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# RECYCLING OF CAST IRON SWARF THROUGH POWDER METALLURGY TECHNIQUE AND ITS PROPERTY EVALUATION

A thesis submitted to the Department of Metallurgical Engineering, Bangladesh University of Engineering and Technology (BUET), Dhaka, in partial fulfillment of the requirements for the degree of Master of Science in Engineering (Metallurgical).


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**CERTIFICATE**

This is to certify that this work has been carried out by the author under the supervision of Dr. Zariff Ahmed Chaudhury, Associate Professor, Department of Metallurgical Engineering, B.U.E.T., Dhaka, and it has not been submitted elsewhere for the award of any other degree or diploma.

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The undersigned examiners appointed by the Committee of Advanced Studies and Research (CASR) hereby recommend to the Department of Metallurgical Engineering, Bangladesh University of Engineering and Technology, Dhaka, the acceptance of the thesis "Recycling of Cast Iron Swarf Through Powder Metallurgy Technique and Its Property Evaluation" submitted by Mr. A.K.M. Bazlur Rashid, B.Sc. Engg. (Metallurgical) in partial fulfillment of the requirements for the Degree of Master of Science in Engineering (Metallurgical).

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# Contents

# ABSTRACT

Powder metallurgical tests have been carried out in connection with an investigation of the recycling possibilities for cast iron swarf. The machining swarf was converted to powder by ball milling. These powders were then sieved, the free carbon removed and the carbon content of the powders further reduced by heating in an oxidizing atmosphere produced by the addition of iron oxide. The characteristics of the powders such as chemical composition, sieve analysis, flow-rate, apparent and tap densities were determined. The compaction and sintering characteristics of these powders were also studied and the green densities under different compacting pressures and sintered densities at various sintering temperatures and pressures were recorded. The effect of the addition of a small amount of nickel powder on compaction and sintering characteristics were also studied.

It was found that gray cast iron swarf can be pulverized in a ball mill and carbon level can be reduced by washing and by reduction with iron oxide. The apparent and tap densities of the particles were increased after washing and decarburization. The flow-rate of the powder was decreased slightly after washing and then increased after

decarburization. The green and sintered densities were increased with pressure and sintering time temperature. The fractured surfaces showed a better finaness of the particle grains with increasing compacting pressure and sintering temperature. The addition of nickel decreases the compactibility of cast iron powders.

The work showed that if we could control the manufacturing processes the reclamation of these powder by powder metallurgy technique is feasible.

# Chapter One

## INTRODUCTION

## 1.1 Introduction

Research work on the reclamation of machining swarf has been carried out in the past, but the cost of the recovered metals did not show a strong economic ground for further work. In fact, until the advancement in powder metallurgy, no big effort was made for the reclamation or recycling of the machining swarf generated in engineering manufacture, other than its remelting in the furnace. In the last decade, a rapid increase in the cost of engineering materials followed by an increase in the cost of energy has drawn the attention of many research workers to find a suitable method, which would result in most economical reclamation of the large amount of machining swarfs generated.

Among the various machining swarf generated in the production shops, swarfs of mild steels, low alloy steels, cast iron, brass, aluminium and its alloys are most common for consideration regarding reclamation. Of these, ferrous machining swarf represents a major portion of the total tonnage of swarf produced. In fact, chips of the ferrous machining swarfs and particularly that of mild steel and low alloy steel possess high bulk and large surface area, but are contaminated with cutting oil. The following problems are faced during remelting:

(a) Because of oxide contamination the metal recovery is low.

(b) To improve recovery from the powders, often briquetting is necessary.

(c) The production of smoke and pollutants as a result of the residual cutting oil.

Due to the above problems, ferrous machining swarf is supposed to be a low grade scrap. Moreover environmental problems and economical reasons tend to decrease its demand for remelting by foundries and steel plants.

On the contrary, ferrous machining swarfs have many good aspects also which can be enumerated as follows:

(a) Inspite of its high bulk machining swarf can be compressed to a certain shape in die.

(b) An efficient mass production system is capable of providing swarf of specific composition on a particular line.

(c) Improved machining methods may result in the production of smaller chips of the swarf, thus reducing the bulk.

The cast iron being weak and brittle, is very easy to pulverize to very fine powder. Furthermore its swarf is not always contaminated with cutting oil due to the adoption of dry machining techniques, and if it is properly pulverized the annealing and reducing treatment may be avoided.

