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Explosive compaction of superconducting powder

H S YADAV and K R K RAO
Explosives Research and Development Laboratory, Pune 411 021, India

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Abstract. Superconducting powder, $YBa_2Cu_3O_{7-x}$, with grains of size varying from 2 to 20μ and superconductivity up to 90°K was compacted to a uniform density of 6·2 g/cc (96% of theoretical maximum density) by explosive-shock loading in cylindrical configuration. A typical size of rod (3·76 mm diameter and 70 mm length) was fabricated using the present technique of explosive compaction. The compacted specimen shows levitation at the liquid nitrogen temperature.

Keywords. Explosive compaction; superconducting powder.

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1. Introduction

Shock waves are increasingly being used for compacting powders mainly because shock wave loading, unlike the sintering and hot pressing types of conventional methods, compacts the specimen without heating it to a very high temperature and therefore offers a technological process which is simple, less time-consuming and very economical eliminating the use of both die and binder. A shock wave which is generated by detonation of an explosive directly in contact with the specimen or by the impact of a flyer plate (Yadav 1983) is always characterized by a sharp rise in thermodynamic and hydrodynamic parameters of the medium at its front. It, therefore, compresses the medium at a very high strain rate and changes its physical properties like strength and hardness Raybould (1981) by increasing the density of dislocations (Yust and Harris 1981) in the medium.

While Leonard *et al* (1969) employed shock loading technique for compacting powders of pure metals, Prummer and Ziegler (1975) used this technique foı compacting powders of metals and ceramic materials. More recently, Murr *et al* (1987) used it for compacting superconducting (SC) powder and by using an explosive of low velocity of detonation and a flyer plate impact in plane geometry for generation of shock waves, they fabricated ring-monoliths of SC powder in solid copper matrix. Another geometry, which is simpler and commonly used for fabricating rods of compacted powder, is described by Prummer (1983). In this configuration, the specimen powder filled in a thin cylindrical metal tube, is surrounded by a coaxial explosive shell. When the explosive is detonated at one end, it transmits an axisymmetrical shock wave into the powder. Depending upon the magnitude and shape of the shock wave, the powder is compressed to a uniform higher density with or without homogeneities in the compact.

A major problem in fabrication of specimen compacted by explosive loading lies in the generation of proper shape and amplitude of the shock wave for uniform compaction. It is reported that metallurgical inhomogeneities and non-uniform densities over the cross-section of the compact result due to over- or under-shock loading of the samples (Prummer 1983). Studying the problem of inhomogeniety, Kostyukov (1981) pointed out that such defects in compacts occur only in the region of shock reflections. The minimum and maximum angles of shock interaction which gives uniform compaction and allows regular shock reflection were determined for typical metal powders. The angles at which the interacting shock waves undergo regular reflection have, however, not been determined in the case of SC powders. Theoretical treatment of the problem of compaction by Hermann (1969) and Pastine *et al* (1970) indicated that an understanding of the equation of state of the powder is a pre-requisite to calculate the final density of the compact. The equation of the state is, however, not readily available for newly developed SC powders. It therefore becomes imperative to establish an optimum condition for compacting SC powders experimentally.

Attempts were therefore made in this study to establish optimum parameters of shock wave loading, in cylindrical configuration for fabricating compacted rods of ($YBa_2Cu_3O_{7-x}$) of uniform density and without inhomogeneities over its cross-section.

One of the most important parameters which controls the shape of the shock wave and the maximum density of the compact in explosive compaction process is the ratio of mass of the explosive and that of the powder (E/M). The optimum E/M value varies inversely to the peak pressure of the detonation wave (Prummer 1983). In the present study on compaction of SC powders, the effect of both E/M ratio as well as diameter of the tube was investigated.

2. Theoretical

When a uniform layer of explosive, placed around a metal tube containing SC powder detonates axisymmetrically, the wall of the tube moves towards the axis and compresses the powder inside. If ρ_{0x} and D represent the initial density and velocity of detonation of the explosive and r the ratio of specific heat of detonation products, then the relation

$$P_D = \rho_{0x} D^2/(r+1) \tag{1}$$

gives the magnitude of pressure of detonation products which acts on the wall of the tube and moves it with a velocity V_p, which is given by the relation (Chanteret 1983)

$$V_p = \left[\frac{2E_G}{\left(\frac{R_e^2 - R_i^2}{R_x^2 - R_i^2}\right)\frac{M_T}{E} + \frac{1}{6}}\right]^{\frac{1}{2}}. \tag{2}$$

