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MECHANICS OF DYNAMIC POWDER COMPACTION PROCESS

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ABSTRACT

In recent years, interest in dynamic compaction methods of metal powders has increased due to the need to improve compaction properties and to increase production rates of compacts. In this paper, review of dynamic and explosive compaction of metal powders are given. An attempt is made to get a better understanding of the compaction process with the mechanicis of powder compaction.

Key Words: Powder compaction

DİNAMİK TOZ SIKIŞTIRMA İŞLEMİNİN MEKANİĞİ

ÖZET

Son yıllarda, metal tozlarının dinamik sıkıştırma metodlarına gösterilen ilgi, sıkıştırma özelliklerini iyileştirme ve sıkıştırılmış malzemelerin üretim hızlarını yükseltmeye olan ihtiyaçtan dolayı artmıştır. Bu makalede metal tozlarının dinamik ve patlamalı sıkıştırılmasının kısa bir özeti verildi. Sıkıştırma işleminin daha iyi anlaşılması, metal tozu sıkıştırma mekaniği ile birlikte sağlanmaya çalışıldı.

Anahtar Kelimeler: Toz sıkıştırma

1. INTRODUCTION

Powder metallurgy is a process in which metal powders are produced, and articles are made from them. The manufacture of semi-finished and finished structural parts by powder metallurgical means has been an established indusrial production process for many years. Powder compaction processes are emloyed in four main areas; the powder metallurgy, pharmaceutical, ceramic and fuel idustries.

The application of powder metallurgical processes has grown because, in many cases, they allow better control of structure and composition of the product, together with more economic manufacture when compared with conventional forming methods. They also avoid much of the material wastage associated with the subsequent machining of, for example, forgings and castings. Powder metallurgical processes also allow the fabrication of components with unusual geometries and from materials whicih may not be obtainable by existing processes. Recently the cold compaction of an aggregate of powder is treated by Fleck (1995) from the viewpoint of crystal plasticity theory.

The pharmaceutical industry employs powder compaction processes to form medicinal powders into tablets. Tabletting has been used mainly as a convenient and simple from of dosage. The heat of compression and work of compression of three common pharmaceutical excipients (Avicel PH-101, anhydrous lastose, and Starch 1500) were determined by Wurster (1995) using experimental instrumentation of original design. Their approach is proposed as a discriminating method to characterize and quantitate fundemantal powder comperssion behaviour.

The ceramic industry has employed compaction techniques to form dry or slightly moist ceramic powders into a wide range of produsts. The dry pressing technique can be fully automated with high rates of production and one operator can take charge of several processes. The compaction behaviour of ultrafine zirconia powders (6-8 μm) without and with alumina additions (0 to 20 wt %) has been studied by Novarro (1995). The results were compared with those obtained in the same experimental conditions on a commercial zirconia powder.

In the fuel industries, many processes lead to the production of powdered fuels which can not be handled easily or re-used. Such powders have often been disposed off as waste, representing an economic loss to industry and, in some cases, a major couse of pollution. Powder compaction processes have been used to form these powders into briquettes. One method of minimizing the amount of radiation damage in the cores of nuclear fuel elements is to disperse the fissile compound, commanly UO_2, in a metal matrix using powder metallurgy methods to produce the fuel elements. UO_2 and AL_2O_3 powder packing structures in cylindrical powder compacts are observed by Yanai (1995) using scanning Electron Microscopy (SEM) which polished cross sections of compacts fixed by low viscosity epoxy resin. The local density of the corner portion of the powder compact fabricated by double-acting dry press is higher than that of the inner portion.

Metal powders for P/M products may be produced by several techniques each of which typically belongs to one or more of the following categories: physical methods, chemical methods and mechanical methods (Klar, 1983).

A very prominent technique called “atomisation” is a method for physically producing powder by solidification of droplets from a disrupted stream of the molten metal. Atomization can be used to produce powders from a wide range of pure metals as well as from ferrous and nonferrous alloys such as stainless steels, nickelbase supper alloys and titanium alloys.

Many metal powders are routinely produced by chemical decomposition of a compound of the metal. Notable in this respect is the reduction of particulate metal oxides in the presence of gaseous reducing agents such as hydrogen or carbon monoxide. Powders of tungsten, molybdenum, copper and iron are manufactured by this technique.

Comminution methods (Mechanical crushing, grinding and stamping) are essential secondary processes in the production of several metal powders. Furthermore, powders produced by comminution of brittle metals are difficult to compact at ambient temperature. The ability of a metal powder to be effectively compacted, and the resulting properties of the compact before and after sintering, are affected by the characteristics of the starting powder. The size and shape, internal microstructure, chemical composition, flowability, compressibilitiy, apparent density and surface condition of the individual particles all play important roles in determining the static bulk properties of the powder as well as its dynamic behaviour associated with flow, compaction and sintering.

