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Experimental Investigation of Metal Powder Compaction without Using Lubricant

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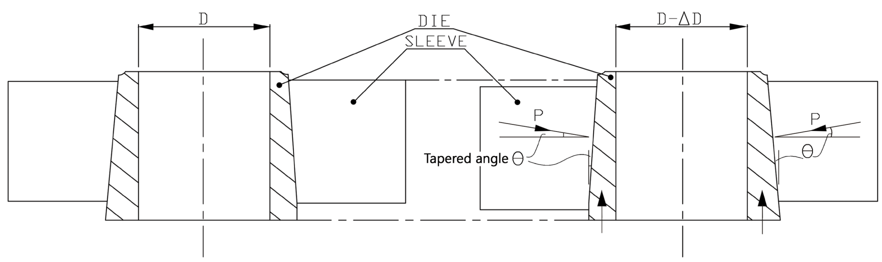
HIGHLIGHTS

- It allows to compacted metal powders without admix or die wall lubrication.
- The force required to eject the compact from the die (the ejection force) was almost zero.
- It was deduced that 0.076 mm contraction of the die diameter was indeed a realistic estimate
- This value provided sufficient shrinkage to cover both, elastic deformation during compaction and elastic spring back of green compact as well as a sufficient clearance between die wall and compact.

GRAPHICAL ABSTRACT



a. - Engagement of die-sleeeve before pressing together.

b. - Engagement of die-sleeeve when pressed together (Die penetrated 2mm into the sleeve) .

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ABSTRACT

The main objective of this work was to design a novel device for compaction of metal powders so that the green parts could be ejected with applying a negligible force and without the need for any lubricant in either an admixed form or applied to the die wall. For this purpose a 40 mm diameter one-piece die was envisaged which would elastically contracted 0.076 mm before compaction and after completion of powder compacting operation, it would be allowed to expand, thus releasing the green compact and so it could be ejected with a force near to weight of the compacts. The experiment indicated that this shrinkage value of 0.076 mm was indeed a realistic estimate which provided sufficient shrinkage to cover both:

I– The "elastic die deformation of 40 mm diameter during compaction" which shows 0.0433mm elastic deformation.

II–The "elastic spring back of the specimen of 40 mm diameter" which was 0.0227 mm after completion of compaction and releasing the compaction force.

The design also provided sufficient clearance of 0.010mm between the compact and the die wall on release of compacting pressure to allow ejection of compact with a force near to weight of compact while no lubricant was used on the die wall nor admixed with powder.

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1. Introduction

In powder metallurgy technique, when metal powders are pressed in rigid dies, there are several types of friction (1,2) such as:
(1) Friction between moving punch (es) and die wall.
(2) Friction between powder particles.
(3) Friction between powder particles and die wall.
(4) Friction between the compact and die wall during ejection of part after compaction.

These frictional effects can be reduced by use of suitable lubricant. Lubricant can either be mixed with the metal powder or applied on to the die wall. The effects of the lubricant on compaction and ejection behavior have been extensively reported by many researchers (3-5). The practice of admixing the lubricant with metal powder and its advantage has been discussed in detail (6-8). In other hand, die wall lubrication rather than admixing and disadvantages of admixing method have been reported by some researcher (9-14).