Here R_x is the radius of stationary surface in the explosive and is obtained from the relation,

$$R_x^3 + 3R_x\left[(R_e + R_i)\frac{\rho_0}{\rho_j}\left(\frac{M_T R_e}{E} + \frac{M_c R_i}{E}\right) + R_i R_e\right]$$

$$- 3(R_i + R_e) \times R_i R_e\left[\frac{2}{3} + \frac{\rho_{0x}}{\rho_j}\left(\frac{M_T}{E} + \frac{M_c}{E}\right)\right] = 0 \tag{3}$$

where M and M_c are the masses per unit length of the metal tubes surrounding the powder and the explosive. R_i and R_e are the interior and exterior radii and ρ_0 and ρ_j, the initial and Chapman Jouguet densities of the explosive. E_G and E denote the Gurney energy and the mass per unit length of the explosive.

The motion of the tube generates a shock wave in the powder. The thermodynamic variables across the shock front are given by the Rankine-Hugoniot relations,

$$\rho_0 U_s = \rho(U_s - U_p), \tag{4}$$

$$P_1 - P_0 = \rho_0 U_s U_p \tag{5}$$

$$E_1 - E_0 = \tfrac{1}{2}(P_1 + P_0)(V_0 - V_1), \tag{6}$$

where P, ρ and E_1 denote the pressure density and specific internal energy, U_s, U_p the shock and particle velocity behind the shock front. The subscripts one and zero refer to the state of the medium behind and ahead of the shock front respectively.

When the shock wave propagates towards the axis of the tube, its pressure increases due to the convergence effect and decreases at the same time due to irreversible processes like heating and compaction of the powder. It was earlier reported that the shape of the shock wave remains conical if the effect of convergence and that of attenuation balances each other (Prummer 1983). Under these conditions, the shock reflection at the axis remains regular resulting in a uniform and homogeneous compaction of the powder. It is evident that during compaction, only a part of the total explosive energy is used which is mainly consumed in deforming the tube and compacting the powder. The energy balance equation can then be written as

$$M_T E_d + M W_p = NEQ, \tag{7}$$

where M_T, M and E represent the masses per unit length of the metal tube, the powder and the explosive respectively, E_d, W_p, and Q denote the specific energy of deformation, compaction energy of the powder and the energy of explosion. Equation (7) can be simplified to yield,

$$\frac{M_T}{E}E_d + \frac{M W_p}{E} = NQ. \tag{8}$$

It is clear from this relation that the explosive-to-powder mass ratio (E/M) increases with increase of energy of deformation and that of the compaction. As the energy of deformation of the tube (E_d) is higher when its diameter is smaller, the explosive energy required for compacting the same quantity of powder in tubes of smaller diameter is therefore greater than that in tubes of bigger diameter. The tubes of higher diameter thus need explosive of smaller E/M ratio and this ratio can be optimized for a fixed thickness of the tube of a particular material.

3. Experimental

The experimental set-up, shown in figure 1, was used to compact the specimen powder in a copper tube of 6·4 mm OD, 0·65 mm thickness and 70 mm length. The copper tube, filled with SC powder ($YBa_2Cu_3O_{7-x}$) of grain size 2–20 micrometer diameter, and initial density 3·269 to 3·511 g/cc, was closed at both ends by metal plugs so that the powder does not come in contact with the surrounding atmosphere and the impurities do not enter the compacted specimen. The copper tube was positioned at the centre of a bigger tube of aluminium with the help of two wooden plugs, fitted at both the ends of the aluminium tube. The space between the inner and outer tube was filled either with ammonium nitrate and TNT (80:20) powder explosive, whose velocity of detonation had been measured separately as 2·3 mm/μs, or with picrite powder, having a velocity of detonation of 3·0 mm/μs.

In order to achieve an axisymmetrical detonation wave in the explosive, the metal plug at one end of the copper tube, facing the initiating end of the explosive was tapered towards the detonator as shown in figure 2. An electric-detonator, accurately positioned at the centre at one end of the explosive charge, was used to initiate the detonation.

To investigate the effect of diameter of tube on compaction, copper tubes (inner diameters, 2·5 mm and 5·0 mm) were used in the present series of experiments. The compacted sample was always recovered in thick hollow metallic cylinders.