In practice, there are several methods to compact powders. For a particular metal powder, the compact properties mainly depend on the method of compaction and subsequent heat treatment. P/M processing may involve compaction in rigid dies, ambient or high temperature isostatic compaction in flexible tooling, high-energy-rate forming (HERF), or consolidation by forging, by rolling or extrusion, or by vibratory packing. Large number of P/M components are compacted in rigid dies using mechanical or hydraulic presses (Lenel, 1980).

SiC particulate reinforced titanium matrix composites have been processed by shock wave consolidation (Tong, 1995). Using schock consolidation, fully dense composite compacts that are free from interfacial reactions and macroscopic cracks have been obtained. The processed materials are ideal for studying effects of interfacial properties on the mechanical behaviour of particulate reinforced metal matrix composites.

In this paper, the theory of mechanics of powder compaction process is attempted.

2. A SHORT REVIEW OF THE DYNAMIC COMPACTION PROCESS

Interest in dynamic compaction methods has increased in recent years due to the need to improve compaction properties and to increase production rates of compacts. Dynamic compaction methods differ from the conventional consolidation methods in respect of the compacting pressure and the speed or rate of compaction used (Clyns, 1977). This work provides some evidence to suggest that increasing the rate of compaction results in a more uniform density distribution, improved green strength and in the case of die compaction, lower compact ejection forces. Dynamic compaction techniques date from the late 1940’s when Mc Kenna, Redmond and Simith (1953) patented a hydrodynamic press to compact titanium carbide. Since then the development of dynamic compaction methods has received attention in many countries.

A great deal of effort has been devoted to investigating the behavior of powders subjected to conventional compaction conditions. Powder consolidation takes place in a number of stages and that in each stage a particular controlling mechanism is dominant. A more detailed discussion of the mechanism governing powder consolidation can be found in the review given by James (1972). In the first stage, compaction is attributed to particles flowing past one another and repackaging-usually referred to as transitional restacking. In the second stage compaction is attributed to elastic and plastic deformations of particles, and in the third to cold working, with or without particle fragmentation. The various stages of compaction listed above is apparent from a conventional compaction curve presented by Donachie (1963). See (Figure 1).

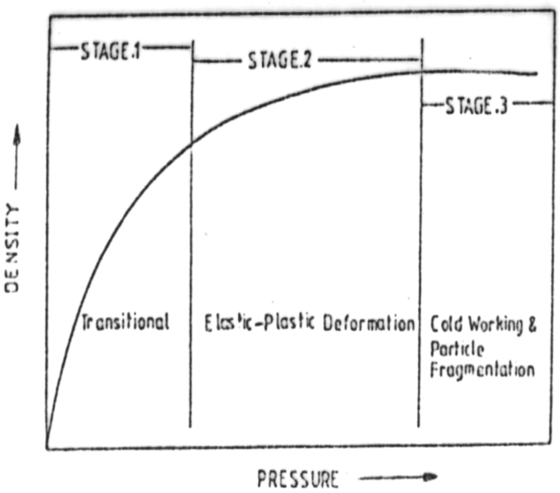

Figure 1. Conventional compaction pressure-density curve.

In the transitional stage of compaction powder consolidation is thought to be the result of powder particles flowing past one another and repackaging. Under these conditions particle movement is controlled by interparticle friction effects (Clyens, 1977). However, most commercial powders used in the powder metallurgy industry are invariably contaminated by oxides, pressing lubricants and adsorbed gases which cover their surfaces. Consequently, before interparticle solid bridges can be formed, these contaminants must be removed by the application of normal end shearing forces to the particle surfaces. Extensive work on the mechanism of friction between various solid materials has been given by Bowden (1967). Ashton (1965) have investigated pressure-density relationships for powders compacted uniaxially under conditions corresponding to the transitional region. They found that for both cohesive and free flowing powders the relationship took the form of a power law, thus

$$p = k\rho^{m} \qquad (1)$$

Where p denotes the compaction pressure, ρ the density and k and m are constants. The values of k and m were derived from the experimental pressure-density curves for each powder. There was no attempt to give each constant a physical significance although k and m must be related to the interparticle friction conditions and the amount of particle movement.

In the second stage of compaction, elastic deformation at interparticle contact point occurs which, as the compaction pressure increases, is followed by plastic deformation. During plastic deformation the contact areas between adjacent particles grow and interparticle bonding can occur.