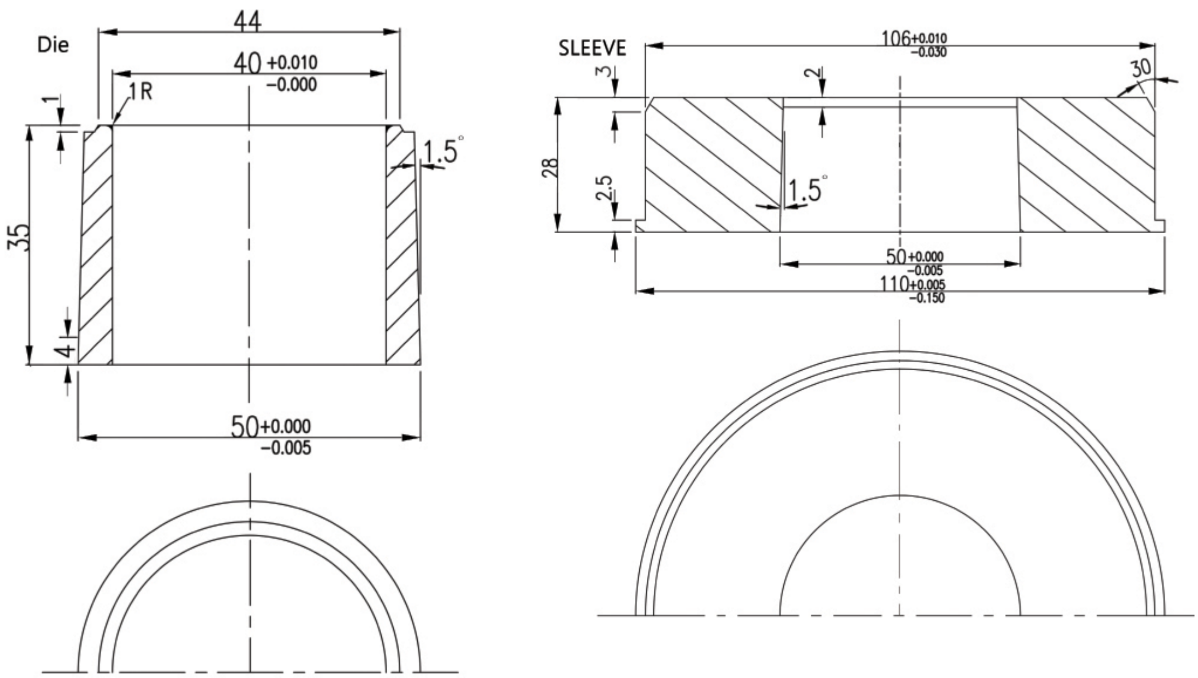
It seems that one of the main functions of using lubricant is to reduce ejection force, this is associated with reducing die wall friction and consequently tool wear. Since the friction between green part and die wall cause cracks on the compacted part as it emerges from the die. So, this study was intended to explore the possibility of a novel die design such that subsequent reduction in ejection forces could be achieved. For this purpose a novel die system was designed so that elastically contract just before powder compaction then the powder compact without using any lubricant in either an admixed formed or applied to the die wall and then the die elastically expands when the powder is compacted and the green part ejected with an almost zero ejection force.

2. Principle of tooling design

Based on previous experience (15) with forging solid bodies, in this design it was estimated that a realistic upper bound value of 0.076 mm lateral shrinkage on 40 mm diameter of the die could be used as a guide.

So, it was therefore decided to attempt to design a solid die rather than a segmental construction. A one-piece die would have obvious advantages over a split die (segmental) which would present the possibility of powder particles jamming between the segments. This one-piece die which would elastically contract radially before powder compaction and after compaction of powder would be allowed to expand radially, this resulted in releasing the green compact, while the die is held within a sleeve (supporting ring). The outer surface of the die and the inner surface of the sleeve are tapered 1.5° as shown in Fig 1.

Both tapered surfaces are carefully polished and coated with suitable lubricants. The object of this was to keep the two metal surfaces a part and to avoid metal to metal contact.



(a) Die (b) Sleeve

Fig. 1. Die and sleeve shown separately

The combined effects of a 1.5° radial taper on both parts (i.e. outer surface of the die and inner surface of the sleeve) and an axial movement of 2 mm of the sleeve with respect to the die by application of an axial force on the sleeve causes a pressure at the interface. Since the outer supporting ring (sleeve) is designed to be substantially thicker than the die, so this interface pressure results a radial displacement of 0.076 mm on the inner 40 mm diameter of the die. The radial displacement (i.e. shrinkage) is mainly inward and tensile hoop stresses in the sleeve are acceptably low. So, it would contract elastically putting the die in hoop compression which resulting contraction of 0.076 mm (i.e. just before starting the compaction). After powder compaction when the axial force is removed, they will disengaged (self- release) and the die expanded (release state) as shown in Fig 2.