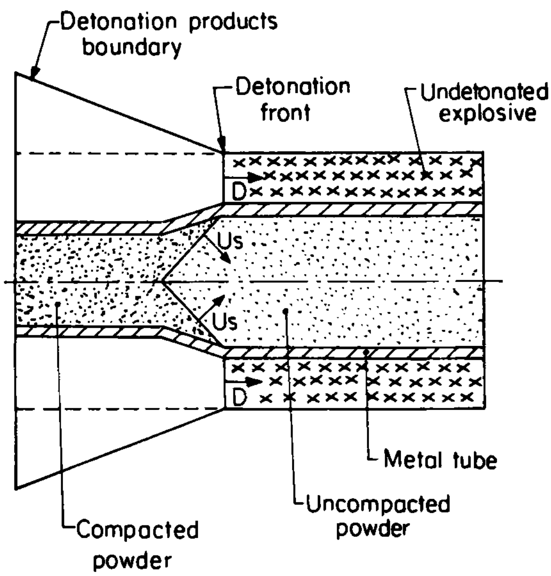


Figure 1. Compaction of powder in a cylindrical tube by axisymmetrical (conical) shock wave.

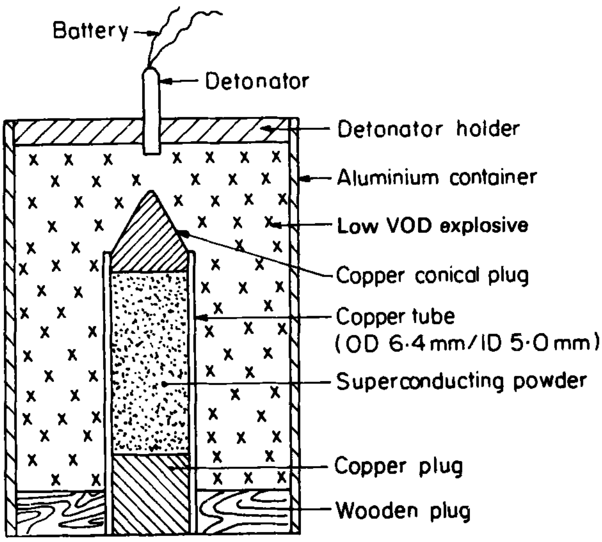


Figure 2. Explosive compaction of superconducting powder.

4. Results and Discussion

In order to investigate the possibility of compacting SC powder directly into wire form, a small diameter copper tube, filled with SC powder was subjected to shock loading of different E/M ratios. As shown in table 1, picrite explosive (E/M ratio, 3·657 and 5·61) produced no compaction in tubes of 2·5 mm internal diameter. However, a good compaction was produced with a mixture of ammonium nitrate and TNT explosive in tubes of internal diameter 5·0 mm. In a separate set of experiments, the velocity of

Table 1. Parameters for explosive compaction of superconducting powder.

Initial density of the powder (g/cc)	Copper tube dimensions OD/ID/Length (mm)	Explosive Type	Explosive Density (g/cc)	Explosive VOD (mm/μs)	E/M	Final density of the compact (g/cc)	Remarks
3·269	5·6/2·5/60·7	Picrite	0·37	3·0	3·657	—	No compaction
3·79	5·6/2·5/60·7	Picrite	0·37	3·0	5·61	—	No compaction
3·384	6·4/5·0/80	(NH_4NO_3/TNT) (80:20)	0·74	2·3	5·6	6·00	Compacted
3·332	6·4/5·0/70	(NH_4NO_3/TNT) (80:20)	0·74	2·3	7·63	6·20	Compacted
3·511	6·4/5·0/70	(NH_4NO_3/TNT) (80:20)	0·74	2·3	9·08	6·22	Compacted

detonation (VOD) of these explosives was measured. These values are also shown in table 1. The high VOD explosive was used for compaction of the powder in tubes of smaller diameter as these tubes offer comparatively higher resistance to deformation and needs greater energy for compaction according to relation (8).

The low VOD explosive, having an E/M ratio of 9·08, produced a rod of 6·2 g/cc density which is approximately 96% of the maximum theoretical density of the specimen. The compacted specimen was subjected to levitation test which showed presence of superconductivity in the specimen at liquid nitrogen temperature. Figures 3(a) and 3(b) show a microphotograph of the original powder and that of the compact, obtained with a scanning electron microscope. It shows uniform densification of the compacted specimen which is free from central inhomogeneities. The micrograph in figure 4 shows the interface of copper tube and compacted SC powder. The wave nature of the interface is a characteristic of explosion bonding.