At the beginning of this stage, particles are deformed elastically while others are unstressed. As the compaction pressure is increased, plastic flow at these points occurs, resulting in compacts with highly localized plastic deformation, the remainder of the compact is undeformed or only elastically deformed. According to Rumpf (1962), there are five basic mechanisms responsible for interparticle bonding: solid bridges, mechanical interlocking, interfacial forces, adhesive and cohesive forces, and electro-static forces.

Solid bridges or cold welding occurs when the interparticle loads become sufficient to break down the surface oxide layers and cause metal-metal contact (Bowden, 1967).

Mechanical interlocking of powder particles occurs when the surface of the powder particles become enmeshed. Generally, as the compaction pressure increases, so does the degree of interlocking, although other factors, such as the type of powder and particle shape are also important. Powder exhibiting plastic behavior interlock much more readily than brittle powders. This occurs due to surface matching and flow of material from one particle into the surface voids of other particles at the interparticle contact points.

Interfacial forces can arise from capillary action of thin, low viscosity liquid films at interparticle contact points. The magnitude of interfacial forces depends on the surface tension of the liquid film.
Adhesive and cohesive bonding forces are set up when particles are bridged by a binding medium such as a pressing wax. The strength of bonds depends to a large extent on the ability of a binding medium to “key” onto the surface of the powder particles.

Electro-static bonding forces are due to the electric field which surround powder particles when they become eletrically charged. Although electro-static forces do not contribute enough to the green strength of most compacts, they can influence the flow behaviour of loose powders and, therefore, precautions have to be taken to avoid charging them during handling. It has been shown (Rumpf, 1962) that, for two spheres in an ionic lattice, the binding forces (H) between them is given by,

$$H = k\frac{Q^2}{d^2} \quad \text{or}$$

$$H = k\pi^2 d^2 \qquad (2)$$

Where Q denotes the charge on a single sphere, d is the distance between the centres of the two spheres, Q denotes the charge density, and k is a constant.

In the third or final stage, compaction is usually attributed to cold working or particle attrition, and in some cases both mechanisms may be responsible for compaction. Hirschhorn (1969) have compacted a number of commercial iron powders and by measuring increases in the particle microhardness have established that individual particles experience significant cold working during the final stage of compaction.

The various methods of dynamically compacting powdered materials are classified and reviewed by Clyens (1977). The methods are considered under two headings: dynamic uniaxial compaction and isodynamic compaction. These methods of powder compaction have been classified according to the compaction rate which they are capable of producing (Clyens, 1977). Recently, Benson (1994) simulated in two dimensions the dynamic compaction of copper powders. The computational results are in good agreement with published shock velocity-mass velocity data for porous Cu compaction. The computational method may be generalized to other materials, particle size distributions, compaction rates, and higher pressures.

3.MECHANICS OF DYNAMIC COMPACTION PROCESS

The high velocity compaction of powders has now been under investigation for the last two decades. A lot of effort has been devoted to identify the significant parameters which govern the process. Many aspects of the process however, are still obscure. One of the important aspects, which to date has not been fully understood, is the mechanics of powder compaction process. This is not surprising, however, due to the complex nature of the problem. It is believed that, as in the dynamic plasticity of solids, adequate understanding of the mechanics of the compaction process could be achieved through prior determination of the yield criterion, temperature distribution, and constitutive equations describing its behaviour together with an assessment of the influence of strain rate. For advancement in the fundamental understanding of the compaction process, close collaboration would be required between an industrialist and an applied mechanician with a broad experience in the response of solids, structures and powders to dynamic loading.

From various quasi-static compaction tests, the pressure-volume relation is found (Al-Hassani, 1981) to resemble closely an adiabatic gas flow law of the from:

$$P_0 V_0^{\gamma} = PV^{\gamma} = k = \text{Constant} \qquad (3)$$

Where γ is a constant for the particular powder.

Under the steel projectile, the compaction takes place at a high speed but not high enough to include rate effects or shock waves. We, therefore, attempt to predict the velocity requirement for the projectile as follows (see Figure 2).

In order to simplify the analysis, friction has been neglected and the equation of motion for the steel projectile during compaction is:

$$M = \frac{dv}{dt} = -PA \qquad (4)$$

Where P is the current pressure acting on the steel projectile, A is the cross-sectional area, M is the mass and v is the velocity of the projectile.