3. Elastic shrinkage requires:

To design such a die it is necessary to determine the amount of elastic shrinkage required. In determining the amount of elastic contraction (shrinkage) to be imposed on the die, consideration must be given to:

(I) The elastic die deformation during compaction

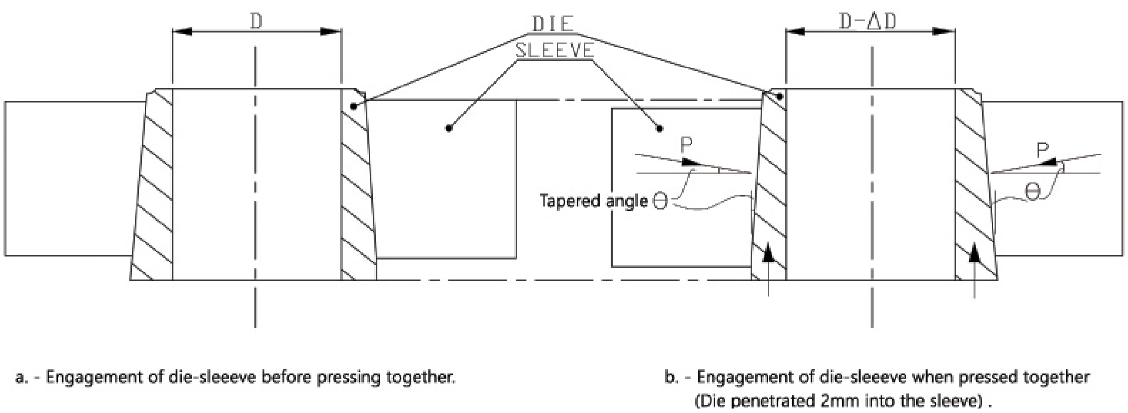
(II) The elastic spring back of the pressed part.

Since the elastic shrinkage of the die must cover these two values.

3.1. Theoretical estimates of elastic die deformation during compaction

The stresses and deformations produced in powder metallurgy dies depends on several factors, such as the axial compaction pressure, the radial (lateral pressure), the type of material being compacted and the physical characteristics and dimension of the die.

It is well known that a powder mass undergoing compaction in a conventional die exerts a lateral pressure on the die walls at right angles to the axis of compaction. Since the lateral pressure (P1) acts over only part of the die length so local deformation occurs, as shown in Fig 3.



(a) (b)

Fig. 2. Assembled die and sleeve (a) release state i.e. before and after compaction, (b) Just before and during compaction

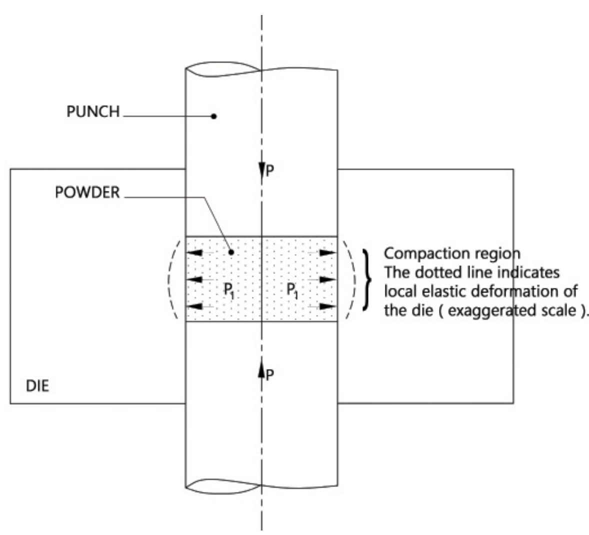


Fig. 3. Shows exaggerated local elastic deformation of a die by dotted lines

Removal of axial force allows the die wall to partially recover. Full recovery is resisted by the compacted part, therefore the amount of elastic deformation remain in the die wall is depend on the yield strength of the compact.

