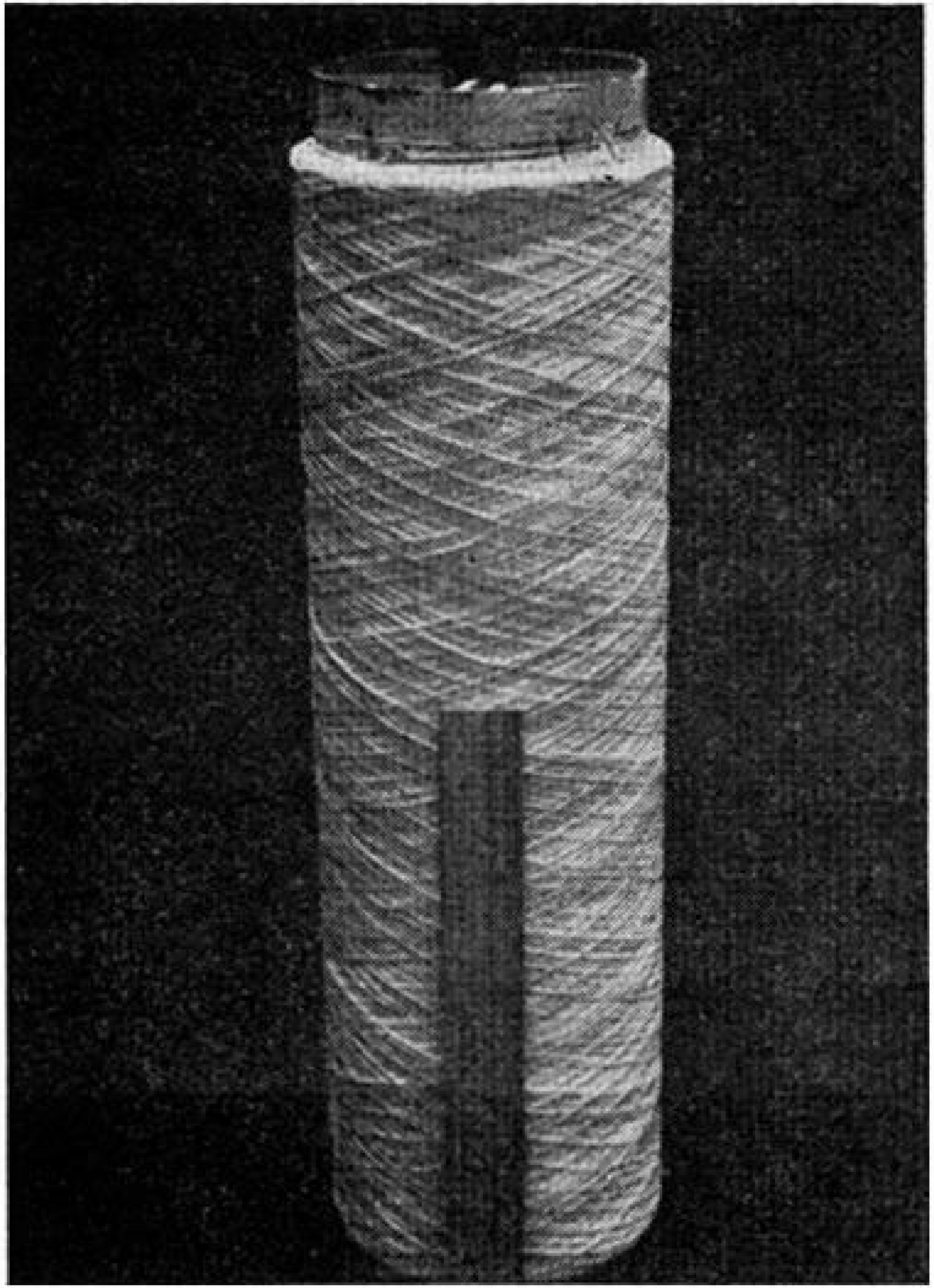

FIGURE 4. Filament wound Fibre FP pre-form for casting FP/Al hollow cylinder.

FIGURE 5. Filament wound Fibre FP/Al hollow cylinder. Fibre FP orientation: ±70°/0°/±70°/0°/±70°.

