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Review

Some physical defects arising in composite material fabrication

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A fairly wide range of physical defects arising during the processing of composite materials is surveyed. The kinds of composites discussed are fibre-reinforced materials, metal–matrix composites, ceramic–matrix composites and bonded sandwich (clad, rolled) materials. The list of defects considered is not exhaustive but the defect phenomena described exemplify the practical value of a knowledge of the difficulties encountered in composite material processing.

1. Introduction

The term composite pertains either to anything made up of various homogeneous parts or a material made of constituents that remain individually recognisable after assembling. Composites are usually manufactured in order to provide materials which possess mechanical properties superior to those of the individual constituents. The study and discussion of defects in metal-formed products has generally drawn very little attention from academic workers even though their economic consequences can be very great. The delightful clause of industrial customers: "the product shall be free from defects" issued to the manufacturer cannot always be taken too literally since manufacturers themselves may not always be able to obtain materials that are free from defects.

The range of material working and fabrication defectiveness embraces [1, 2]:

(i) the occurrence of defects due to interaction between the workpiece material, the tooling, the friction between the latter and the process-geometry;

(ii) some forms of metallurgical structure which result from purely mechanical action;

(iii) the limits of performance imposed by the material properties themselves with a given tooling and stressing system;

(iv) elastic spring-back and generated residual stresses.

Interaction of the above mentioned features during material processing makes it difficult to account precisely for the defects met in terms of the mechanics: certain defects are associated with particular processes whilst some defects are peculiar to some materials. As the range of defects in composite material processing is not well documented in the available literature and grouped for discussion under particular process headings, an attempt is now made to achieve this and, hopefully, it will be of value to workers in this field.

2. Fibre-reinforced plastics

To reinforce many materials and especially plastics, fibres of wool and cotton, wood, glass, carbon and metallic materials have all been widely used in this century [3]; this is particularly the case for aircraft built since 1940. Fibres may be used for reinforcement in both warp and fill directions; weaves, harness-satin and hybrid constructions of fibres are usually employed to reinforce the matrix material, see Fig. 1. Recently, fibres with an average tensile strength of 2000 MPa have been demonstrated on a laboratory scale [4, 5]. The specific strength (the ratio of strength to density) of conventional materials can be improved to a degree by suitable thermomechanical processing (see, for example, the data given in Fig. 1 of Green and Bowyer [5]), whilst a proper combination of fibre kind, weave, matrix material and manufacturing technique may lead to a composite whose specific stiffness (modulus of elasticity divided by density) and

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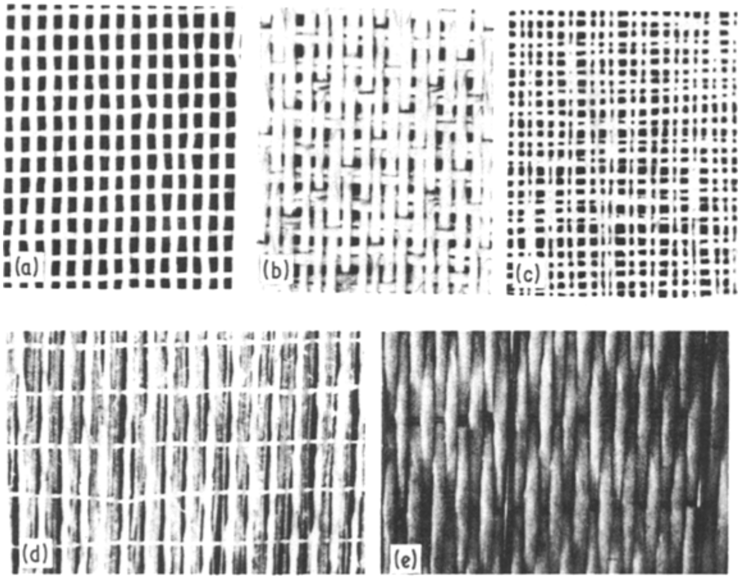


Figure 1 Examples of fabric patterns (after [24]) Fibre FP fabrics: (a) plain weave (16 × 16); (b) 8-harness satin (26 × 26); (c) 12-harness satin (30 × 30). Fibre FP hybrid fabrics: (d) FP/Kevlar; (e) FP/aluminium wire.

specific strength increases by a factor of 3 to 4 [5]. There is a vast amount of literature available about fracture and failure characteristics in relation to the mechanical strengths of fibre-reinforced plastics (FRP) as well as other types of composites; some of this information is discussed below. The manufacture and subsequent fabrication of composites governs, to a great extent, the failure characteristics of finished products and their defects.

In glass-fibre reinforced plastics (GFRP) the defects which arise in their manufacture may comprise one or more of the following [6–21]: incomplete impregnation of fibre, incomplete cure of resin, poor wetting and subsequent poor adhesion of fibre to the matrix, the presence of bubbles, voids, delaminations, broken strands, loose ends of fibres, knotted strands, wrinkled strands and crevices, crazing cracks and local resin-rich areas. Since these defects evidence themselves differently at different load levels, the forming and fabrication (which involves the gradual increase of load until the desired shape and size of product is obtained) of GFRPs does not produce wholly sound parts; additionally, in-service performance of these parts may be poor since the defects are potential failure initiators. Furthermore, forming operations may introduce concealed cuts and the rupture of resin starved layers. Bending (and also impact loading) may introduce severe delamination in GFRP composites even when the operation is carried out on the material after sandwiching it between two metallic sheets, see Fig. 2. Delamination is enhanced especially when interply or interlaminar porosity occurs, as shown in Fig. 3. The latter, in conjunction with bonding voids and trapped foreign substances, reduces interlaminar shear strength and may give rise to edge delamination. In general, the more forming and fabrication flaws enlarge, the greater is the severity of the initial defect. Since forming and fabrication involves forces of either a tensile, compressive or torsional nature, either separately or combined, the mechanical testing of composites is usually carried out for all three types of loading. Typical examples of such tests are shown in Fig. 4a to c. Tensile failures show fibre pull-out and fibre–matrix debonding. Compressive loading shows failure by splitting and buckling; compressive and flexural strengths are most affected by transverse cracks whilst splitting is detrimental to shear strength. Piercing and penetration, both static and dynamic, of carbon fibre-reinforced composite (CFRP) and other fibre-reinforced composites show failure by transverse cracking of the fibres and by parallel splitting of the laminates, see, for example, the photographs [9] of the specimens shown in Fig. 5a to c. For low-velocity impact, damage lies between two extremes [9, 11]; delamination is predominant for components of low span-to-depth ratio and low interfacial bond strength whilst for high span-to-depth ratio and high interfacial bond strength, the damage is mainly due to translaminar cracking perpendicular to the fibres. High-velocity impact may give rise to spalling on the back face of a test

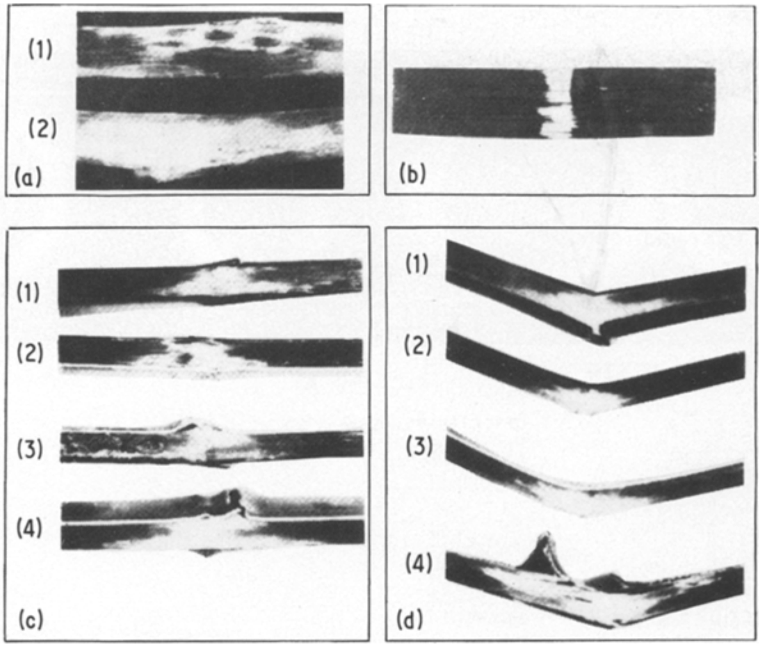


Figure 2 (a) Fracture of R-GFRP (1) and M-GFRP (2) under repeated impact load, (b) fracture of CFRP under repeated impact load, (c) fracture of the hybrid composites belonging to R-GFRP under repeated impact load, (1) CF-R-CF, (2) CF-R-Al, (3) Al-R-CF, (4) Al-R-Al and (d) fracture of the hybrid composites belonging to M-GFRP under repeated impact load, (1) CF-M-CF, (2) CF-M-Al, (3) Al-M-CF, (4) Al-M-Al (after [16]).