Using atmospheric pressure and loose powder volume P_0 and V_0 respectively, and combining equations (3) an (4) we obtain:

$$M = \frac{dv}{dt} = -\frac{kA}{V^{\gamma}} \qquad (5)$$

Where $k=P_0V_0^{\gamma}=PV^{\gamma}$

The powder volume is given by V=AH, where H is the current height of the specimen and the velocity is related to the height through

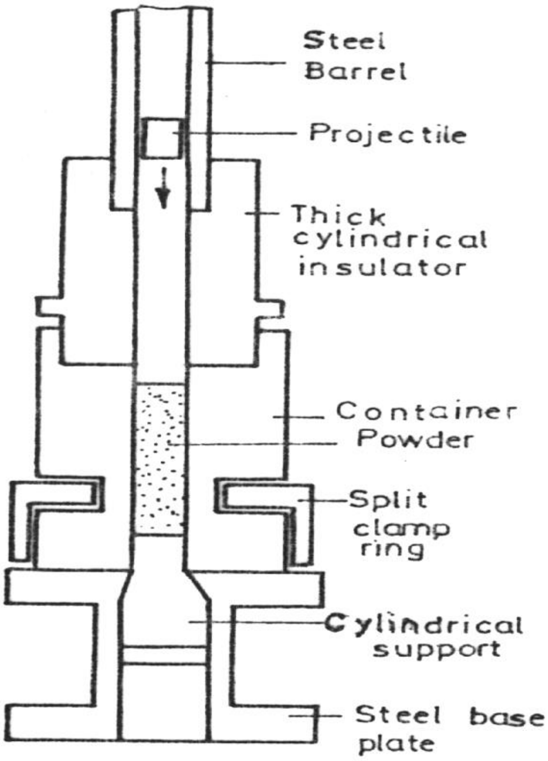

Figure 2. Schematic diagram showing details of dynamic compaction process.

$$v = -\frac{dH}{dt}$$

of the latter equation gives:

$$\frac{dv}{dt} = -v\frac{dv}{dH} \qquad (6)$$

Substituting equation (4) into (5) and noting that V=AH, we obtain;

$$Mv\frac{dv}{dH} = \frac{kA}{A^{\gamma}H^{\gamma}} = \frac{kA^{1-\gamma}}{H^{\gamma}} \qquad (7)$$

Which upon integration and the substitution of the initial condition $v=v_0$ when $H=H_o$ gives;

$$\frac{1}{2}M(v_0^2 - v^2) = \frac{kA^{1-\gamma}}{1-\gamma}(H_0^{1-\gamma} - H^{1-\gamma}) \qquad (8)$$

The LHS of equation (8) represents the loss in the kinetic energy of the projectile in decelerating from v_0 to v . The RHS represents the energy input to the powder compact or the mechanical work down on the specimen.

Substituting $v=v_f=0$ at $H=H_f$. we have;

$$\frac{1}{2}Mv_0^2 = \frac{kA^{1-\gamma}}{1-\gamma}.(H_0^{1-\gamma} - H_f^{1-\gamma}) = \frac{k(AH_0)^{1-\gamma}}{1-\gamma}.\left[1-(\tfrac{H_f}{H_o})^{1-\gamma}\right]$$

or in terms of volumes

$$\frac{1}{2}Mv_0^2 = \frac{kV_0^{1-\gamma}}{1-\gamma}\left[1-\left(\frac{v_f}{v_o}\right)^{1-\gamma}\right] = \frac{P_0V_0}{1-\gamma}\left[1-(\frac{V_f}{V_0})^{1-\gamma}\right] \qquad (9)$$

now, for compaction to take effect (i.e. for particle adhesion in the green form), we must have at least 50% volume reduction (Al-Hassani, 1981) (see Fig.3). Therefore, the minimum velocity of the particular steel projectile should be;

$$v_0 = \left[\frac{2P_0V_0}{(1-\gamma)M}(1-2^{\gamma-1})\right]^{\frac{1}{2}} \qquad (10)$$

The final volume may also be obtained from eq (9) as;

$$\frac{V_f}{V_0} = \left[1-\frac{Mv_0^2(1-\gamma)}{2P_0V_0}\right]^{1/1-\gamma} = \frac{\rho_o}{\rho_f} \qquad (11)$$

Since $\gamma>1$ where ρ denotes density.

However, it is worthy to mention that for the dynamic compaction of powders, the mechanics of the process is quite complicated.

Substituting $v=v_f=0$ at H=Hg equation (8) becomes:

$$\frac{1}{2}Mv_0{}^2 = \frac{kA^{1-\gamma}}{1-\gamma}(H_0{}^{1-\gamma} - H_f{}^{1-\gamma}) \qquad (12)$$

If the pressure p(t) can be measured during compaction, the equation of motion (4) can be integrated to give the position of the projectile at time tas

$$H(t) = H_0 - v(o)t + \frac{A}{M}\int^t (t-s)P(s)ds \qquad (13)$$

Where s is a dummy variable of integration. If H(t) con also be measured this equation provides a check.