Bustamante,S.j etal (16) studied hoop stresses induced in a cylindrical steel die for compacting metal powder, they concluded that maximum deformation is obtained for the same powder height and applied load with finer powder particles, more ductile powders, addition of lubricant and also with powder height in the die cavity. Aren et al (17) in their research, they conclude that the lateral die wall pressure due to the powder is expected to have an exponential distribution. However, details of the distributions for specific powders for actual pressure levels are not given.

To find the amount of elastic deformation of the die, thick walled cylinder theory is used to calculate hoop and radial stresses. However, it must be noted that the die length is partially pressurized as shown in fig 3 where as in thick walled cylinder theory the total length of the bore is considered to be pressurized.

The hoop and radial stresses at any point in the wall cross- section of a thick cylinder at radius "r" are given by the lam´e equations:

$$\sigma_\theta = A + \frac{B}{r^2} \tag{1}$$

$$\sigma_r = A + \frac{B}{r^2} \tag{2}$$

Where σ_θ is hoop stress, θ_r is radial stress and r is radius of the die.

As it can be seen in Fig 4, at $r = r_o$ $\sigma_r = 0$

By substitute in equation (2) gives:

$$A = \frac{B}{r_o^2} \tag{3}$$

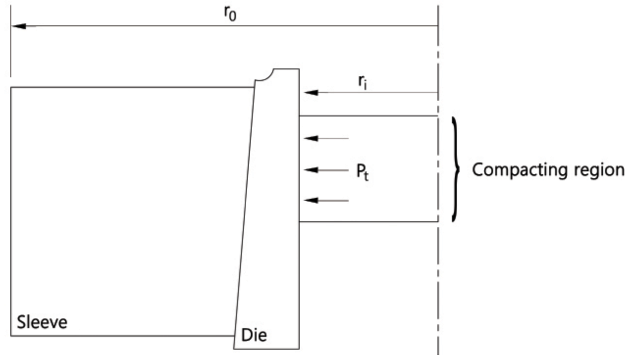


Fig.4. Shows boundary conditions on the die & sleeve

And at $r = r_i$ $\sigma_r = -Y_{compact}$

Where $Y_{compact}$ is yield strength of compacted part.

By substitute in equation (2) gives:

$$\sigma_{r_i} = -Y = A - \frac{B}{r_i^2} \tag{4}$$

And substitute in (3) gives:

$$B = \frac{-Y}{\frac{1}{r_o^2} - \frac{1}{r_i^2}} \tag{5}$$

Where r_i is inside radius of die = 0.020 m

r_o is outside radius of sleeve = 0.053m

Y is yield strength of compacted part.

Since three types of powders (Fe, Cu & Al) have been used, the extreme case is when iron powder is compacted with Y_{Fe}= 165 MN/m^2

Substitute in (5) gives:

B= 77×10^3 N

Substitute in (4) gives:

A= 27.4 × 10^6 N/m^2

By substituting A & B in equation (1) at $r = r_i$ gives:

σ_θ=220 MN/m^2

To find the corresponding radial strain which is related to the stresses, by using equation:

$$\varepsilon_r = \frac{1}{E}\sigma_r - \nu(\sigma_\theta + \sigma_z) \tag{6}$$

As Den Hartog,J.P.(18) assumed: σ_z= 0

By this assumption and substituting in equation (6) gives:

ε_r= 1.083× 10^{-3} m/m

Therefore the calculated elastic deformation on the die with 40 mm inside diameter when iron powder is compacted would be 0.0433 mm.