sheet. (Spalling and delamination at low incident energies support the view that layers act relatively independently compared with the interactions of layers in the formation of damage zones.) The punching of holes and the impact of steel balls against these composites at high incident velocities are also associated with spalling [11]. The plugging of a disc of material and the peeling of strips at the weak interface between laminae has also been observed after examining the damage to fibre-reinforced composites resulting from impinging foreign objects. Recent work on stress-wave and spallation damage in graphite/epoxy laminates has been conducted by Roylance [22] and Davies [23].

In addition to the conventional metal wires, glass strands and carbon fibres, whiskers of high-purity and single-crystal materials are often used to reinforce both metallic and non-metallic matrix materials. In general, when an ideal interface between a whisker and matrix can be obtained, the strength of the whisker in a composite may be higher than in air alone. Any defect present in the whisker would act as a "stress raiser" during fabrication and could precipitate fracture. Okuno and Miura [20] reported the effect of stress concentration due to various surface flaws in ceramic Al_2O_3 and SiC whiskers; these defects, illustrated in Figs 6a to e and 7a to e, respectively, are called step, hole, ripple, branch and fissure.

Although it is beyond the scope of the present discussion, defective materials, in the sense of creating possible health hazards during the manufacture of fibre-reinforced composites, should be noted. These hazards are of two main kinds: allergy to, and inhalation of, fibre dust.

3. Metal–matrix composites

Although the uses of both metallic and non-metallic fibre-reinforced resins and other polymers have been extensive for application at "high" temperatures (up to about 500° C) and loads, matrix materials are being increasingly altered from epoxy to include metals such as aluminium, titanium, molybdenum, cobalt and nickel and their alloys. The latter materials constitute a class of their own called metal–matrix composites. Aircraft engine inlet structures, turbine and aerospace components are some of the applications where these composites are superior to their conventional (metallic material) counterparts. Metal–matrix composites are given their required shape by diffusion bonding, brazing, powder metallurgy techniques, casting, metal spraying and by forming operations such as extrusion, drawing, swaging and bending. A review of the literature on this topic reveals that there are formidable difficulties in encapsulating whiskers and fibres in a metallic matrix; some of these are due to incompatibility of the fibre and the matrix,

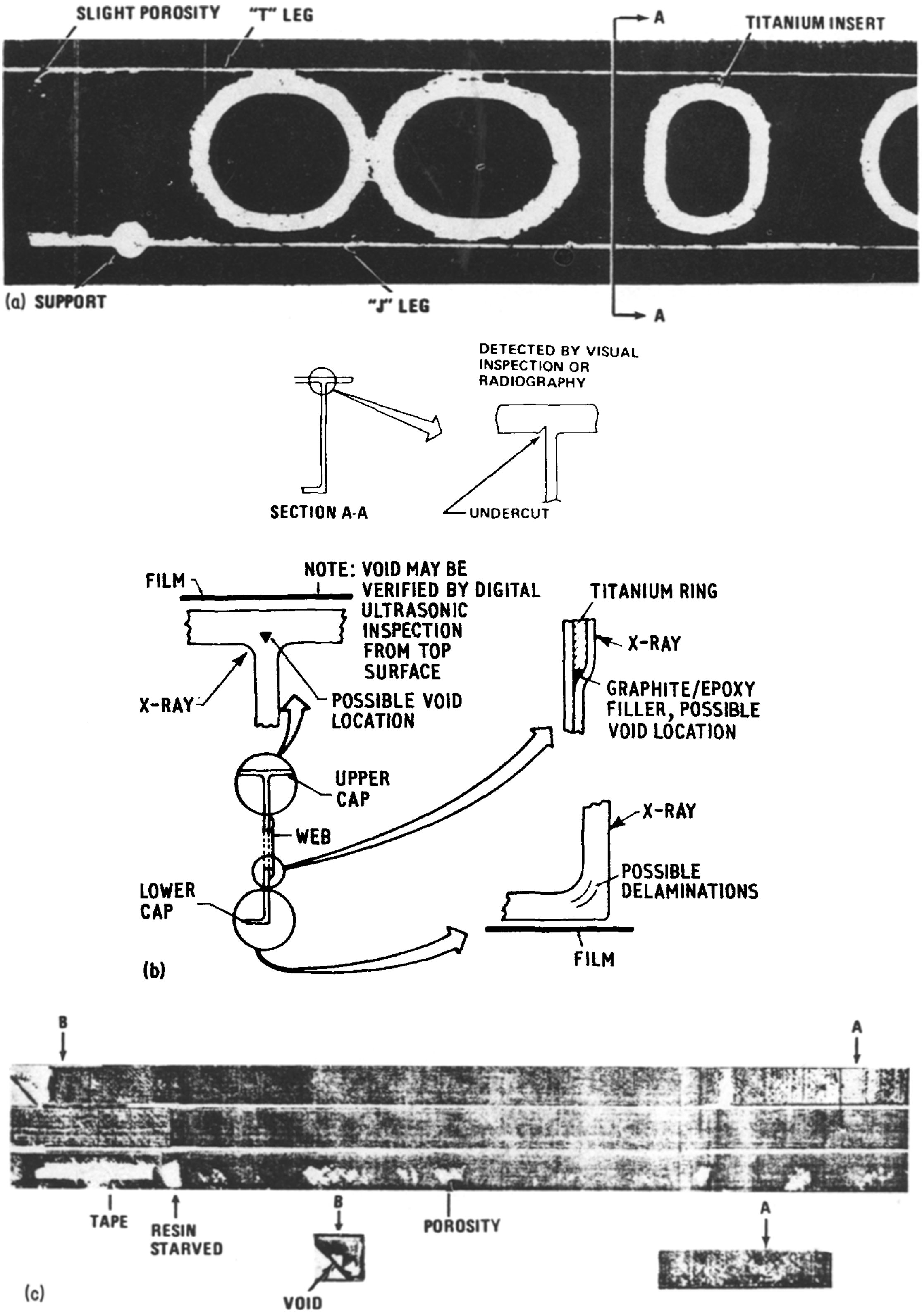
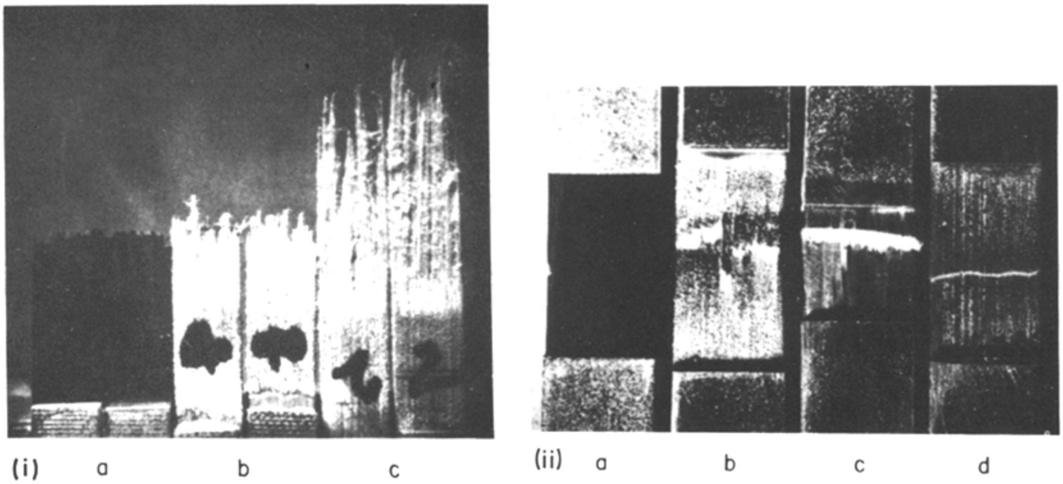


Figure 3 (a) Ultrasonic C-scan recording of DC-10 composite floor beam web, (b) radiographic inspection of DC-10 composite floor beam and (c) ultrasonic C-scan recordings of graphite/epoxy composite floor beam struts (after [8]).