It has also been observed in this study that the initiating end of the specimen is less dense than that of the farther end leading to the conclusion that the proces of tube collapsing and propagation of the detonation wave gets established only some distance away from the initiating end.

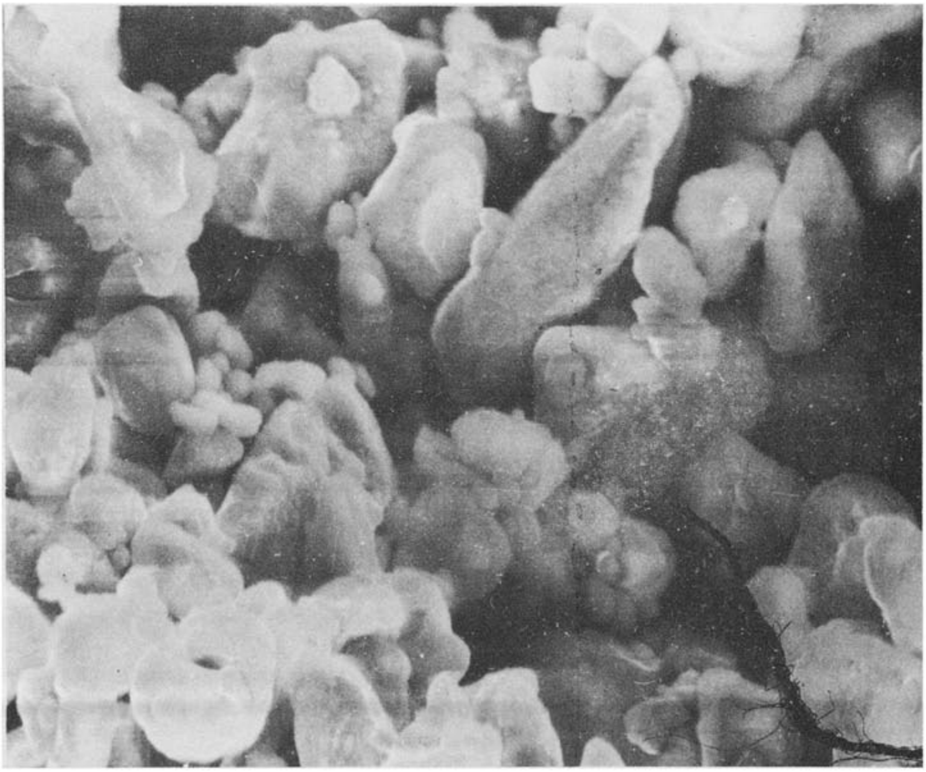
The characteristics of detonation and shock wave have been calculated using the experimental parameters of table 2. In order to calculate V_p from equation (2), Gurney energy was assumed as 70% of the energy of explosion, Q, which was theoretically determined from the relation.

$$D^2 = 2(r^2 - 1)Q$$

by taking $r = 2{\cdot}5$ and $D = 2{\cdot}3$ mm/μs for AN/TNT (80:20) explosive. After determining the V_p which is initially equal to the particle velocity behind the shock front and assuming the density of the shocked powder equal to the final density of the compacted specimen as a rough approximation, the pressure of shock wave, generated during compaction, was estimated from relations (4) and (5) and is shown in table 3.

Table 2. Explosive, powder and metal parameters.

Explosive		Powder	Tube
Mass per unit length (E):	5·945 g	Material: $YBa_2Cu_3O_{7-x}$	Material: copper
Velocity of detonation (D):	2·3 mm/	Initial density: (ρ_0) 3·332 g/cc	Density: 8·9 g/cc
Inner radius (R_i):	3·2 mm	Final density (ρ): 6·20 g/cc	Thickness: 0·65 mm
Outer radius (R_e):	16·75 mm	Powder mass per unit: length (M): 0·654 g	OD: 6·4 mm
Initial density: (ρ_{0x})	0·759/cc		ID: 5·0 mm
C-J Density (ρ_j):	0·98 g/cc	Length size: 2–20 μ	
Specific heat ratio (r):	2·5		



(a)

b)

Figure 3. Scanning electron photomicrograph (× 5000) of **a**. superconducting powder ($YBa_2Cu_3O_{7-x}$) used in explosive compaction experiments. **b**. Compacted superconductor.

