Deformation and fracture mechanism during forging of Sintered preform

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Abstract--- Metal powder technology is currently arousing global interest as an economic method of producing components from metal powders. The process is attractive because it avoids large number of operations, high scrap losses and high-energy consumption associated with the conventional manufacturing processes such as casting, machining, etc. The properties of the metal powder products are comparable and in some cases even superior to those of cast and wrought products. The bulk processing of metal powder has therefore wide industrial applications because of good dimensional accuracy and surface finish with enhanced load bearing capacity of the component. So far this technology has been developed and employed without substantial theoretical background. A systematic approach is important to analyze and predict, the behavior of powder perform. Such as, the deforming loads necessary to deform the product plastically, or the density of the product, etc. In conventional wrought metal forming analysis, volumetric constancy is assumed for the deforming material, but this assumption cannot be made in the plastic deformation of porous metals where density does not remain constant and changes with load. The present work will help academician and the person associated with metal powder working in analyzing various properties. Sinter-forging has been commercially exploited in recent times for developing requisite product.

Keywords-Sintered Preform, Compaction, Metal Forming, Deformed load, Porous Metal.

I . INTRODUCTION

Powder Metallurgy is a process that has been utilized for centuries, dating back to 2500 B.C. It has become one of the most common, most efficient processing techniques. Powder metallurgy components are being used in ever increasing quantities in a wide variety of industries as the technology combines unique technical features with cost effectiveness by reducing quantity of scrape and at the same time cost of machining is less. Among the various metalworking technologies, powder metallurgy (P/M) is the most diverse manufacturing approach. One attraction of P/M is the ability to fabricate high quality, complex parts to close tolerances. In essence, P/M takes a metal powder with specific attributes of size, shape, and Packing, and then converts it into a strong, precise, high performance shape by compression (1-4). Key steps include the shaping or compaction of the powder and the subsequent thermal bonding of the particles by sintering in the furnace and cooling in the control environment. The cooling rate also has effect on properties of metal components. The solution developed in the present work may find a great potential in automation and solving bulk-processing problems of metal powder performs (5-7).

The process effectively uses automated operations with low relative energy consumption, high material utilization, and low capital costs. These characteristics make P/M well aligned with current concerns about productivity, energy, and raw materials. Consequently, the field is experiencing growth and replacing traditional metal-forming operations. Further, powder metallurgy is a flexible manufacturing process capable of delivering a wide range of new materials, microstructures, and properties (8-13). The formability of porous metal powder preform has been discussed critically to illustrate the various processing parameters involved and the results are presented graphically.

II. Study and Design of Experimental Setup

2.1 Metal Powder Used

Basic experiments were conducted on Copper and Aluminium metal powder preforms.

(a) Aluminium Powder:-

Atomized Aluminium powder of purity 99.5% and finer than 100 μm was used throughout the experiments. The physical and chemical property of Aluminium powder is given in the Table-2.1 and Table-2.2 respectively.

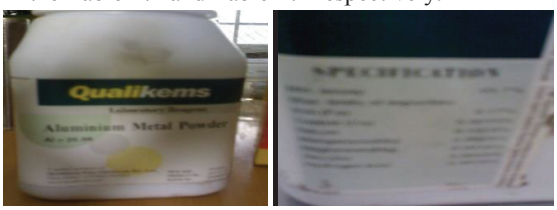

Fig.2.1Aluminium powder used in experiment

Apparent Density 1.20 g/cc
Tap Density 2.1 g/cc
Maximum Limits of Impurities-

Iron Contents	0.17%
Copper	0.00159%
Silicon	0.1313%
Manganese	0.0023%
Magnesium	0.00160%
Zinc	0.0053%
Hydrogen Loss	0.4879%

Table 2.1: Physical Characteristics of Atomized Aluminum Powder used

(b) Copper Powder:-

Electrolytic Copper powder of greater than 99% purity was used for preparation of test piece. The physical and chemical property of Copper powder is given in the Table-2.3 and Table-2.4 respectively.