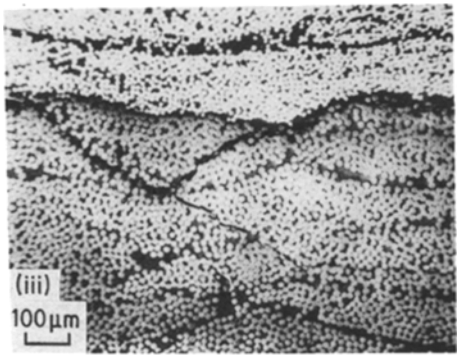


Figure 4 (i) Tensile failures in unidirectional fibre/epoxy composites, (a) in CFRP, (b) one layer KRP(Kevlar-49 reinforced plastic)/four layers CFRP/one layer KRP and (c) all KRP. (ii) Compression failures in unidirectional fibre/epoxy composites, (a) all CFRP, (b) one layer KRP/four layers CFRP/one layer KRP, (c) two layers KRP/eight layers CFRP/two layers KRP and (d) all KRP. (iii) Shear failures in a unidirectional KRP/CFRP/KRP composite (after [9]).

poor wettability, reaction between the fibre and the matrix and inadequate percolation of the matrix material to properly surround the fibres; the latter results in a lack of proper bonding, see Fig. 8. To promote wetting, matrix materials are modified by additions of small amounts of such active metals as lithium, calcium and magnesium [24]. Differential thermal shrinkage between fibres or filaments and the matrix, filament–filament contact and abrupt bending may give rise to highly localized stresses that cause filament breakage and splitting, see, for example, Fig. 8d. Non-parallel plies cannot be stacked to allow any degree of interply filament nesting. The presence of voids and non-uniform filament spacings results in a non-uniform stress distribution through the cross-section of the composite when it is being formed. Voids pores and matrix–filament debonding defects act as a group of voids and thus lower the apparent strength of a composite to a value less than that of an unreinforced matrix metal. Manufacturing incompatibilities giving rise to porosity and poor spacing [25] of filmantes are shown for three alloys in Fig. 9. Filament degradation (and also matrix degradation) may arise from both elastic strain and physical property incompatibility and is also due to the effects of thermal processing. Fig. 10 shows the simultaneous fracture of boride and boron filaments in a titanium matrix into short lengths; such filament break-up gives rise to inadequate matrix reinforcement [26].

Kandeil *et al.* [27] report on the forging of thorium-coated tungsten wires embedded in a fine-grain, nickel-based superalloy composite. (This fine-grain alloy matrix flows superplastically at about 1000° C for strain rates below 10^{-3} sec^{-1}.) It is also reported that substantial defects could easily occur during forging; the damage usually starts by void formation at the poles of fibres normal to the direction of loading; transmatrix cracks later propagate along lines of maximum shear stress and decohesion at a matrix–fibre interface at small strains also limits formability of this composite, see Fig. 11.

One defect which invariably arises in a compressive forming operation on both metal–matrix and polymer–matrix fibre-reinforced composites, is brooming or crushing of the ends of components [28, 29]. This defect is exemplified in Fig. 12a to c taken from a study of the energy absorption capabilities of composite tubes [30]. To prevent

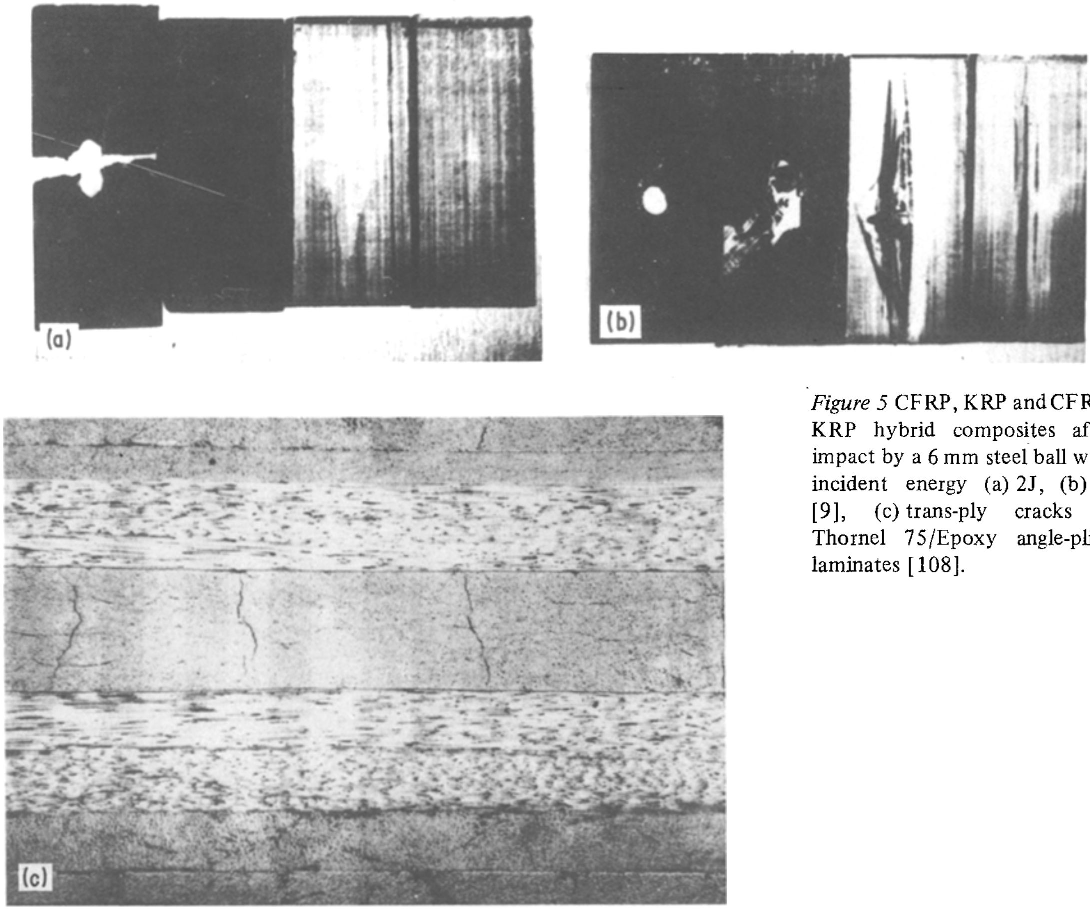


Figure 5 CFRP, KRP and CFRP/KRP hybrid composites after impact by a 6 mm steel ball with incident energy (a) 2J, (b) 8J [9], (c) trans-ply cracks in Thornel 75/Epoxy angle-plied laminates [108].