3.2. Elastic Spring Back of green part

It is known that when compaction has completed and upper punch and die base removed the compact does not fall out of the die. The compact remains in its die under a residual radial pressure of appreciable magnitude and has to be forced out. When the compact ejected from the die expands radially. This behavior is usually called "elastic spring back".

However the elastic behavior of green compact has received little attention, but Morgan, V.T (19) mentions that the elastic spring back amounting to 0.2% on the diameter is quite common in practice. He does not give any evidence in support of this value. Anyway, the elastic spring back of the compact on release of applied pressure depends on several factors such as the magnitude of the compacting pressure, the type of powder being consolidated and the size and shape of the product. But the most effective parameters are the magnitude of compaction pressure and the type of powder which has been used for compaction.

3.2.1.Theoretical estimates of elastic spring back of green compact

The phenomenon of elastic spring back of a specimen appears when the powder is fully compacted, and can be treated as a solid plug, according to the following analysis.

A solid plug is placed in a die in which it is a perfect fit, and a punch exerts pressure on the plug. Assuming that the material of the plug is isotropic, and friction between the plug and the die is negligible. When the axial pressure is increased so that yield takes place in the material of the plug, by removal of axial pressure the principal stresses in the plug are σθ and σr (assuming $\sigma_z = 0$). The radial pressure (P_1) will then be determined by conditions of yield i.e. when $(P_1)_{max} = Y_{\text{compacted material}}$ as shown in Fig 5.

Now, by considering Mohr´s theory (circle) when $\sigma_r = P_1$, $\sigma_\theta = \sigma_r$, $\sigma_z = 0$ and $(P_1)_{max} = Y$, where Y is yield strength of compacted material. The stress system and corresponding Mohr´s circle are shown in Fig 6.

The radial strain in the plug which is related to the stresses is given by stated equation (6):

$$\varepsilon_r = \frac{1}{E}\sigma_r - \nu\left(\sigma_\theta + \sigma_z\right) \tag{6}$$

Substitute mentioned value in (6) gives:

$$\varepsilon_r = \frac{Y}{E}\left(1 - \nu\right) \tag{7}$$

Now, by substitute the values of Y, E and ν of the material which has been used the radial strain of the green compact is determined. Since three types of