Apparent Density 2.60 g/cc

Tap Density 7.2 g/cc

Screen Analysis (micron)	+100	-100 +150	-150 +200	-200 +240	-240 +350	-350
Percentage Weight Retained	0	35.00	15.00	14.50	20.00	14.50

Table2.3: Physical Characteristics of Copper Powder used

Maximum Limits of Impurities-

Copper	99.80%
Phosphorous	< 0.001%
Iron	< 0.006%
Silicon	< 0.002%

Table 2.4: Chemical Analysis of Sintered Copper Powder (Weight Percentage)

2.2 Preparation of Specimens and Density Measurement.

In the preparation of metal powder compacts the following steps are necessary:

1.Die preparation
2.Compaction
3.Sintering
4.Machining

2.2.1 Die preparation

Firstly we made the five dies (circular, square, rectangular, hexagonal) for filling the powder in these, so that we can get the specimen as our required shape and size. For this circular dies are made and then we prepare the head and base for the die.

SPECIFICATION OF DIES

S.No.	Die	Internal Diameter	Height
1.	circular die 1	16 mm	70mm
2.	circular die 2	25.4mm	85mm

S.No	Die	Side	Width	Outer diameter	Length
1.	Hexagonal die	16mm	-----	40mm	65mm
2.	Square die	20.3 mm	-----	-----	75
3.	Rectangular die	25.4 mm	20.3 mm	-----	65 mm

Extrusion die set

1. Circular cross-section
   Cone angle -7
2. Circular cross-section
   Cone angle -10
3. Circular cross-section
   Cone angle -15

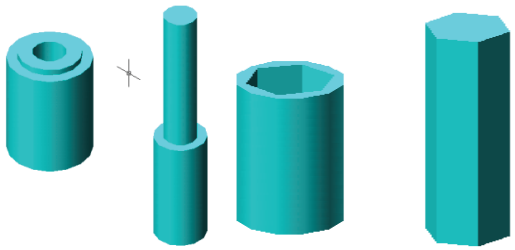

Fig.2.2 Circular & Hexagonal cross-section die

2.2.2 Compaction

For compaction firstly the powder material is filled in the die as shown in the image, in which copper powder is filled up in the die.

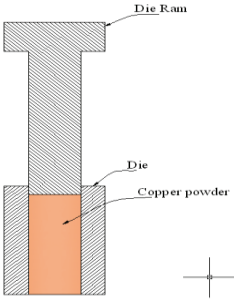

Fig.2.3 Filling of copper powder material

Aluminium and copper both powder was separately compacted in a closed circular die using a hydraulic press at various recoded pressures. The die wall was lubricated with fine graphite powder. After that compaction is done as shown in next figure. Compaction is done by the help of universal testing machine (UTM), on which dies are placed and after then pressure is applied as our requirement.

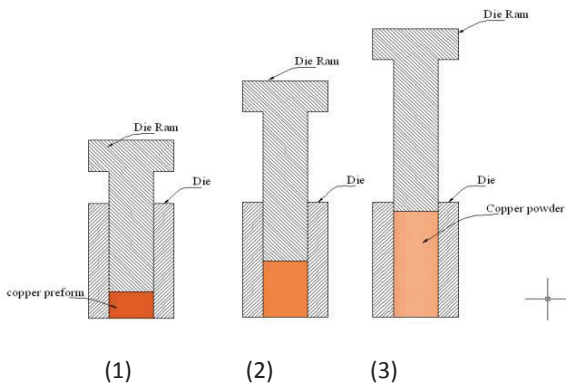

Fig.2.4 Compaction process on Hydraulic press and UTM

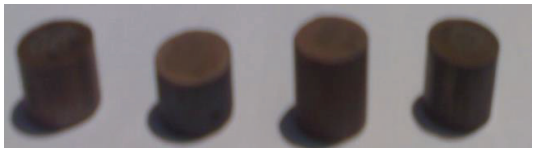

Fig.2.5 Compacted billets of copper

Fig.-2.6 compacted billets of aluminium

2.2.3 Sintering

The basic purpose of sintering is to develop mechanical strength in the metal powder compacts. Sintering of aluminium compacts was carried out at 4000C and 4500C for two hours in an endothermic sand atmosphere and sintering of copper compacts was carried out at 6000C and 7000C for two hours in an endothermic sand atmosphere. All sintering operations were carried out in a muffle type silicon carbide furnace capable of providing sintering temperature of an accuracy of ± 50C.

In order to minimize the non-uniformity of density distribution, the sintered compacts were re-pressed at the same compaction pressure in the same die. The specimens were resintered at the same temperature and time.