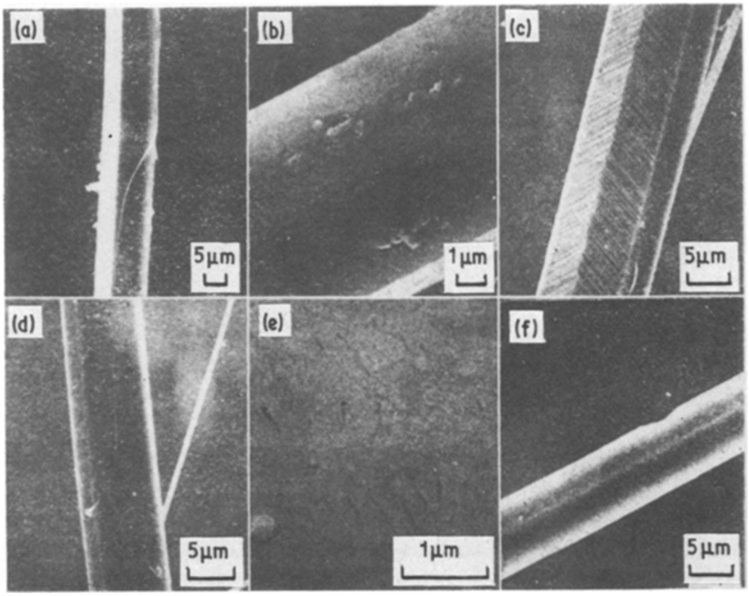


Figure 6 Surface flaws of α-Al_2O_3 whiskers [20] (a) step, (b) hole, (c) ripple, (d) branch, (e) fissure and (f) crack.

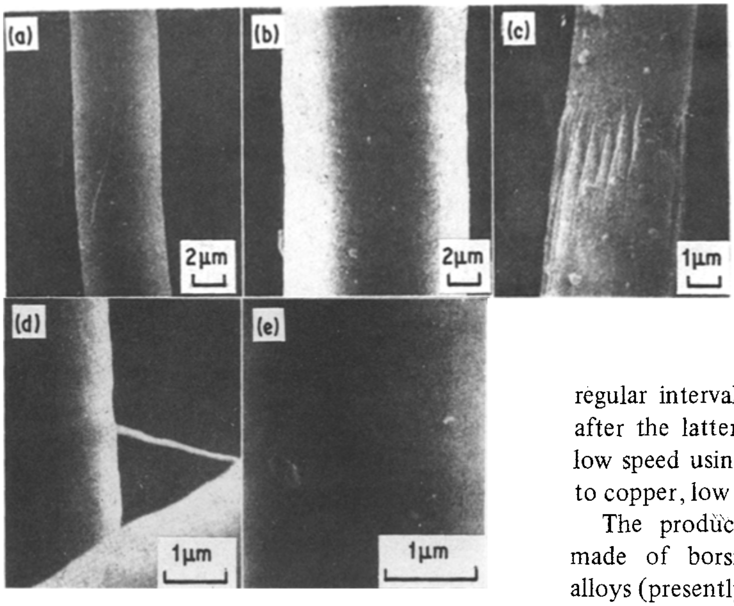


Figure 7 Surface flaws of β-SiC whiskers [20] (a) step, (b) hole, (c) ripple, (d) branch and (e) fissure.

such extensive fibre separation, "potting" of the components is usually performed. (Potting may be done with a room-temperature epoxy compound to facilitate the machining of component ends so that they are flat, parallel and perpendicular to the face sheet; the potting is left on the component to prevent crushing of the component ends, thus hindering a premature failure.)

The influence of brittle interface layers in metal–matrix composites, has been thoroughly investigated and reported [31, 32]; these studies show, generally, that ultimate tensile strength is increased if the thickness of an interface layer is greater than a certain critical amount. Well-developed intermetallic interface layers, however, lead to brittle fracture in the reinforcing wires of fibres, known as the corn-cob type of structure [32].

Structural components such as rods, billets, tubes, beams and channels may suffer from two additional defects which are metallurgical in origin. They are attributed to: (i) the depletion of some matrix constituent during the formation of the fibre–matrix bond which lessens the amount of intermetallic phase in the final composite [24]; and (ii) the local build-up of elements due to their uneven distribution in different zones but with enhanced diffusion along grain boundaries [33–46].

Crampton [47] has recently describe the so-called bamboo shape defects which can arise at regular intervals in both the coating and the wire after the latter has been drawn through a die at low speed using a polymer melt as a lubricant coat to copper, low C-steel and stainless steel.

The production of closed geometrical shapes made of borsic filament reinforced aluminium alloys (presently, widely employed in the aerospace industry) reveals that powder compaction by the radial densification technique almost invariably causes filaments to break; axial densification, however, prevents filament breakage since it does not involve excessive radial fibre movement during pressing [48]. Even when great care is taken during densification it does not always prevent the occurrence of such defects as density gradients, delaminations and filament buckles; an example of the latter defect is shown in Fig. 13. The bending, curling and folding of filaments due to the constraint of a surrounding medium makes the situation too complex at this stage to be worth discussing the flow characteristics of these composites. The above features, together with the development of a ribbon-like shape and some flattening of the ribbons, have been shown very clearly by scanning electron micrographs for *in situ* formed Cu–Nb multi-filamentary composites; these are shown in Fig. 14 a to c.

In the drawing of bars, rods or wires of metal–matrix composites, the breakage of some continuous fibres or filaments may occur at natural points of weakness [49]; the form of loading in the die region forces the matrix material to flow into voids and debonded areas created by the discontinuous fibre segments, and these thus effectively "heal" defects which may arise during forming. Since drawing action loads the uniaxial reinforcement in axial tension, i.e. along the direction of maximum strength, minimum fibre and interface damage is thus believed to occur; high compressive surface stresses balance internally

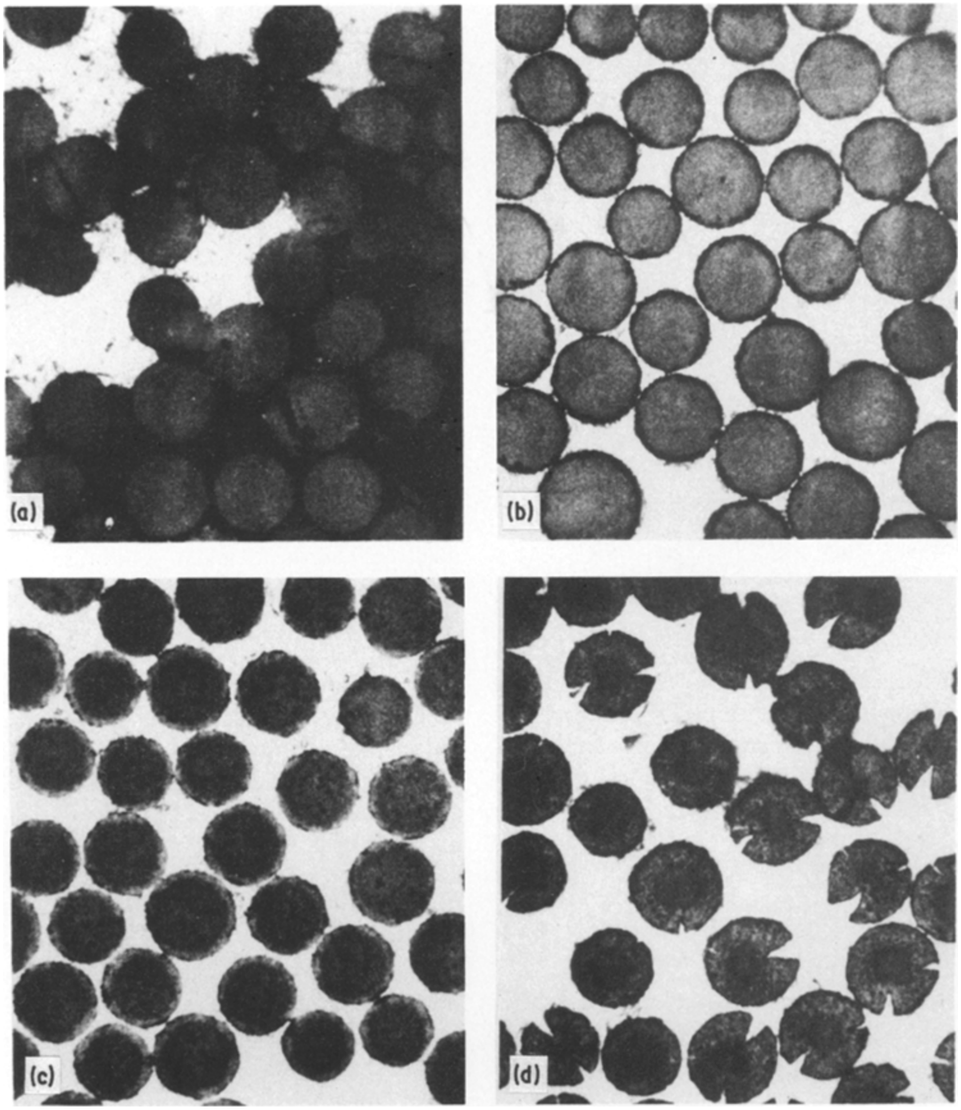


Figure 8 Reaction of molten aluminium–lithium alloy with fibre FP [24] (× 600) (a) poor infiltration resulting from insufficient time, temperature, or lithium concentration, (b) excellent wetting with minimal fibre/matrix reaction, (c) excessive fibre/matrix reaction. Reduced composite properties will result, and (d) fibre degradation and splitting.

generated tensile stresses, resulting in a state of nearly homogeneous deformation, see Fig. 15.