## 1.2 Theoretical Background

The advances in powder metallurgy techniques, and particularly powder preform forging in the beginning, indicated a possibility of its application in machining swarf reclamation by considering it as coarse powder. In the first probable work regarding reclamation by this method, gray cast iron turnings were re-utilized as a material for hot forging. Another work done at General Motors suggested the conversion of steel machining swarf into coarse powder which was then sintered and forged for consolidation [1]. A more detailed investigation was then made on the reclamation of mild steel and non-ferrous swarfs by hot coining and extrusion of preforms [2,3].

The work done by T. Nakagawa and C.S. Sharma [4] follows a preliminary attempt made by the authors for the consolidation of machining chips of considerably smaller sizes obtained by turnings under special conditions [1]. Since the preliminary investigation showed that the surface porosity was a major problem in products consolidated by hot forging, the machining swarf is crushed to coarse powder and then consolidated by powder forging.

However, it was observed that the macro-mesh pulverized steel powder from machining swarf have some disadvantages such as weak strength and rough surface in the sintered products, and surface porous layer in powder forged products. These defects are supposed to come from the bigger powder particle size as compared to the conventional iron powder [1,2,4]. Thus it is essential to developed the micro-mesh cast

iron swarf powder as a substitute for macro-mesh steel swarf powder in the reclamation of machining swarf.

In the sintering of the above cast iron powders, the strength being equivalent to the wrought nodular cast iron can be obtained in the presence of considerable large shrinkage [5]. Therefore, it was not possible to get a high strength sintered product together with high dimensional accuracy in any sintering condition. As the result of investigation, the excess amount of carbon inside the cast iron powder has been confirmed to cause the weak strength and the large shrinkage in sintered cast iron products. The carbon content of cast iron powder can be reduced to the level of high carbon steel by iron powder and a significant improvement in strength and dimensional change was experimentally achieved [5]. A remarkable increase in the tensile strength was observed for 50wt% addition of iron powder at the sintering temperature of 1150$^{O}$C where the shrinkage is within 0.5%. Thereby an idea was born to reduce the carbon content of cast iron powder by extracting free graphite flakes instead of admixing iron powder.

The work done by T. Nakagawa and F.S. Dai [6,7] was confirmed the fact that a high strength of sintered product with good dimensional accuracy can be obtained from the decarburized cast iron powder as compared to the sintered product of cast iron powder. The mechanical properties of those products are excellent enough to be used for heavy duty mechanical parts and are recognized to be little better than those of wrought nodular cast iron.

A sucessful sintering of cast iron swarf has not only provided a method of recycling of the swarf, but also it seems that this swarf may become a substitute for iron powder in many industrial applications. Although some industrial requirements have been difficult to fulfill, however, the production of iron powder may be possible by this scrap iron powder method. Though the basic objective of an economical transformation of all kinds of metal swarf to engineering components is not achieved fully, many new ideas on the economical recycling of various swarfs are foreseen.

Currently attention in Powder Metallurgy (PM) is focusing on three areas: improving powdermaking techniques, developing materials to accommodate more demanding applications, and finding better methods for forming parts [8]. Not surprisingly, all three areas are interrelated. New powdermaking techniques can improve properties of existing materials, and in many cases lead to the development of new material that couldn't have been made before.

## 1.3 Scope of Present Work

Works on the recycling of cast iron swarf have been started in the USA, Japan and some other developing countries, like India, only in the last few years. The USA, Japan, and India are trying to evaluate

the sintering properties of iron powders produced from cast iron swarf [1-7,9,10]. Besides, Japan is producing sponge iron using a certain percentages of cast iron swarf with other raw materials. It is to be mentioned here that Bangladesh is one of those countries from which Japan imports this swarf [11].

Currently small scale workshops are rapidly growing throughout Bangladesh. These along with other foundry shops of our country produce enormous quantity of cast iron swarf. This swarf is damped alongside the mills as waste product and constantly hampered the normal work of the mills. Since our country lacks the mineral resources and has to import all the pig iron it uses, suitable recycling of these huge quantity of cast iron swarf might make it possible to better utilize the limited resources of the country. With this background in view, research work has been taken up in this department in this new field.