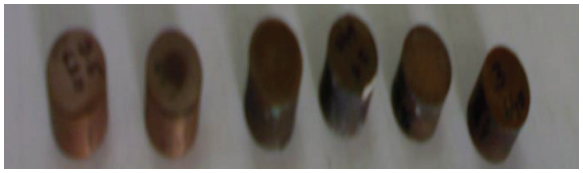

Fig.-2.7 Sintered billets of copper power

Fig.-2.8 Sintered billets of aluminium powder

Fig.- 2.9 Hexagonal Sintered billets of copper & aluminium powder

Fig.-2.10 Rectangular Sintered billets of copper & aluminium powder

2.2.4 Experimental Procedure and Measurements

Experiments were conducted on a Universal Testing Machine and hydraulic press using appropriate dies. The Aluminium and Copper powder preform of known relative density was placed between flat dies and was compressed at room temperature by applying the load. The compression was carried out in dry and lubricated conditions. Fine graphite powder was applied as lubricant. The following important measurements were made:

(i) Increase in relative density of the preform with increase in compressive load.
(ii) Increase in relative density of the preform with decrease in height.

In order to evaluate the formability (limit reduction) the sintered Aluminium and Copper powder preforms of known initial relative densities were deformed at room temperature between flat dies. The compressive load was gradually increased until cracks were observed on the equatorial free surface of the Aluminium and Copper powder preform. The percentage compression and the corresponding compressive load value just at the time of the appearance of cracks were recorded for all specimens. The experimental procedure was repeated for five compacts under the similar processing conditions and an average reading was recorded.

Sr. No.	Metal Powder Used	Sintering Temp. & Time	Shape/Size of the Preform
1.	Copper	6000C 6300C 6500C For 3 hours	1.Cylindrical ϕ16mm X 12mm 2. Square 20mm X 20mm X 11mm 3.Hexagonal side-15mm height-12mm 4.cilinderical ϕ16mm X 12mm ϕ16mm X 12mm
2.	Aluminium	4000 C 4500C For 3 hours	1.Cylindrical ϕ16mm X 15mm ϕ16mm X18mm 2. Cylindrical ϕ25.4mm X 16mm ϕ25.4m X18mm ϕ16mm X 20mm 3.Hexagonal side-20.3mm height-13mm 4.cilinderical ϕ16mm X 22mm

repeated for five compacts under the similar processing conditions and an average reading was recorded.

2.3 Metallographic Test Preparation

Preparation of metallographic specimens generally requires five major operations: sectioning, mounting (which is optional), grinding, polishing and etching. A well-prepared metallographic specimen is sectioned, ground and polished so as to minimize disturbed or flowed surface metal caused by mechanical deformation, and thus to allow the true microstructure to be revealed by etching.

Sectioning

Important uses of metallography other then process control include: examination of defects that appear in finished or partly finished products and studies of parts that have failed in service. Investigations for these purposes usually require that the specimen be broken from a large mass of material, and often involve more than one sectioning operation.

2.3.1 Mounting of Specimen

Compression mounting, the most common mounting method, involves molding around the specimen by heat and pressure such molding materials as Bakelite diallyl phthalate resins, and acrylic resins. Bakelite and diallylic resins are thermosetting, and acrlyic resins are thermoplastic. Both thermosetting and thermoplastic materials require heat and pressure during the molding cycle, but after curing, mounts made of thermosetting materials may be ejected from the mold at maximum temperature. Thermoplastic materials remain molten at the maximum molding temperature and must cool under pressure before ejection.

Mounting presses equipped with molding tools and a heater is necessary for compression mounting. Readily available molding tools for mounts having diameters of 1 inch are used for mounting of specimen. Consist of a hollow cylinder of hardened steel, a base plug, and a plunger.

Fig.-2.11 Specimen mounting machine mounted specimen

A specimen to be mounted is placed on the base plug, which is inserted in one end of the cylinder. The cylinder is nearly filled with molding material in powder form, and the plunger is inserted into open end of the cylinder. A cylindrical heater is placed around the mold assembly, which has been positioned between the platens of the mounting press. After the prescribed pressure has been exerted and maintained on the plunger to compress the molding material until it and the mold assembly has been heated to the proper temperature nearly for 10 minute, the finished mount may be ejected from the mould by forcing the plunger entirely through the mold cylinder.