The forming of a metal–matrix composite shapes by extrusion and rolling is not very successful as is evidenced by the severe transverse cracking, the very rough "tree-bark" surface finish, and the delamination defects of glass fibre reinforced aluminium composites, see Fig. 16a to c [50, 51]. In the case of the hot extrusion of B_2O_3–SiO_2 glass reinforced aluminium alloy composites, it has been observed [50] that a high proportion of the B_2O_3 tends to burst on emerging from the extrusion die-throat because the matrix material is too weak to contain the sudden expansion of the glass. With an increased B_2O_3 content ($>$ 14%), the extruded rods have been seen "to split into bundles of metal-coated fibres" [50]. In addition, microcracks surrounding the fibres and voids between the matrix and the fibres were obtained. Internal tensile loading may also give rise to multiple necks in the fibres as reported [52] for molybdenum/copper/nickel matrix materials.

The causes and nature of fibre rupture during rolling and cold extrusion have recently been

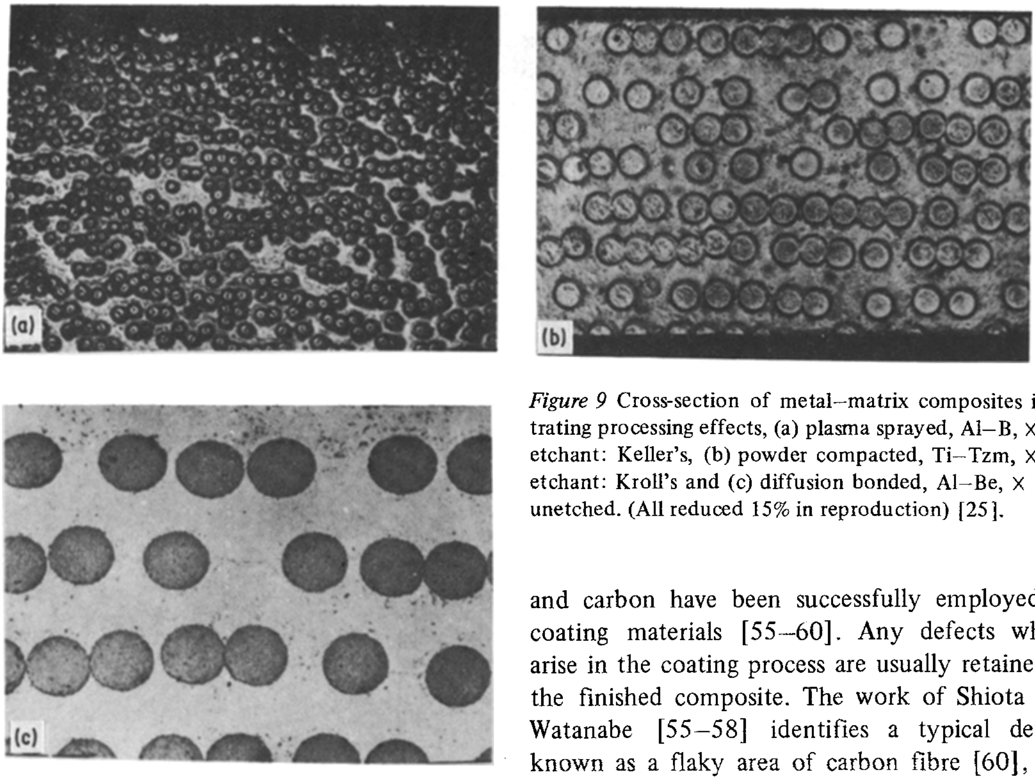


Figure 9 Cross-section of metal–matrix composites illustrating processing effects, (a) plasma sprayed, Al–B, × 20, etchant: Keller's, (b) powder compacted, Ti–Tzm, × 20, etchant: Kroll's and (c) diffusion bonded, Al–Be, × 100, unetched. (All reduced 15% in reproduction) [25].

studied [53, 54]; the principal cause of fibre failure is identified as multiple necking occurring within a certain range of working pressures.

In order to produce metal–matrix composites, the fibres employed as reinforcements are generally coated with a metal which is used as matrix or an intermediate metallurgical phase. Depending on the fibre-coating combination, one of several methods may be employed, e.g. electrolytical, chemical, vapourizing deposition or chemical decomposition at high temperature. Copper, nickel and carbon have been successfully employed as coating materials [55–60]. Any defects which arise in the coating process are usually retained in the finished composite. The work of Shiota and Watanabe [55–58] identifies a typical defect known as a flaky area of carbon fibre [60], and this is found inside the coating metal; graphitized carbon fibre is considerably weaker than the original fibre and fractures readily when the forming and fabrication involves bending. An example of a flaky area of carbon is shown in Fig. 17.

Additional information on metal–matrix composites relating to their manufacture, testing, mechanical properties and application may be obtained from [33–46, 52, 61–78].

4. Sandwich, clad/bonded materials

For large-area structural purposes, bonded sandwich

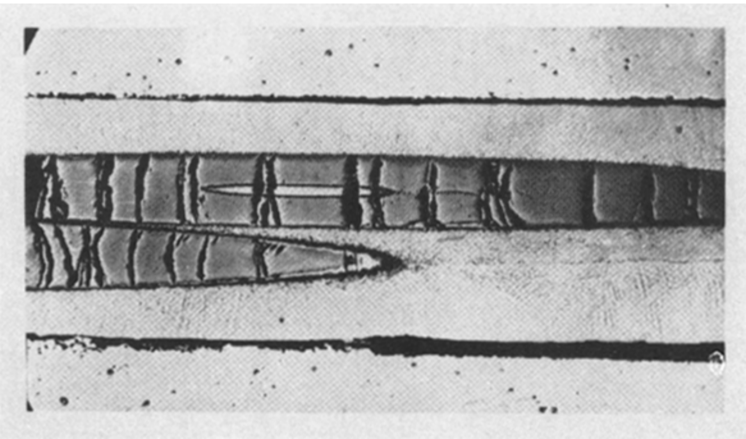


Figure 10 Break-up of boron filaments into ineffective lengths induced by boride fracture [26].