The primary aims of the present work are :

(a) to reduce the carbon content of the ground swarf to as low a level as possible so as to avoid the embrittling effects of graphite in the final product,

(b) to study the compacting and sintering characteristics of these powders,

(c) to compare the microstructures of the sintered specimens.

(e) to examine the effects of additions of small amount of copper, nickel, etc. on the sintering characteristics.

# Chapter Two

## POWDER METALLURGY : A REVIEW

## 2.1 Introduction

Introduction

The science of powder metallurgy has developed and enormously expanded in the last few years. By powder metallurgy, a new way has been provided of making either compact blocks of metal for subsequent mechanical working, or finished metal articles having specific properties which could not be produced at all, or atleast as economically, by any other means.

The term 'Powder metallurgy' covers the art of producing fine metal powders and objects from metal powders, with or without the addition of non-metallic constituents and without completely melting the material. The powders may be pressed to a desired form in a suitable die subsequently or simultaneously heated to produce a welded, alloyed, or coalesced mass. The material may then be suitable for immediate use or may be further worked by conventional methods.

The requisite steps in making a part by powder metallurgy include making, preparing and blending of metal powders, compacting and simultaneous or subsequent heating at elevated temperature in a furnace under a protective atmosphere with or without fusion of a low-melting point constituent only so as to develop metallic or metal-like bodies with satisfactory strength, density and without losing the essential shape imparted during compacting.

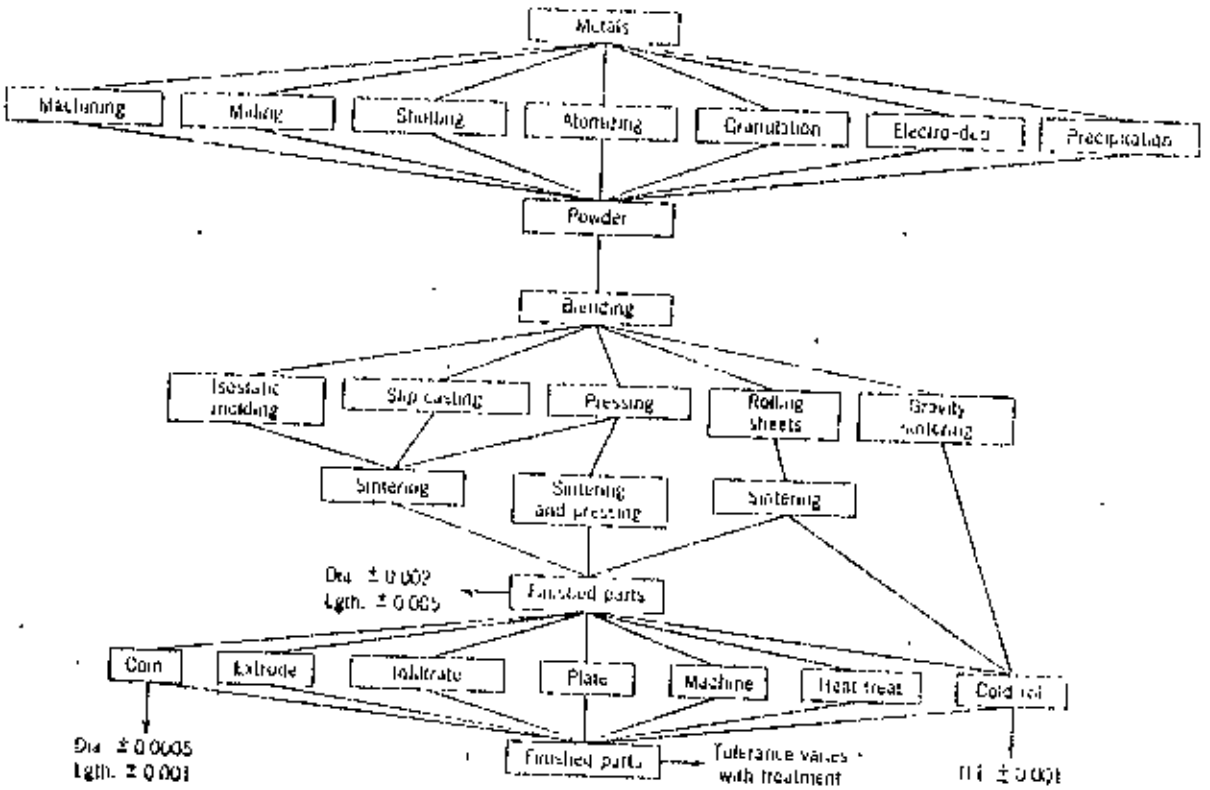



Figure 1. Flow chart showing the basic steps in producing powdered metal parts.