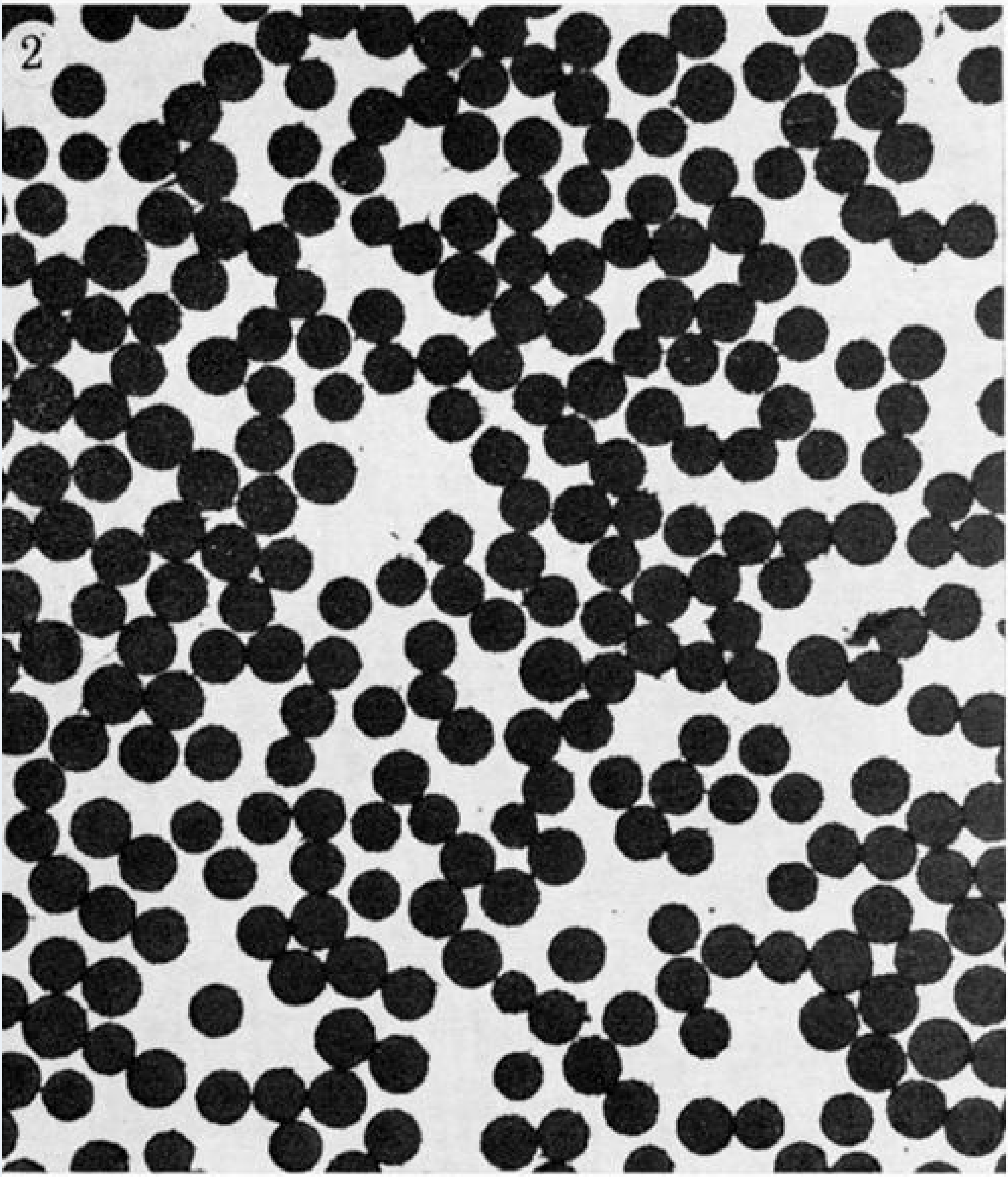

Figure 2. Polished cross section of FP/Al composite.

