the position of the crack and the arrows show the mode of opening. The letters A and B mark the same particles in successive photographs.

In Fig. 2c the outlines of the glass particles are visible as fine lines. As loading proceeds, segments of the surface of individual particles suddenly pull free from the matrix in a zone surrounding the crack tip; the debonded segment then grows in size, spreading round the particle surface. The zone itself grows in size until (in our experiments) its diameter becomes comparable with a frame of Fig. 2. Finally, the crack advances into the debonded zone.

The sudden nature of the initial debonding is most strikingly seen by direct observation, or on movie or video recordings made through the microscope eyepiece. Fig. 2 shows 4 frames from such a video recording. Debonding is visible as a thickening and darkening of the outlines of the particles as the interface pulls open, scattering more light. The sequence shows an increasing number of debonded particles as the crack tip is slowly loaded. Fig. 2d, taken immediately before fast fracture, shows debonded particles up to 10 particle diameters distant from the crack tip, while closer into the crack tip nearly every particle has debonded from the matrix. There were no indications of crazing or of shear zones originating at particles in this composite.

When a crack propagates through epoxy stiffened with a dispersion of glass spheres, the spheres pull free from the matrix in a zone ahead of the advancing crack. The debonding of a single particle occurs by the sudden appearance of segments of debonding at points on the particle where one would expect the tensile stress to be greatest. These segments then spread more slowly round the surface of the particle.

When particles debond, the modulus of the composite falls. The crack tip, therefore, is advancing into a zone of locally reduced modulus. The stress intensity at the crack tip is changed by this – it is lower than it would be if no debonding occurred. It is thought that this is an important contribution to the toughening in filled polymers and we are now developing a model and conducting experiments to examine it more closely.

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References

1. R. GRIFFITHS and D. G. HOLLOWWAY, *J. Mater. Sci.* 5 (1970) 302
2. L. J. BROUTMAN and S. SAHU, *Mater. Sci. Eng.* 8 (1971) 98.
3. P. K. MALLICK and L. J. BROUTMAN, *ibid.* 18 (1975) 63.
4. P. W. R. BEAUMONT, *J. Mater. Sci.* 12 (1977) 1845.

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ANNE B. OWEN
University Engineering Department,
Trumpington Street,
Cambridge, UK

A new powder metallurgy method

We wish to report preliminary findings of a new powder metallurgy technique which has some novel features. Parts produced by powder metallurgy are generally made by cold pressing, followed by sintering, or in some cases, if superior properties are sought, by sinter forging. To produce a satisfactory product, a significant time at high temperature is required. Explosive compaction of cold powder generally produces a product similar to statically pressed materials [1–3], although if the powder is heated, much better properties may be obtained [4]. Explosive compaction is, however, dangerous and difficult to control. Compaction in a high speed press can

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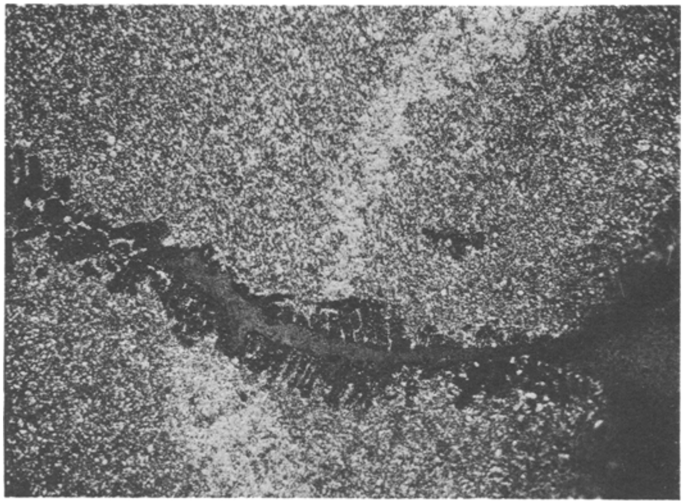

Figure 1 Interface between two 800 μm diameter spherical particles of lead, showing, at the interface, a region which has been melted (× 90).

produce high densities, but the properties are not significantly different from those of statically pressed material [5].

We have investigated the compaction of a variety of metal powders under impact by projectiles launched by compressed air in the speed range 300 to 1200 m sec^{-1} [6]. Compaction occurs during the passage of an intense shock wave through the powder. It is found that if the rise-time of the shock is sufficiently short, the powder particles are thrown against each other so violently that any interparticle oxide film is broken, and a metallurgical bond is formed. Under some circumstances, the heat generated at the points of contact is sufficient to melt the surface of the powder particles. Such a melted zone in a lead compact is shown in Fig. 1. The required impact conditions depend upon the thermal properties of the metal (melting point, conductivity, specific heat and latent heat of fusion), and such parameters as the powder particle size, shape and packing. Typical impact speeds necessary to obtain melting are: lead 500 m sec^{-1}, aluminium 1000 m sec^{-1}, steel 1000 m sec^{-1}.

At impact speeds below these conditions, although interparticle melting is not normally observed, compacts with useful properties can be obtained. It is found that higher compact densities are obtained during dynamic powder compaction than if the powder is compacted statically to the same pressure, and that the density is more uniform in dies of reasonable complexity. Both of these effects are thought to be due to the heat-softening of the powder particle surfaces during compaction, resulting in a "self-lubricating" effect, and the dynamics of the powder flow.

Regarded simply as an improved process for obtaining compacts which will subsequently be sintered, the technique presents the following advantages:

(1) High initial densities, and hence higher dimensional accuracy and green strength.

(2) Because of the higher green strength, there will be less loss due to breakage on removal from the die, and hence simpler and less expensive die ejector systems may be used. This raises the possibility of shorter production runs.