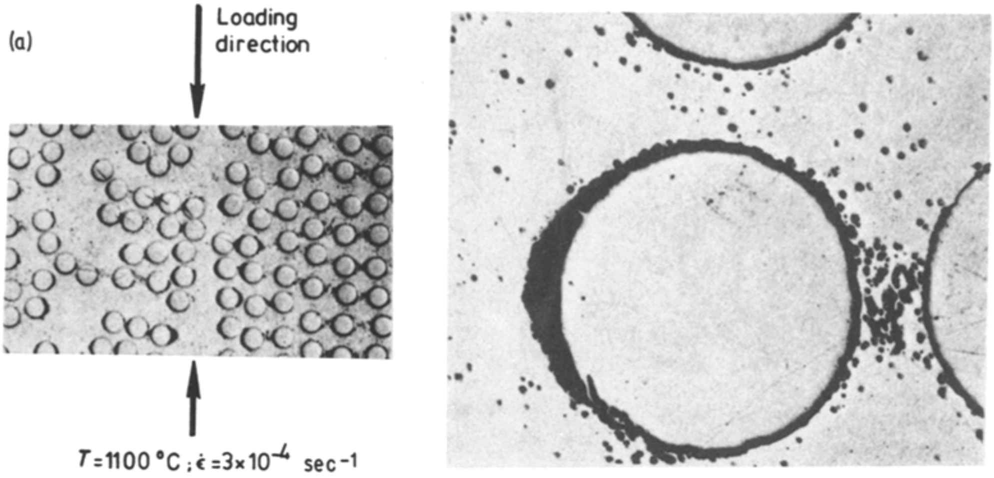


Figure 11 Transverse section through a composite blank deformed by 10% at 3×10^{-4} sec^{-1} and 1100° C. (a) × 3.5; (b) × 70 [27].

materials are extensively used in the form of various types of honeycomb and corrugated cores (see Figs 18 and 19) sandwiched between two thin metallic sheet facings; the latter are generally made from aluminium alloys, low carbon steels and, for high strength applications, from magnesium, titanium and beryllium alloys, If, however, electrical and thermal insulating properties are called for, fibre-reinforced plastics, or plastic or plywood facings are used. The production of cores is usually achieved by roll-bending flat sheets between grooved discs. For the fabrication of cores and facings either adhesive bonding or brazing or welding techniques are employed [4]. The most common defects in the fabrication of sandwich materials are bond-breakage resulting from poor flexibility, the warping of the sandwich especially at high temperatures and edge-delamination.

Sandwich materials made up of bi- and tri-layer flat metallic sheets are also employed extensively. Casting, hot rolling, sintering, deposition and explosive welding techniques are some of the basic methods used to fabricate the multi-layer

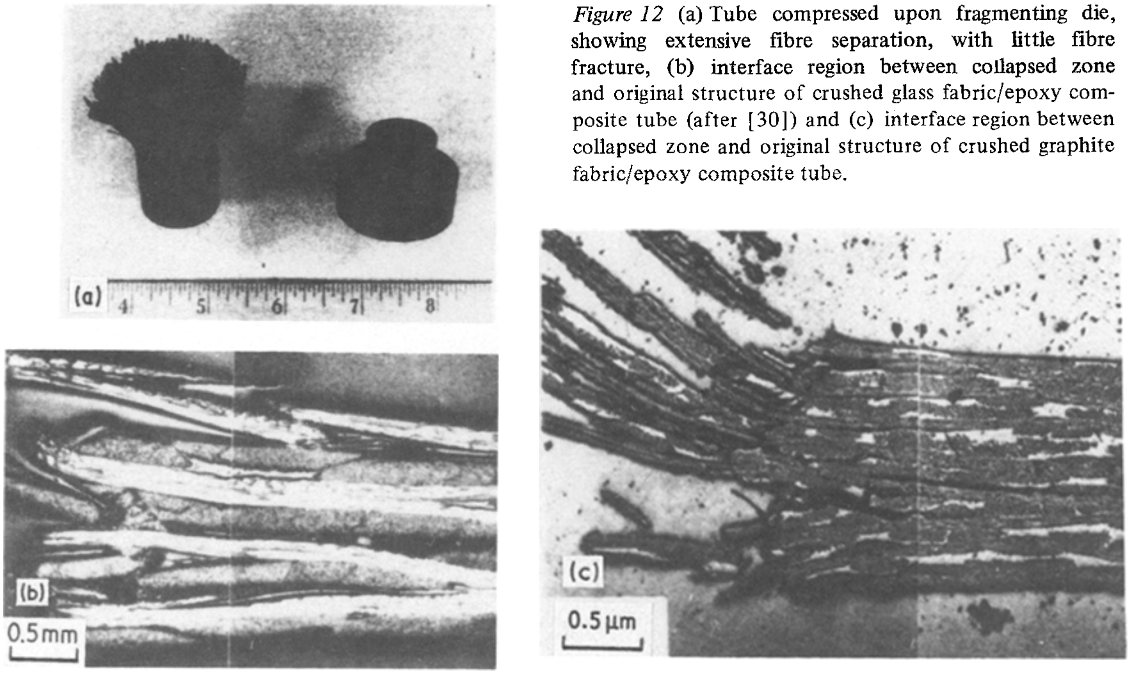


Figure 12 (a) Tube compressed upon fragmenting die, showing extensive fibre separation, with little fibre fracture, (b) interface region between collapsed zone and original structure of crushed glass fabric/epoxy composite tube (after [30]) and (c) interface region between collapsed zone and original structure of crushed graphite fabric/epoxy composite tube.

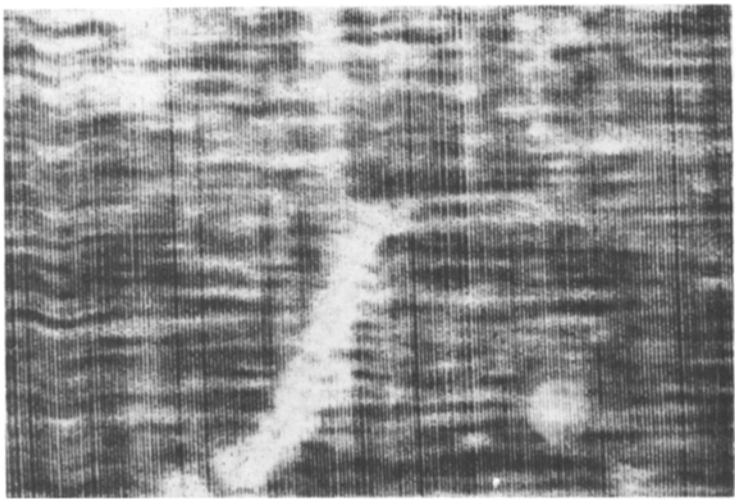
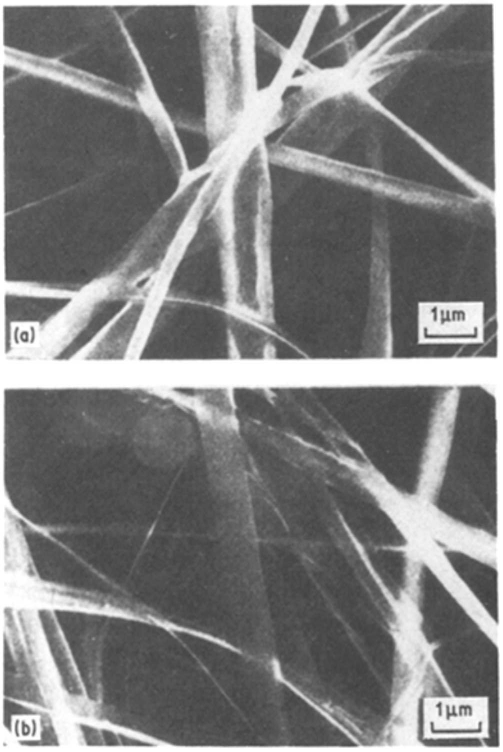


Figure 13 A C-scan trace revealing a buckling defect on the inner surface [48] of a Borsic–Al cylinder.

combination of either similar or dissimilar metals. Poor bonding may result from endeavouring to bond by hot rolling oxidized layers or dirt films onto surfaces. In the case of cladding by using high detonation explosives [78, 80], the destruction of the flyer plate may occur when the latter is too thin or brittle, the angle between the base plate and the flyer inaccurately set or when an inadequate buffer layer is introduced. An improper impedance matching of the bonded materials and the anvil may produce bond-breakage due to reflected tensile shock waves. Conventional forming operations applied to both hot-rolled and explosively cladded sandwich materials may also give rise to the breaking of bonds.