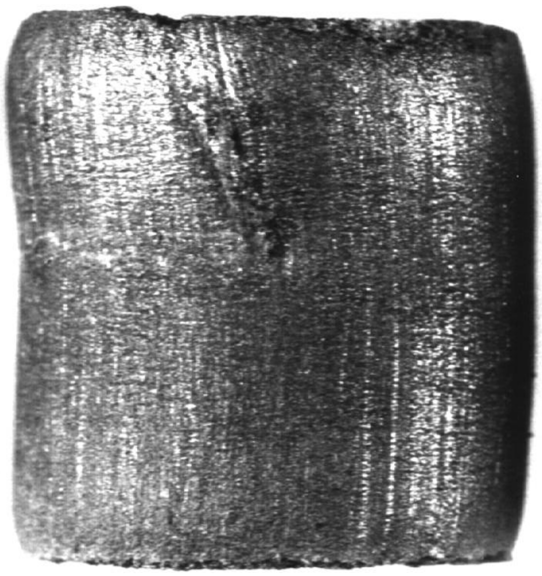

Figure 3. Product of pure iron powder (-100+150#) obtained using dynamic compaction process x 2,5

4. CONCLUSION

It is believed that a more fundamental understanding of the mechanics of the compaction process can be achieved through prior determination of the yield criterion, temperature distribution, and constitutive equations describing its behaviour together with an assessment of the influence of strain rate. However; further analysis is required to examine and to set a better understanding the mechanics of dynamic compaction process.

5. REFERENCES

AL-Hassani, S.T.S. 1981. Powder Compaction Under the Drop Hammer, Lecture notes , Applied Mechanics M.Se Course.

Ashton, M.D., Cheng, D.C.H., Forley, R.and Valentin, F.H.H., 1965. Apparatus for Measuring Tensile Strength of Powders, Roheol. Acta, 4, P 206.

Benson, D.J. Neills,W.J., 1994. Dynamic Compaction of Copper Powder Compaction and Experiment, Applied Physics Letters, 65, p. 418-420.

Bowden, F.P. and Tabor, D., 1967. Friction and Lubrication, Methuen, London.

Clyns, S. and Jahnson, W., 1977. The Dynamic Compaction of Powdered Materials. Material Science and Eng., 30, p. 121-139.

Donachie, M.J. and Burr, M.F., 1963. Effect of Pressing on Metal Powders, Journal of Metals, 15, p. 844.

Fleck, N.A., 1995. A Crystal Plasticity View of Powder Compaction, Acta Metallurgica Et Materialia, 43, p.3177-3184.

Hirschhorn, J.S., and Garey, M.W. 1969. Plastic deformation of Compacted Iron Powders, Int.J. Powder Met., 5, p. 35-44.

James, P.J., 1972, “Fundamental aspects of the consolidation of Powders”. Powder Met.Int., Vol. 4, p. 82-85.

Klar, E., 1983. Metals Handbook, Vol.7, Powder Metallurgy, American Society For Metals, Ohio, U.S.A.

Lenel, F.V., 1980. Powder Metallurgy; Principles and Applications, Metal Powder Industries Federation, Princeton, New Jersey, U.S.A.

Mc Kenna, P.M., Redmond, J.C. and Smith, E.N. 1953. US. Patent 2648125.

Navarro, L.M., Recio, P., Duran, P. 1995. Preparation and Properties Evaluation of Zirconia-Based Al_2O_3 Composites Electrolytes for solid Oxide Fuel-Cell Systems. Journal of Materials Science, 30, p. 1939-1948.

Rumpf, M., Knepper, N.A., 1962. Aglomeration, Interscience, N.Y. P.374.

Tong, W., Ravichadran, G., Christman, T., Vreeland, T., 1995. Processing SiC-Particulate Reinforced Titanium-Based Metal-Matrix Composites by Shock-Wave Consolidation, Acta Metallurgica Et Materialia, 43, p.235-250.

Wurster, D.E., Rowlings, C.E., Creekmore, J.R., 1995, “Calorimetric Analysis of Powder Comperssion. 1. Design and Development of a Comperssion Calorimeter”, International Journal of Pharmaceutics, Vol. 116, p.179-189.

Yanai, K., Ishimoto, S., Kubo, T., Ito, K., Ishikawa, T. 1995. Characterization of Ceramic Powder Compacts, Journal of Nuclear Materials, 224, p.79-84.