(3) Because the high compaction pressures are generated by inertial forces, the compressed-air launcher and associated equipment are lighter and more compact than a static press. A 70 mm bore compaction unit weighs less than 1 t, and does the work of a 1000 t hydraulic press.

This combination of advantages has enabled us to obtain high strengths in medium alloy steels. Table I compares properties obtained after compaction and sintering of Höganäs Distalloy AE with wrought En 24 which has a similar composition.

The main interest of the technique, however, lies in the possibility of making metallurgical structures which have not previously been obtainable. These range from the retention of the cold-worked or shock-hardened structure in the finished part, to the co-compaction of powders which have been subjected to different heat treat-

TABLE I

Property		Höganäs distalloy AE, compacted by plastic projectile at 350 m sec^{-1}, sintered and heat-treated	En 24 wrought and heat-treated
Density		92%–96%	100%
Hardness	H_V	350–600	450
	HR_C	35–55	46
Bend strength (MN m^{-2})		1500–2500	1500

TABLE II

Property	Wrought 304 L		Dynamically compacted 304 L powder	
	Annealed	Cold-worked	Compacted by plastic projectile at 1100 m sec^{-1}; unsintered	Compacted by plastic projectile at 400 m sec^{-1}; annealed at 1100° C
Density	100%	100%	99%	95%
Hardness H_V	100	200	400	160–240 (2g microhardness 300)
Bend strength	650	1200	400–700	1000

ments, or to the combination of materials which are chemically incompatible at normal sintering temperatures. A variety of metastable materials may be compacted, including, for example, glassy metals.

Results obtained from the compaction of 304 L stainless steel are shown in Table II. It is of interest to note the high value of the 2 g microhardness in the annealed material. Metallographic examination has shown that the shock-hardened structure is substantially retained even after annealing for 1 h at 1100° C.

An example of an unconventional microstructure is steel dispersed in an aluminium matrix. Some properties of a compact of 20% M2 tool steel in aluminium are given in Table III. This material exhibits good wear resistance against iron and steel. Its seizure properties are similar to those of cast iron, while in abrasive testing with silica particles, it gives a wear rate similar to that of a

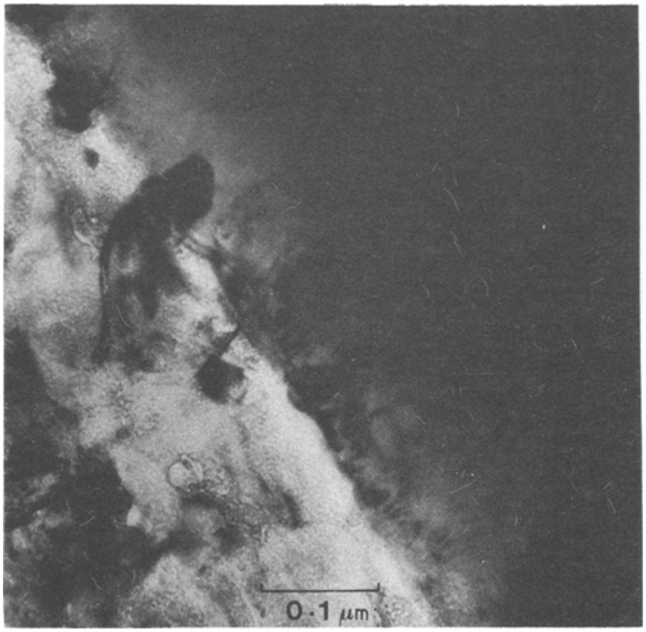

Figure 2 Interface between aluminium and type 304 L stainless steel after dynamic compaction. A good metallurgical bond is seen, with no evidence of intermetallic phase formation. The material near the interface often contains very small grains which produce diffraction spots consistent with those of the parent materials. No spots corresponding to any intermetallic phase were detected.

TABLE III Properties of a compact of 20 vol% M2 tool steel in aluminium produced by impact of a plastic projectile at 1000 m sec^{-1}

Density		> 99%
Hardness H_V		110
Microhardness	Al	50
	Steel	1000
Bend strength ($MN\,m^{-2}$)		300

medium alloy steel or twice as good as aluminium–silicon casting alloys.

A question of interest is whether, during compaction, the aluminium and iron can react together to form an intermetallic phase. So far, we have not been able to detect any reaction product: Fig. 2 shows an electron micrograph of a typical boundary region. No precipitate particles can be seen, and no evidence of intermetallic phases can be detected in the electron diffraction image.

If these observations prove to be generally true, we believe that it should be possible to make a wide range of novel microstructures from mixtures of materials which have had different prior thermal or mechanical treatments, which are metastable, or which are normally chemically incompatible.

References

1. R. A. PRUEMMER and G. ZIEGLER, *Powder Met. Int.* 1 (1977) 11.
2. C. R. A. LENNON, A. K. BHALLA and J. D. WILLIAMS, *Powder Met.* **21** (1978).
3. D. S. WITKOWSKY and H. OTTO, 4th High Energy Rate Forming Conference, Denver (1973).
4. V. G. GOROBTSOV and O. V. ROMAN, *Powder Met. 2 Tech.* **11** (1975) 55.
5. S. ELWAKIL and R. DAVIES, Proceedings of the 13th International Machine Tool Design and Research Conference, Birmingham (MacMillan, London, 1972).
6. D. RAYBOULD, Proceedings of the 15th International Machine Tool Design and Research Conference, edited by S. A. Tobias and F. Koenigsberger (MacMillan, London, 1975) p. 627.

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D. RAYBOULD
D. G. MORRIS
G. A. COOPER
Institut CERAC SA, Chemin des Larges Pièces, Ch-1024 Ecublens, Switzerland