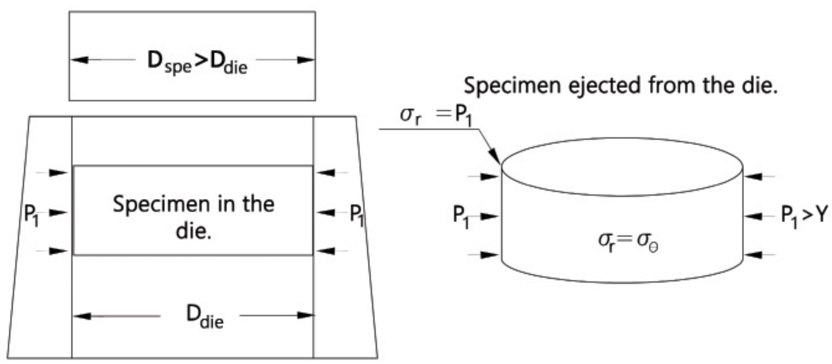


Fig.5. Shows green compact in the die & ejected from the die

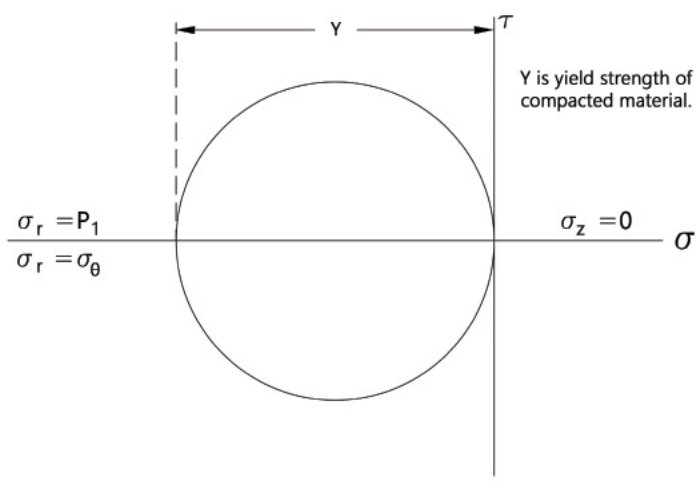


Fig.6. Mohr´s circle of stress system on the die

powder have been used the results are shown in table 1.

Table 1.
Radial strain for 3 types of compact

Material	Y MN/m^2	E GN/m^2	ν	ε_r m/m (calculated Value)
AL	50	71	0.34	4.65×10^{-4}
Cu	75	117	0.35	4.17×10^{-4}
Fe	165	206	0.29	5.69×10^{-4}

So, as it can be seen the largest elastic spring back of the green compact of 40 mm diameter is when the Iron powder has been used and it is 0.0227 mm.

4. Estimation of external pressure on the die for the shrinkage

Calculations of the contraction and expansion of the die were based on the mechanics of a thin-walled cylinder which is subjected to an external uniform pressure along its length. This theory is used for simplicity since the ratio of the mean wall thickness to the internal diameter of the die is $\frac{4.65}{40}=0.11$ however the die wall thickness is not uniform along its length so the mean wall thickness has been used.
From elastic theory, the hoop stress in a thin walled cylinder subjected to an external pressure is:

$$\sigma_\theta = \frac{P.D_i}{2t} \tag{8}$$

Where 'P' is External pressure on die, produced at interface of die and sleeve as shown in Fig 2,
'D_i' is inside diameter of die and 't' is mean wall thickness of the die.
Knowing that

$$\sigma_\theta = E.\varepsilon_\theta \tag{9}$$

$$\varepsilon_\theta = \frac{\Delta D_i}{D_i} \tag{10}$$

gives

$$\sigma_\theta = E\frac{\Delta D_i}{D_i} \tag{11}$$

By substitute in (8) gives:

$$P = \frac{2t.E.\Delta D_i}{D_i^2} \tag{12}$$

Where E = 210 GN/m^2, $\Delta D_i = 0.076\times10^{-3}$ m (i.e. inward radial shrinkage), D_i = 40×10^{-3} m, t = 4.65×10^{-3} m
By substitute these values in (12) gives: P=92.8 MN/m^2

This is the external pressure on the die which produces 0.076 mm shrinkage on the die diameter of 40mm.

5.Preparation of the tooling

Initially, the two matching tapered surfaces i.e. outer surface of the die and inner surface of the sleeve which have important functions in the operation are carefully polished using a sequence of polishing media (Diamond paste) ranging from 6μm to 1/4μm diamond particles. Then the surfaces were cleaned using acetone. The surface roughness of the tapered surfaces was found to be 0.08μm for the inner surface of the sleeve and 0.10μm for the outer surface of the die. Finally both tapered surfaces were coated, the sleeve with molybdenum disulphide spray and the other (die) with P.T.F.E. (Polytetrafluorethylene) and left to dry. Also, before assembly of the die unit both coated surfaces were greased using molybdenum disulphide grease. This combination prevent the problem of die seizure inside the sleeve, so that they disengaged easily (self-releasing). The object of this operation was to keep the two metal surfaces a part and to avoid metal to metal contact which would have two inherent advantages:
(a) To obtain a low coefficient of friction which would facilitate the self- releasing action i.e. disengagement of the die from the sleeve.
(b) To minimize damage due to sliding metal to metal contact i.e. on engagement-disengagement cycles.

5.1.Performance testing of the tooling

Cyclic loading tests were carried out on an Instron machine to determine the required axial load to push the die a distance of 2mm into the sleeve as shown in Fig7.