2.3.2 Finishing Process

Grinding is accomplished by abrading the specimen surface through a sequence of operations using progressively finer abrasive grit. Grit sizes from 40 mesh through 150 mesh are usually regarded as coarse abrasives and grit sizes from 180 mesh through 600 mesh as fine abrasives. Grinding should commence with coarse grit size that will establish an initial flat surface and remove the effects of sectioning within a few minutes. An abrasive grit size 150 or 180 mesh is coarse enough to use on specimen surfaces sectioned by an abrasive cutoff wheels. Hacksawed, band sawed or other rough surfaces usually require abrasive grit sizes in the range 80 to 150 mesh. The abrasive used for each succeeding grinding operation should be one or two grit size smaller than that used in the preceding operation. A satisfactory grinding sequence might involve grit sizes of 180, 240, 400, 600, 800, 1000 and 1200 meshes.

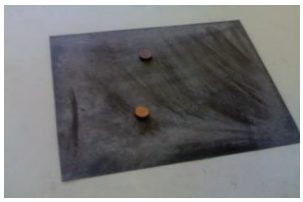

Fig.2.12 Amery paper used for primary finishing

Grinding Mediums

The grinding abrasives commonly used in the preparation of specimens are silicon carbide (SiC), aluminium oxide (Al2O3), emery (Al2O3 - Fe3O4), diamond particles, etc. Usually are generally bonded to paper or cloth. Aluminium oxide abrasive material has a trigonal crystal structure and a hardness of 9.1 on the Morhs scale and is synthetic corundum.

Lapping

Is a grinding technique similar to disk grinding. The grinding surface (lap) is a rotating disk whose working surface is charged with a small amount of a hard abrasive material. Laps are made of wood, lead, nylon, paraffin, paper, leather, cast iron and laminated plastics. The abrasive charge may be pressed into lap material by means of a steel block, or the lap may be charged directly with a mixture of abrasive and distilled water during lapping. A groove in the form of a spiral is a direction counter to the lap rotation is often cut in the surface of laps, particularly of lead and paraffin laps. The spiral groove aids retention of cooling water and abrasive.

2.3.3 Polishing

Polishing is the final step in production a surface that is flat, scratch free, and mirror like in appearance. Such a surface is necessary for subsequent accurate metallographic interpretation, both qualitative and quantitative.

Polishing Cloths

A cloth without nap or with a very low nap is preferred for the preliminary or rough polishing operation. The absence of nap ensures maximum contact with the polishing abrasive, and results in fast cutting with minimum of relief. The cloths most frequently used are canvas, low-nap, cotton, nylon and silk. After installation, the cloths are charged with the appropriate abrasive (usually in sizes from 15 microns down to 1 micron) and carrier. Rough polishing is usually done with the laps rotating at 500 to 600 rpm.

Fig.-2.13 Polishing machine polishing process

Polishing Abrasives

Polishing usually involves the use one or more of five types of abrasive: aluminium oxide (Al2O3), magnesium oxide (MgO), chromic oxide (Cr2O3), iron oxide (Fe2O3), and diamond compound. With the exception of diamond compound these abrasives are normally used in a distilled water suspension. Aluminium oxide (alumina) is the polishing abrasive most widely used for general metallographic polishing. The alpha grade aluminium oxide is used in a range of particle sizes from 15 microns to 0.3 micron. For some hard materials the 0.3 micron size is sufficient for a final polish. The gamma grade of aluminium oxide is available in a 0.05 micron particle size for final polishing.

Fig.2.14 Aluminium Oxide (polishing abrasive)

2.3.4 Etching

Although certain information may be obtained from as-polished specimens, the microstructure is usually visible only after etching. Only features which exhibit a significant difference in reflectivity (10% or greater) can be viewed without etching.

Chemical Etching

Chemical etching is based on the application of certain illumination methods, all of which use the Kohler illumination principle. This principle also underlies common bright-filed illumination. These illumination modes are dark field, polarized light, phase contrast and interference contrast. They are available in many commercially produced microscopes, and in most cases, the mode may be put into operation with few simple manipulations.

Fig.-2.15 Etching Agent (methanol)

Cleaning

Cleanliness is an important requirement for successful sample preparation. Specimens must be cleaned after each step; all grains from one grinding and polishing step must be completely removed from the specimen to avoid contamination, which would reduce the efficiency of the next preparation step. Through cleaning is particularly critical after fine grinding and before rough polishing and all subsequent steps.