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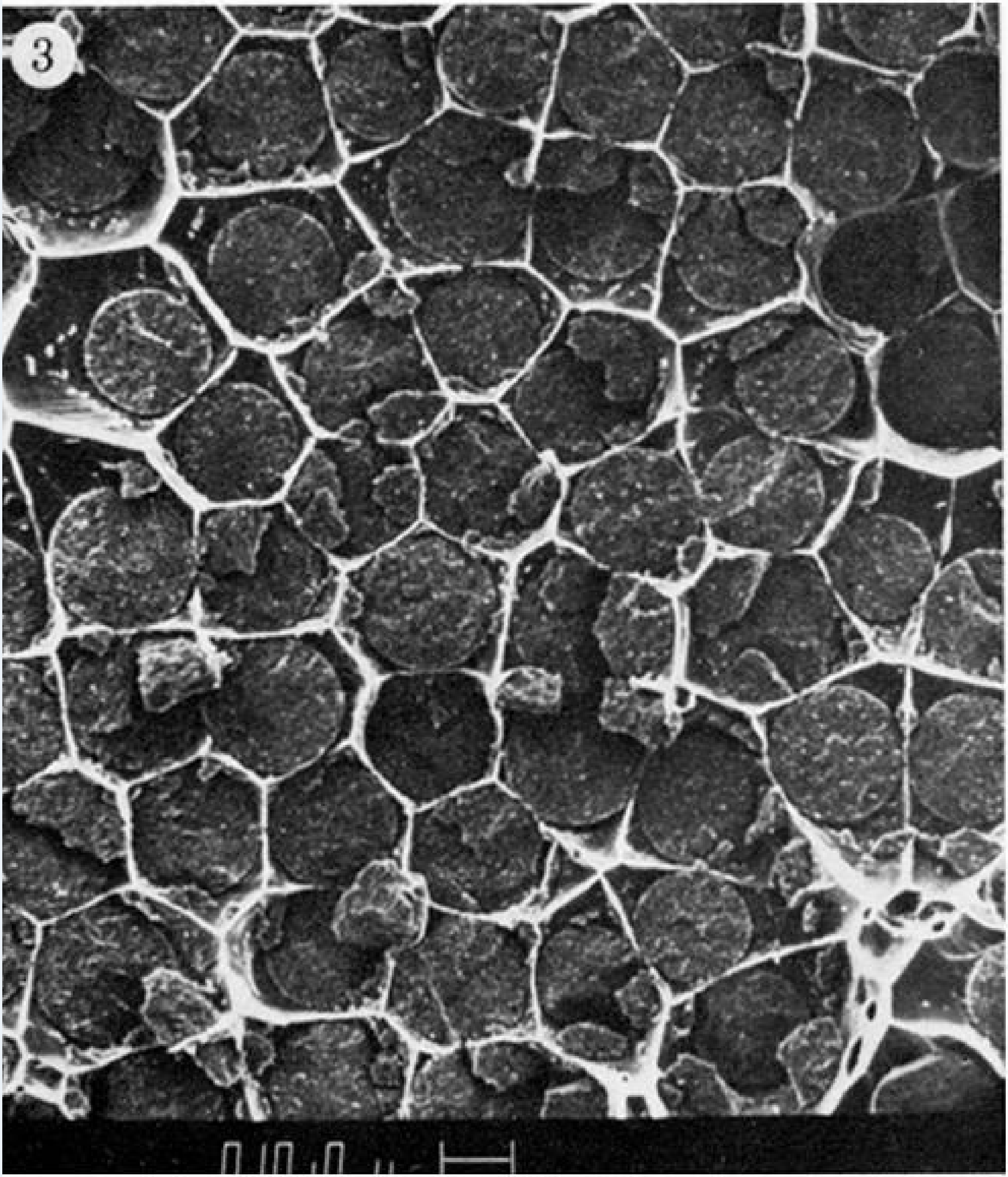

FIGURE 3. Scanning electron micrograph of FP/Al composite fracture surface.