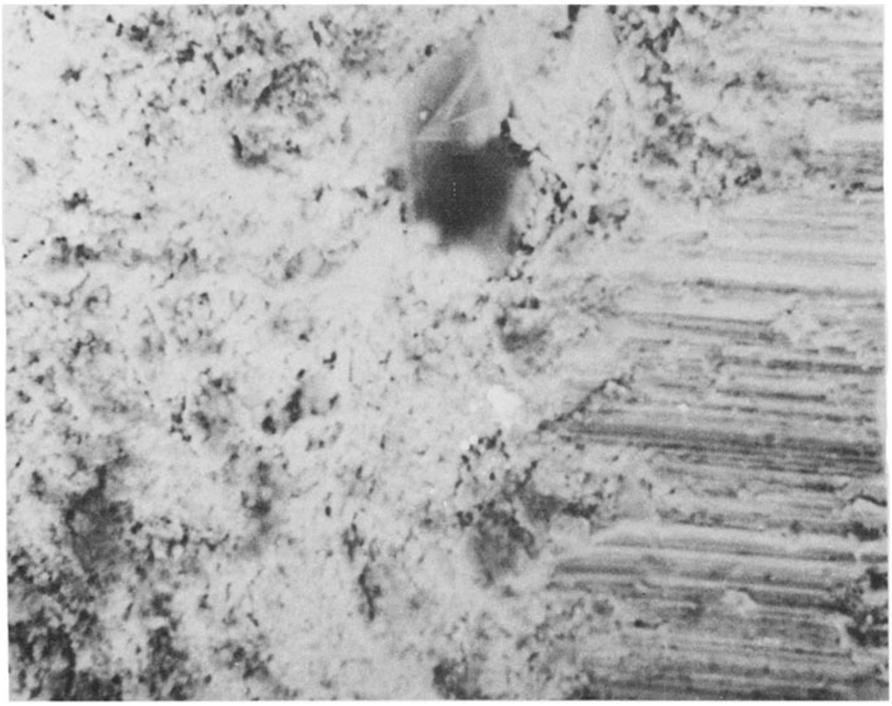


Figure 4. Microphotograph of cross-section of copper tube and superconductor solid monolith (× 1000) obtained by compaction.

Table 3. Computed parameters of the detonation wave and the shock wave.

Wave	Particle velocity (mm/μs)	Wave velocity (mm/μs)	Pressure (kb)
Detonation	0·6571	2·30*	11·18
Shock	0·79	1·694	44·60

*Measured value.

5. Conclusion

Superconducting powders can be compacted in cylindrical geometry without inhomogeneities in the centre by adjusting E/M ratio and velocity of detonation of the explosive. The solid ($YBa_2Cu_3O_{7-x}$) compacted by explosive loading retains its property of superconductivity even if its final density reaches 96% of the maximum theoretical density.

References

Deribas A A 1970 *Fiz. Goreniya Vzryva* **6** 122

Hermann W 1969 *J. Appl. Phys.* **40** 2490

Kostyukov N A 1981 in *Shock waves and high-strain-rate phenomena in metals* (eds) M A Meyers and L E Murr (New York and London: Plenum) p. 843

Leonard R W, Laber D and Linse U D 1969 *Proc. Second Int. Conf. HERF* (USA: Estes Park Co.)

Murr L E, Hare A W and Error M G 1987 *Nature (London)* **329** 37

Pastine D Y, Lambardi M J, Chatterjee A and Tchen W 1970 *J. Appl. Phys.* **41** 3144

Prummer R 1983 in *Explosive welding, forming and compaction* (ed.) T Z Blazynski (London and New York: Applied Science Publ.)

Prummer R A and Ziegler G 1975 in *Fifth Int. Conf. on High Energy Rate Fabrication* (Denver, Colarado) 24–26 June

Raybould D 1981 in *Proc. Seventh Int. Conf. of High Energy Rate Fabrication* (Leeds: Univ. of Leeds) p. 261

Yadav H S 1983 *Study of plane and spherical shock waves and their effect on free surface conical cavities in metals*, Ph.D. thesis, Punjab University

Yust C S and Harris L A 1981 in *Shock wave and high-strain-rate phenomena in metals* (eds) Marc A Meyers and L E Murr (New York and London: Plenum) p. 881