The flow chart in Figure 1 summarizes the various processes and operations used in manufacturing powder metal parts [12]. This chart shows in proper sequence the operations from raw material to the finished parts. The finished parts may undergo several further operations that are not shown on the chart. These include tumbling, and sometimes, additional sintering.

## Advantages of Powder Metallurgy

Metal in powder form is higher in cost than in solid form, and the process, adaptable only to mass production, requires expensive dies and machines. This higher cost is often justified by the unusual properties obtained. Some products cannot be made by any other processes; others made by this process compete favorably with their counterparts made by other methods, because the close tolerance maintained in this process eliminate the necessity of any further processing.

The powder metallurgy process has certain basic advantages over conventional melting and casting methods of producing metals, alloys and finished articles. Following are some of the advantages of powder metallurgy :

1. Ability to start with raw materials of high purity characteristics of consistent uniformity. The powders available in pure state produce items of extreme purity.

2. Better control of composition and structure of the component because of the nature of the technique. Control of grain hence size and relatively much uniform structure is possible [13].

3. Possibility of producing articles having unique properties unobtainable by other methods, e.g., controlled porosity in bearing and filters.

4. Suitability for mixing metals and non-metals, e.g., copper and graphite in self-lubricating bearings, dynamo brushes; metal-ceramic mixtures for high temperature services.

5. Offers a method of producing parts with metals which cannot be melted commercially or only with considerable difficulty, and do not lend themselves to casting, e.g., tungsten, molybdenum, and tantalum.

6. Can be used for metals which do not alloy having widely separated melting points or greatly different densities, e.g., copper-molybdenum, copper-tungsten.

7. Excellent reproducibility.

8. Improved physical properties, for any metal, by proper die pressure, particle size, and sintering temperature.

9. Economy, greater accuracy, and smooth surface finish. 10. Cleaner and quieter operation and longer life.

## Limitation of Powder Metallurgy

The powder metallurgy process has definite limitations and many difficulties to overcome, which distinctly limits its application at

the present time. Some of the limitations and disadvantages inherent to the process are as follows:

1. Metal powders are expensive and sometimes difficult to store without some deterioration.

2. Intricate designs in products are difficult to attain, since there is little flow of the metal particles during compaction.

3. A completely dense product is not possible to attain by this process. Hence the physical properties obtained by this process are lower than those obtained by other processes. lower tensile and yield strengths, lower elongation and much lower impact strengths are obtained due to the inherent porosity in powder metallurgy parts.

4. Some thermal difficulties appear in sintering operations, particularly with low-melting powders such as tin, lead, zinc, and cadmium. Most oxides of these metals can not be reduced at temperatures below the melting point of metal; hence, if the oxides exist, they will have detrimental effects on the sintering process and result in an inferior product.

5. Some products can be made more economically by other methods since the size of powder-fabricated parts is controlled by the capacity of the process available and also by the compression ratio of the various powders.

6. The precision dies in which the parts are pressed and the press itself are expensive, and unless the high cost can be distributed over large production runs, the overall cost per piece

produced may become expensive.

7. Difficulties are experienced in obtaining alloy powders such as steel, brass, bronze,etc., because of the nonavailability of simpler methods.

8. Porous materials are liable to oxidize at the surface as well as throughout the whole body due to its porosity.

9. The larger products obtained in this process are likely to have non-uniform density due to non-uniform distribution of pressure in the powder.

10. Some powders in finely divided state present explosion and fire hazards. Such metal includes aluminium, magnesium, zirconium, and titanium [12].

## Application of Powder Metallurgy

The process of powder metallurgy is utilized for manufacturing numerous types of materials and products. Its use is rapidly increasing day by day. A large number of applications of powder metallurgy can be listed. Among these are fabrication of (1) high-melting metals, (2) cemented carbides, (3) porous objects, (4) physical mixtures of two or more metals or metals and nonmetals, and (5) structures parts.