> "In general the strength of the bond depends on the cleanness of the two surfaces, the amount of reduction in the bonding pass (usually of the order of about 40–50%) and the temperature of the bonding pass. When attempts are made to bond two metals that are sufficiently ductile but which have widely different flow strengths and rates of work hardening, limits are imposed on the amount of deformation by the onset of plastic instability in the stronger component" [81];

see also Fig. 1 of Wilson *et al.* [81], which illustrates strain concentration due to localized cooperative shearing followed by necking of stainless steel in aluminium–steel laminates.



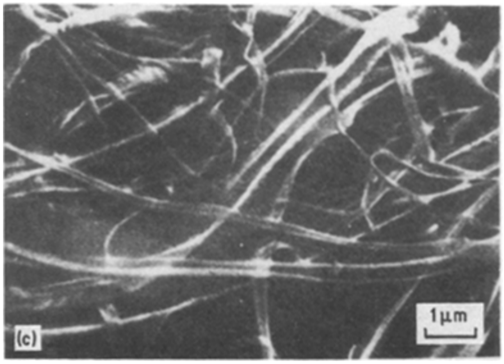


Figure 14 Sequence of changes in filament shape and dimensions for Cu–18.2 vol% Nb composite drawn to (a) 0.51 mm, (b) 0.25 mm, and (c) 0.13 mm, as revealed by scanning electron microscopy [107].

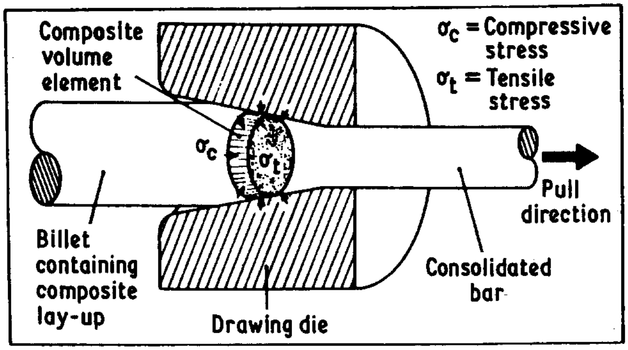


Figure 15 Schematic illustration of drawing forces acting during consolidation of a uniaxial reinforced metal–matrix bar [49].

One particular sandwich material which is widely used in structures (architectural applications) is lead-clad steel produced by the roll-bonding technique [82]. Lead-clad steel is formed by bending, roll-forming, lock-forming, break-pressing and deep-drawing operations. Thinning of the lead coating inevitably occurs at the outer surface of a bend but this is said to be of little practical significance, see Fig. 20. When forming to bends of small radius, interfacial slip may produce delamination or bowing. In addition, the folding sequences are important in reducing the risk of delamination, see the examples in Fig. 21

The defects commonly encountered in the deep-drawing of conventional materials, i.e. wrinkling, earing and wall fracture [1, 2] are also found in deep-drawn components of clad/sandwich materials; the same applies concerning surface defects due to abrasive wear [83, 84]. However, the difference in the drawing-in of different layers, see Fig. 22, and the tendency of individual skins

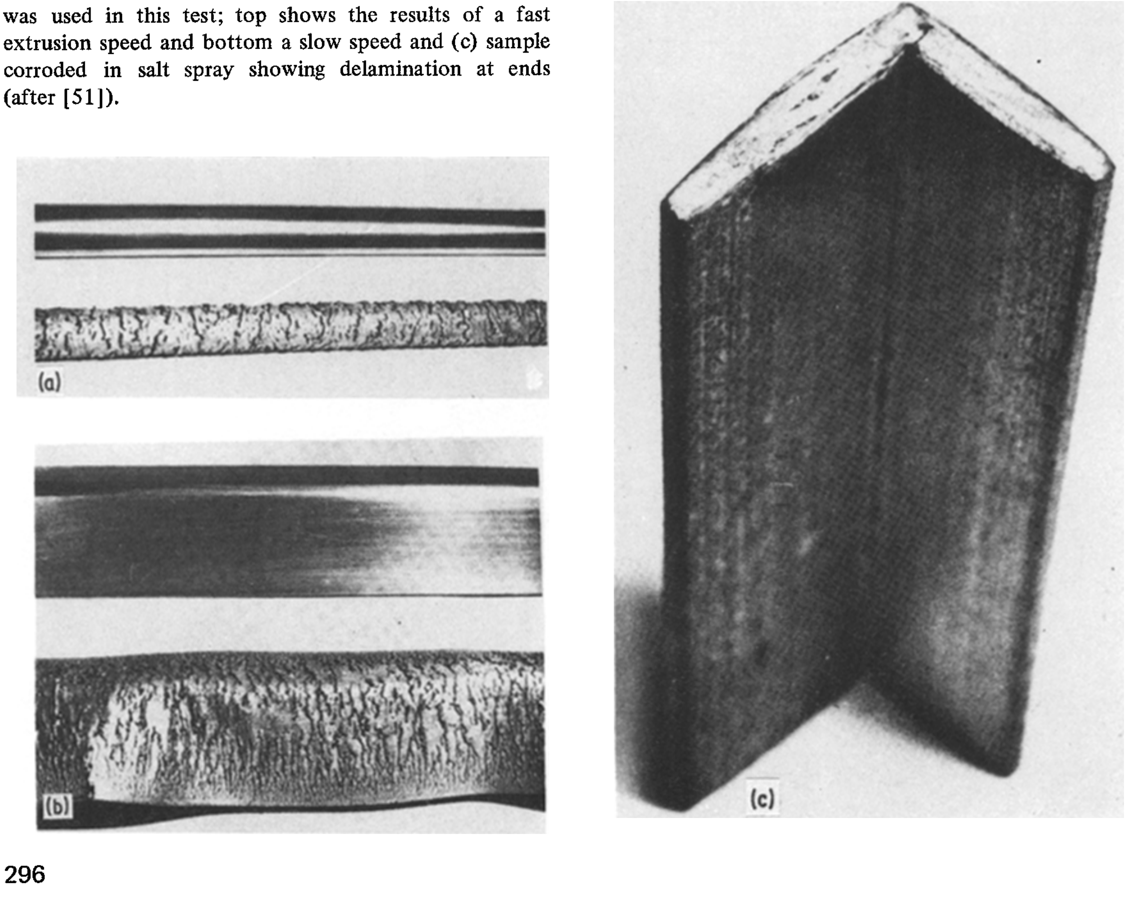


Figure 16 (a) Extruded rods; top shows a rod from a test (slow extrusion speed and coating of HE30 alloy), and bottom shows the rod from a test (slow extrusion speed but no coating), (b) an extruded angle section, no coating was used in this test; top shows the results of a fast extrusion speed and bottom a slow speed and (c) sample corroded in salt spray showing delamination at ends (after [51]).

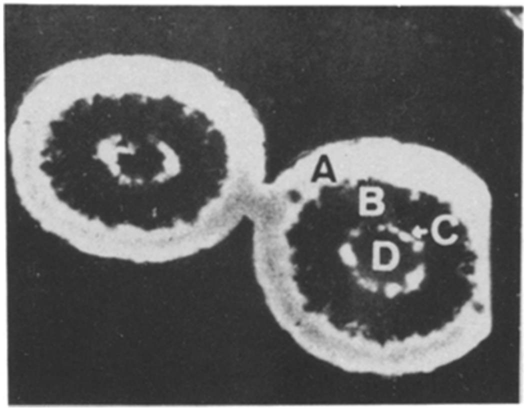


Figure 17 Scanning electron micrograph of carbon fibre coated with nickel (800° C, 4 h) (X 4100) A: nickel layer, B: flaky area of carbon, C: white ring, D: intact area of carbon [57].

to flow independently into the tooling during pressing operations, increases the tendency to wrinkling. Increased blank holder pressure and the application of the thinnest possible layer of bonding material [85], have been recommended in order to achieve better deep-drawability and generally to avoid defects, see Fig. 23. Sandwich-type steels, because of their sound attenuation property, are being used today as sound-deadening materials in press-shops, in the automobile industry and on airports; the use arises from increasingly stringent social demands for the control of environmental noise, [82, 85–91].