After cleaning, specimens may be dried rapidly by rinsing in alcohol, benzene, or other low-boiling-point liquids, then placed und a hot-air drier for sufficient time to vaporize liquids remaining in cracks and pores. Rinsing is most frequently used and consists of holding specimen under a stream of running water and wiping the surface with a soft brush or cotton swab.

Fig.2.16 Prepared specimen for metallography

Fig. 2.17 Metallurgical Microscope

3. Experimental Results And Discussion

Densification

Densification of Aluminium and Copper powder preform before and after deformation is governed by several factors, which interact with each other in a complex manner. Some of the important factors considered here are as follows:

(a) Powder Particle Size-

Powder particle size has a remarkable effect on the relative density which in turn affects deformation characteristics and fracture mechanisms of the metal powder preforms. The influence of powder particle size on the relative density of the copper powder preforms compacted at 30 kg/mm2 and sintered at 6500C and the influence of powder particle size on the relative density of the aluminium powder preforms compacted at 10 kg/mm2 and sintered at 4500C and. The decrease in grain size of powder, however, results in more densification and improvement in formability of the powder preforms. Poor flow rate for finer particles are also observed.

(b) Compacting Pressure-

Figure 3.1.1 & fig 3.1.2 shows the relative density variation with increase in compacting pressure. It is seen that the relative density of the Aluminium and Copper powder preform increases gradually with increase in compacting pressure. The formability of Aluminium and Copper powder preforms improves at higher compacting pressure.

Combine figure and table for various compacting pressure and different temperature range (600˚C - 650˚C) for copper

Table.3.1.1

At Temp- LOAD	620˚C REL. DEN.	630˚C REL. DEN.	640˚C REL. DEN.	650˚C REL. DEN.
1.5	0.574588	0.61553	0.62821	0.6351683
2	0.613005	0.64388	0.6541	0.65117385
2.5	0.676908	0.67877	0.70448	0.71921792
3	0.696438	0.6979	0.71242	0.74385264
3.5	0.705491	0.72734	0.75162	0.763821478

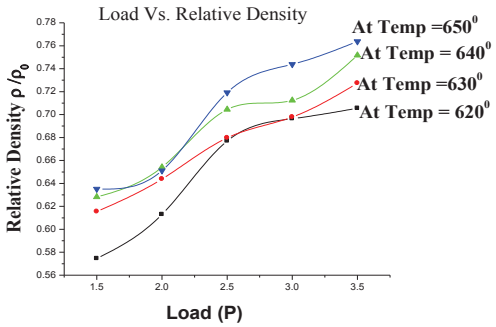

Fig.-3.1.1

Fig. 3.11 shows load Vs. relative density for various sintering temperature, considerable pattern for increase in relative density. In Fig: 3.1.1 relative density increases with rapid rate from load 0 - 2.5 tone. After that rate of increase in relative density decrease in the range of load from 2.5 – 3 tone. Further increase in load shows an increased rate of increase in relative density. So we can conclude that compacting pressure range for copper components is 3 tones to 4.5 tones per inch square for better quality and for obtaining relative density near to unity i.e. density of copper powder components approaches to the density of solid copper .

Combine figure and table for various compacting pressure and different temperature range (400˚C-450˚C) for aluminium

Table.-3.1.2

At Temp LOAD	410˚C Rel. Density	420˚C Rel. Density	430˚C Rel. Density	440˚C Rel. Density
1.5	0.707582	0.70397	0.71835	0.71081079
2	0.757399	0.76256	0.76758	0.8302024
2.5	0.775723	0.78334	0.79867	0.83108403
3	0.819335	0.82335	0.82836	0.84860878
3.5	0.853088	0.86611	0.87309	0.88458159

Fig: 3.1.2 load Vs. relative density for various sintering temperature shows a considerable pattern for increase in relative density. In Fig: 3.1.2 relative density increases with rapid rate from load 0 – 2 tone. After that rate of increase in relative density decrease in the range of load

from 2 -2.5 tone. Further increase in load shows an increased rate of increase in relative density. So we can

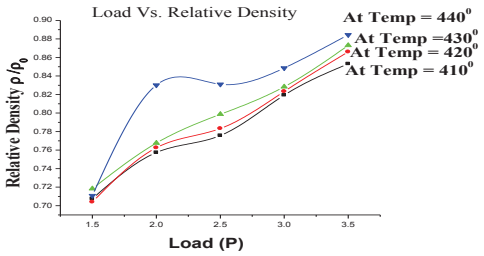

Fig.- 3.1.2 Variation between load in tone and relative density

conclude that compacting pressure range for aluminium components is 3 tones to 4 tones per inch square for better quality and for obtaining relative density near to 1. i.e. density of aluminium powder components approaches to the density of solid aluminium.