It was found that about 16KN force was required to push the die 2mm into the sleeve.

To determine the die shrinkage corresponding to axial movement of the die with respect to the sleeve, the die and its associated parts were put together. The die penetration into the sleeve was measured by a depth micrometer while the diameter shrinkage of the die was measured simultaneously by a bore gauge. The extents of axial movements in relation to die shrinkages are shown on Fig 8.

6. Materials Studied

Compacts were made from three types of materials:

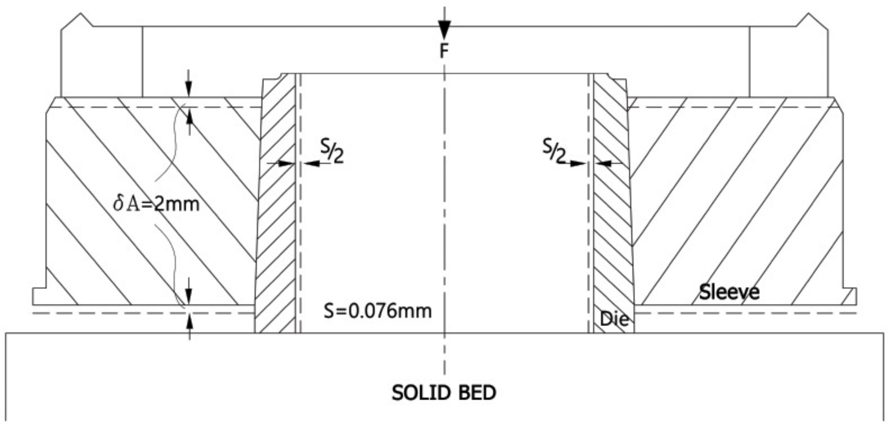


Fig.7. Die & sleeve assembly under cyclic loading

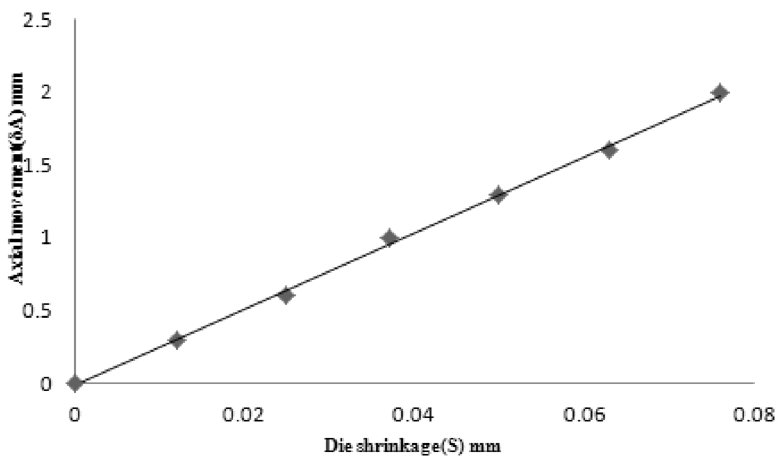


Fig.8. Axial movement of the die/its shrinkage

(a) Irregular atomized pure copper powder.
(b) Irregular atomized pure Iron powder.
(c) Irregular atomized pure Aluminum powder.

Two particle size ranges of each powder were selected for compaction with mean particles size range, 150μmm>d>75μmm and 75μmm>d>50μmm.

Since the clearance between the die base (lower punch) and the die is 0.076mm on diameter i.e. the circumferential gap is 0.038mm on release state i.e. before compaction, the powder particle ranges were chosen so that no powder particles could pass through the gap or trapped in the clearance gap, this could have interfered with the design of the die.

These powder were used for producing simple flat cylindrical disc, no admix lubricant or die wall lubrication was used during compaction.