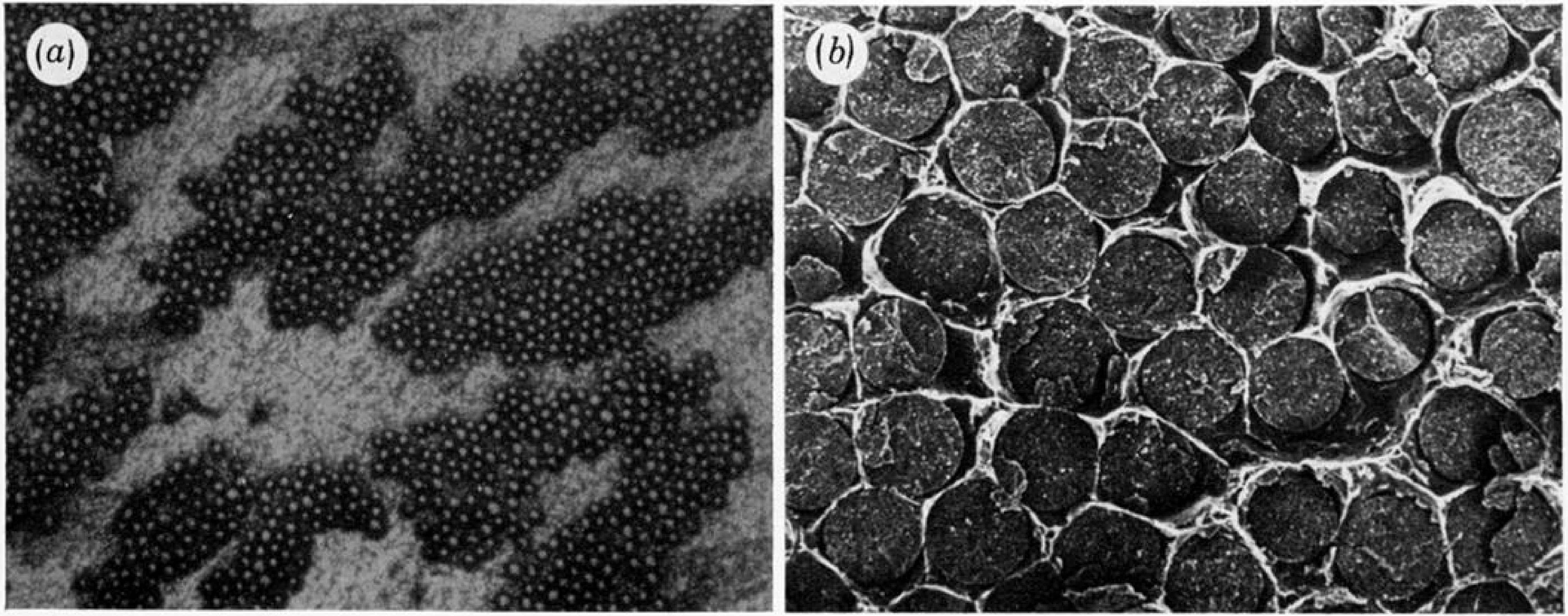

Figure 7. (*a*) Microstructure of FP/Mg tube (matrix commercially pure Mg). (*b*) Scanning electron micrograph of FP/Mg composite fracture surface (matrix ZE41 magnesium alloy).

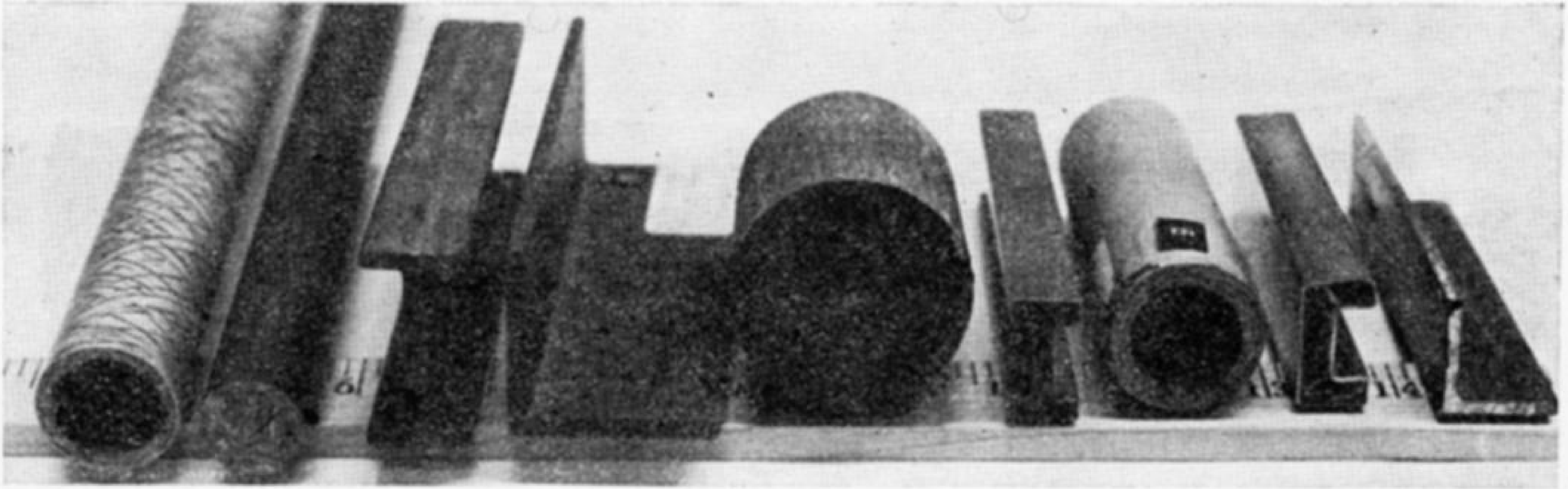

FIGURE 6. Unidirectional FP/Mg composite structural beams, tubes and rods with fibre volume loadings of up to 65 %.