(c) Sintering Temperature

The basic purpose of sintering is to improve the strength of green compacts. Fig: 3.3.1 & Fig: 3.3.2 shows the variation of relative density with the sintering temperature for preforms compacted at various compacting pressure. It is observed that the relative density of the Aluminium and Copper powder preform increases with both the sintering temperature and compacting pressure.

3.3 Relation Between Temperature And Relative Density At Different Load

Table.-3.3.1

	1.5 load	2.0 load	2.5 load	3.0 load	3.5 load
Temp.	Rel. Den	Rel. Den	Rel. Den	Rel. Den	Rel. Den
410	0.707582	0.757399	0.775723	0.819335	0.853088
420	0.70397	0.76256	0.80334	0.82335	0.86611
430	0.71835	0.76758	0.77786	0.82836	0.87309
440	0.71081	0.8302	0.83108	0.84861	0.88458

3.3.1 For Aluminium

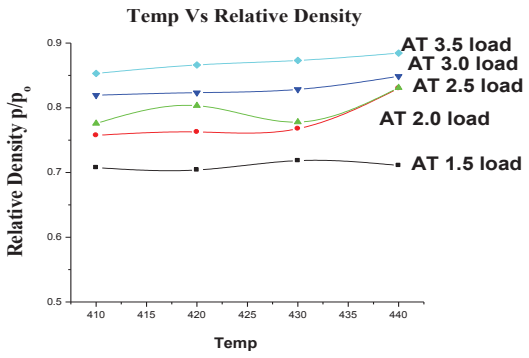

Fig .-3.3.1

As shown in the Fig: 3.3.1 relative density increases with the increase in sintering temperature. It is experimentally found that the pieces held at greater sintering temp. have the high density as compared to the pieces held at relatively low sintering temp. This difference in the density occurs due to the bonding formation between the powder particles. At relatively high temp. Crystallization takes place and bonding starts between the particles as a result void reduced in the metal preform hence density increases. Crystallization Temp. for aluminium is 450˚C.

3.3.2 For Copper

Relation between Temperature and Relative density at different Load

Table.-3.3.2

	1.5 load	2.0 load	2.5 load	3.0 load	3.5 load
Temp	Rel. Den	Rel. Den	Rel. Den	Rel. Den	Rel. Den
620	0.574588	0.613005	0.676908	0.69643823	0.705491
630	0.615528	0.633882	0.678769	0.69789954	0.727345
640	0.628212	0.654097	0.704478	0.71241793	0.751617
650	0.635168	0.651174	0.719218	0.74385264	0.763821

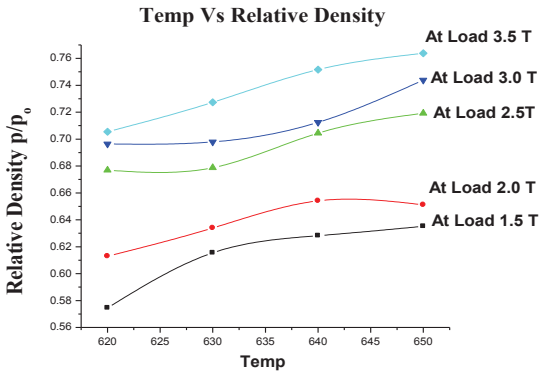

Fig:-3.3.2

As shown in the Fig: 3.3.2 relative density increases with the increase in sintering temperature. It is experimentally found that the pieces held at greater sintering temp. have the high density as compared to the pieces held at relatively low sintering temp. This difference in the density occurs due to the bonding formation between the powder particles. At relatively high temp. Crystallization takes place and bonding starts between the particles as a result void reduced in the metal preform hence density increases.

(d) Compression

The influence of compression is to increase the relative density of the metal powder preform. The relative density of the preform increases with increase in compressive load as shown in Fig: 3.1.1 and Fig: 3.1.2. The relative density of the preform increases very sharply at the beginning of loading and then increases slowly with increase in load. After attaining $\rho \approx 1$ the preform starts yielding significantly.