7. Experimental Work

The die and its associated parts which have been designed and manufactured were put together (assembled) and fixed on a platform of a double action press for powder compaction. The standard experimental sequence consisted of weighting powder (50 gr) and filling the die cavity by hopper feeding and then leveling the powder in the die cavity before compaction. As mentioned compacts were made from three types of powders: copper, Iron and aluminum powders. By removing the hopper powder compacted. From each kind of powder particles, 20 compacts of same weight were produced for different destructive and non-destructive tests as green and sintered state.

8. Results and discussion

By application of almost 16KN axial force on the sleeve, an axial movement of 2mm of the sleeve with respect to the die caused a pressure of about 93 MN/m^2 at the interfaces. This interface pressure on the outer surface of the die resulted a radial shrinkage of 0.076 mm on the inner diameter of the die just before compacting of the powder.

Thus, powder compacted in the die cavity is 0.076 mm smaller in diameter than its normal state (i.e.40mm). By completion of compaction the upper punch was removed, it was found that all compacts could be ejected from the die with a force near to weight of compacts i.e. no extra force needed for die wall friction between compact and the die. All green compacts diameter was measured and are given in table 2 as a sample.

These values are in agreement with the predicted behavior of the die i.e. specimen diameters were smaller than the die diameter on normal position (the diameter of the die was 40.018mm) and larger when the die 0.076mm shrank (i.e. the diameter was 39.942mm). So, the experiment indicated that this shrinkage value of 0.076 mm was indeed a realistic estimate which provided sufficient shrinkage to cover both the local elastic die deformation of 0.043 mm and the elastic spring back of the green compact of 0.0227mm. Moreover, this value also provided sufficient clearance of 0.010mm in diameter between the compact and the die wall so that on release of compacting pressure to allow ejection of compacted part at a force near to weight of the compact while no lubricant was used on die wall nor admixed with powder.

Durability tests on the die were carried out after completion of powder compactions. These tests were devised to obtain some indications of the:

(a) potential life (cycles)

(b) wear characteristics

(c) General performance of the die assembly.

The outer surface of the die was coated with P.T.F.E. lubricant and inner surface of the sleeve with molybdenum disulphide lubricant spray. A simulated test was conducted in which the die was cycled relative to the sleeve. Displacement was equal to the movement of the die during compaction of powders (2mm).The die and sleeve set up on an Instron machine and cycled at 6 cycles per minute, approximately to expected industrial rate.

9.Conclusions

This novel die design shows that:

1. It allows to compacted metal powders (Fe, Cu and Al) without admix or die wall lubrication.
2. The force required to eject the compact from the die (the ejection force) was near to compacts weight (i.e. no extra force needed for die wall friction between compact and the die).
3. It was deduced that o.o76mm contraction of 40 mm die diameter was indeed a realistic estimate which provided sufficient shrinkage to cover both, the elastic deformation during compaction (0.043mm) and the elastic spring back of the green compact (0.0227mm) as well as a sufficient clearance (0.010mm) between the die wall and the compact.
4. It was shown that the 1.5° tapered on outer surface of the die and inner surface of the sleeve was an excellent taper angle for self releasing the die and sleeve, so that by completion of compacting cycle and removing the applied load which was on the sleeve, the die and sleeve easily disengaged i.e. self- releasing.

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Table 2.
Diametral details of compacted powders

Samples	Fe 150>d>75 µmm	Fe 75>d>50 µmm	Cu 150>d>75mmµ	Cu 75>d>50µmm	Al 150>d>75 µmm	Al 75>d>50 µmm
1	39.987	39.992	39.992	39.990	39.997	39.992
2	39.992	39.975	39.990	39.988	39.995	39.990
3	40.005	39.992	39.997	39.992	39.996	39.989
4	39.992	39.993	39.993	39.985	39.997	39.989
5	39.991	39.975	39.989	39.999	39.997	39.987
6	39.990	39.985	40.007	39.987	39.995	39.995

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