5. Coated materials

A coating is employed to modify the surface properties (e.g. corrosion resistance and wear resistance) of a product as a whole and together with the base metal should be considered as one item with its own particular properties of coating material. The range of composites on a metal substrate may include metallic and organic coatings; for example, steels may be galvanized, tin-plated, terne-plated (with lead), enamelled, plastic- or paint-coated, galvaprimed with vinyl and PVC-coated depending on the design considered necessary for their successful use [92–98]. Coated sheets are usually formed by deep-drawing, roll-forming, bending and press-brake forming operations; the coating therefore requires to be inherently flexible enough to withstand the particular forming operation in mind, i.e. to stand up to the demands of contact with the tooling under load, wear and the flow of base material. In practice, several defects may arise that are introduced either in the coating process itself or in the forming stage. Poor coating adherence is very common and is attributed to improper pretreatments such as insufficient pickling of the base metal and/or coat material flashing. Thinning and

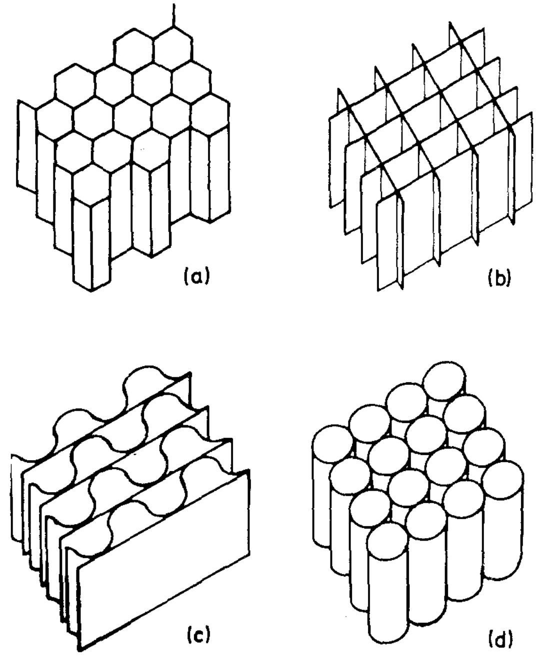


Figure 18 Various types of honeycomb cores.

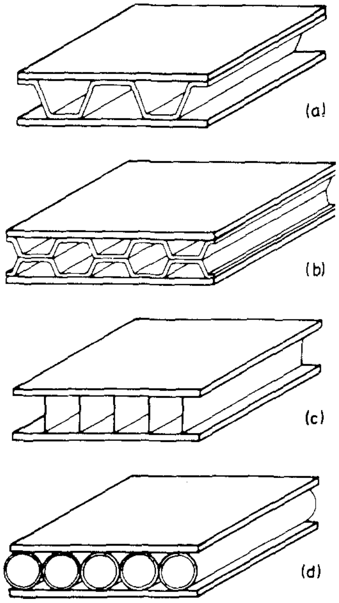


Figure 19 Various types of corrugated cores (after [4]).

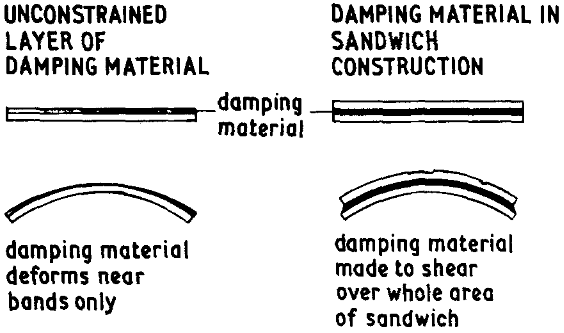


Figure 20 Comparison of the damping mechanism of unconstrained and constrained layer damping [86].

chipping are also frequently encountered, especially at the corners and edges of coated products. Excessive pickling may produce large quantities of smuts which give rise to bubbles and specks. Adsorbed hydrogen, concentrating in the boundary between a coating and the base material, eventually produces fish scale. The forming of a coated sheet with fish scales would invariably rupture these regions so that such coats usually flake or peel off. Press-formed articles in which there are curved portions with extremely small radii therefore present an undesirable appearance; they tend to be repaired locally by the application of another coat. The coating, before forming, may also be thinned down by firing to avoid this defect.

The coating of metallic materials is carried out by spraying or deposition forming. The latter includes either an electrochemical or a welding process. Molten metal in the form of extremely small droplets may be deposited by flame spraying, plasma-arc spraying, detonation-gun spraying, electrostatic spraying and spraying by mechanical atomization. The major defects in spray-deposits occur due to severe oxidation of the deposit and substrate, voids and porosity and overspraying. The presence of oxides gives rise to effects which promote the formation of brittle porous deposits of low structural integrity. The deposit, as first laid down, requires consolidation which is achieved by working the deposit mechanically by rolling, shot-peening or forging, [99–104]; the difficulties and limitations in working spray-deposits are also discussed in the latter references.

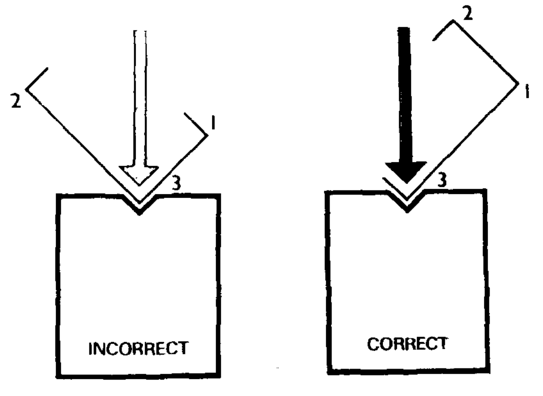


Figure 21 Folding sequence for sound-deadened steel [86].

In the forming of coated sheets, unwanted surface marks and other defects such as wrinkling, earing and spring-back are encountered as a result of conventional sheet-forming operations. Extreme care must be taken to design and schedule press tooling for coated materials; an excellent discussion of this is presented by Wilson [93].

6. Conclusions

A summary of the common principal defects that arise in composite material production and subsequent forming and/or fabrication has been presented. The categories of composites treated are fibre-reinforced plastics, metal–matrix composites, sandwich, clad/bonded materials and coated composites. The literature on this subject is vast but the extensive list of references provided will furnish interested readers with a substantial background.

It is thought that, in addition to the usual studies made of the mechanical characteristics of composites: strength, stiffness, foreign object damage, resistance, environmental effects and fatigue, the principal defects likely to be encountered in the processing stage can be anticipated somewhat and, certainly, examinations can then be carefully made for each new composite material system considered. It is hoped that the present survey contributes to this end.

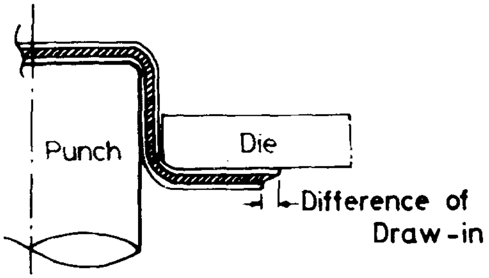


Figure 22 Deformation of damping sheet [85].

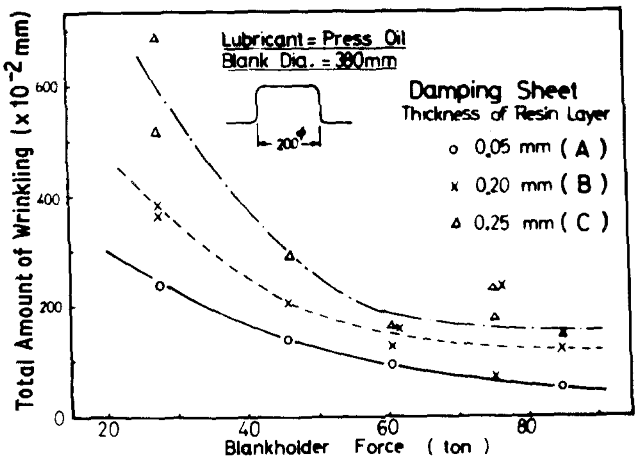


Figure 23 Effect of resin thickness on the flange wrinkling [85].

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