For simple compression, the pressure distribution at the die-work piece interface decreases from the center towards the edge. The decrease in adhesion friction results in a further decrease in the pressure distribution which in turn affects the relative density. Therefore, the relative density is a function of pressure and flow stress of the metal powder preform.

3.4 Result and discussion of matelography test

Effect of sintering temperature on microstructure of copper preform

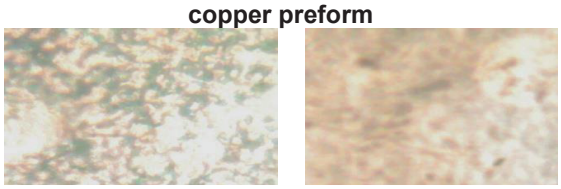

Fig: 3.4.1 Copper (sintering temp=600˚C) & Copper (sintering temp=620˚C)

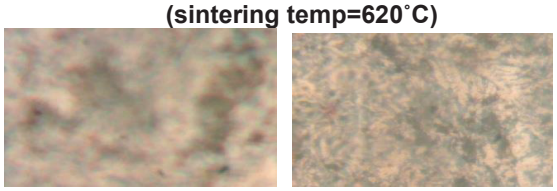

Fig: 3.4.2 Copper (sintering temp=640˚C) & Copper (sintering temp=650˚C)

The above photograph of microstructure shows the effect of sintering temperature on bonding of metal powder. These micrograph shows that the grain size was enlarged approximately 2 times (from about 0.4µm at 600c to about 0.75 µm at 650˚C after 120 min.). Grain size increases with increase in sintering temperature. At low temperature bonding between the particle does not take place. When there is increase in the sintering temp. , crystallization stage reached where bonding between particles takes place which result in the uniform micrograph as shown in above fig for sintering temp. 650˚C. A densification of about 12% and relative density of approximately 65% to 77% of the pore-free value were obtained during the solid state sintering of Cu. From temp.600˚C to 650˚C.

Fig: 3.4.3 Void between the bonded particles of powder

The above micrograph shows the formation of void due to interruption of air between the metal powders during compaction process. Air does not release from the preform and filled between the interstitial sites which result in the formation of void as shown in the above micrograph. These void are formed due to compacting pressure simultaneously void can be reduced by increasing the compacting pressure and by using suitable die design.

Effect of sintering temperature on microstructure of aluminium perform

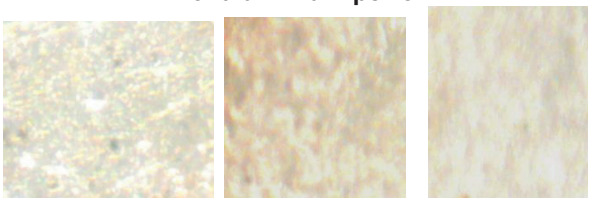

Fig: 3.4.4 Aluminium (sintering temp=400˚C); Aluminium (sintering temp=420˚C) &Aluminium (sintering temp=430˚C)

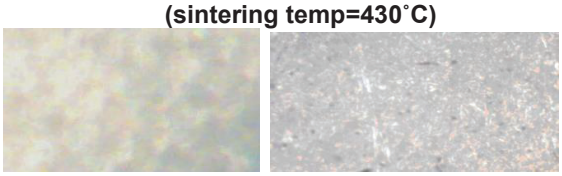

Fig: 3.4.5 Aluminium (sintering temp=440˚C) & Aluminium (sintering temp=450˚C)

The above photograph of microstructure shows the effect of sintering temperature on bonding of metal powder. These micrograph shows that the grain size was enlarged approximately 2 times (from about 0.1µm at400˚C to about 1.75 µm at 450˚C after 150 min.). Grain size increases with increase in sintering temperature. At low temperature bonding between the particles does not take place. A densification of about 5% and relative density of approximately 84% to 89% of the pore-free value were obtained during the solid state sintering of Cu. From temp.400˚C to 450˚C. When there is increase in the sintering temp. , crystallization stage reached where bonding between particles takes place which result in the uniform micrograph as shown in above fig for sintering temp. 450˚C.

V. CONCLUSION

On the basis of above experiments some basic rules are established and these rules will be very much helpful for analysis of the deformation characteristics of the metal powder performs for evaluating the various parameters such as die load, internal power of deformation, relative density distribution etc. These rules are also used for verifying the experimental results with theoretical mathematical solutions.

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