## 2.2 Powder Manufacture

### Introduction

Although all metals can be produced in the powdered form, only a few are widely applied in manufacturing pressed-metal parts. Some lacks the desired characteristics or properties described earlier which are necessary for economical production. The various manufacturing processes can be grouped into two headings: (1) mechanical processes, and (2) physico-chemical processes. Included in the former group are (a) machining, (b) crushing, (c) milling, (d) shotting, (e) graining, and (f) atomization. The latter group includes: (i) condensation, (ii) thermal deposition, (iii) reduction, (iv) electro-deposition, (v) precipitation from aqueous solution, (vi) precipitation from fused salts, (vii) hydrometallurgical or gaseous reduction, (viii) intergranular corrosion, (ix) spark erosion, and (x) oxidation and decarburization methods. Of them the most commonly employed commercial methods for making metal powders are: milling, atomization, thermal decomposition, reduction of oxides, gaseous reduction of solutions, and electrolysis.

Practically any material can be made into a powder by using one or more of these methods. The particular method chosen depends upon the types of raw materials readily available, the desired properties and structure, type of application, the intended market of the final product, the economics of the whole powder production process and the limitations of the special types of Powder Metallurgy Processes.

## 2.3 Characteristics and Testing of Metal Powders

### Introduction

The process of manufacturing powder metallurgy articles economically depends on the physical and chemical characteristics of the initial metal powders. They have definite effects on characteristics and physical properties of the compacted product. The characterization of powders is difficult because of the complex nature of a solid material in powder form and the many characteristics of an individual powder particle. There are various methods of manufacturing metal powders and there is a wide range in their characteristics.

The main purpose of powder testing is to ensure that the powder is suitable for subsequent processing. A sample of metal powder is always selected for the determination of its characteristics and control of these characteristics is necessary for maintaining the required uniformity in different powder lots.

The basic characteristics of a metal powder are (i) chemical composition and purity, (ii) particle size and its distribution, (iii) particle shape, and (iv) particle microstructure. Apparent and tap densities, flow rate as well as its compacting and sintering characteristics are the others which are dependent entirely or to a large extent on the above primary properties of metal powders. Primary properties such as the particle size distribution and the important secondary properties such as apparent density and flow rate are most widely used in the specification and control routine.

## Chemical composition

The chemical composition of metal powders is not as important as their physical and mechanical properties. However, composition, and particularly impurities, will greatly influence the characteristics of any powder. The term impurity refers to some elements or compounds which has an undesirable effect. It may exert a decisive effect on pressing, sintering, and other post-sintering operations which are essential for the production of finished product from powder. [13]

The most important factor is the amount of oxygen that may be found in the powder as oxides. The oxides found in the metal powder from manufacturing may greatly weaken the powdered product. In iron powders, the presence of carbon (as cementite $Fe_3C$), silica, sulfur, and manganese may greatly influence the plasticity of iron powders, making them difficult to cold press. Carbon in the form of graphite may be desirable from the viewpoint of lubrication during cold pressing, and its presence during sintering may result in changing the iron to a product similar to steel. Graphitic carbon is often added to iron products for the purpose of making a harder iron similar to steel [14].

## Particle Size

Particle size is one of the most important characteristics of any metal powder because it affect most of the properties such as density of compact, porosity, green strength, expulsion of trapped gases, dimensional stability, agglomeration and flow and mixing characteristics.

Particle size is expressed by the diameter for spherical shaped particles and by the average dimension for non-spherical particles. Average dimension is defined in different ways according to the method employed for size distribution. When the method involves sizing, the particle size is measured as the opening of a standard screen which just retains or passes the particles [13].

| Nominal aperture (micron) | Taylor | | | A.S.T.M. Standard | | British Standard | | DIN Standard | |
|---|---|---|---|---|---|---|---|---|---|
| | Mesh ∛ series | Aperture (mm) | Mesh ⁴√ series | Mesh | Aperture (mm) | Mesh | Aperture (mm) | Mesh | Aperture (mm) |
| 5660 | – | 5.613 | 3½ | 3½ | 5.660 | – | – | 1 | 6.000 |
| 4760 | 4 | 4.699 | 4 | 4 | 4.760 | – | – | – | – |
| 3360 | 6 | 3.327 | 6 | 6 | 3.360 | 5 | 3.340 | 2 | 3.000 |
| 2380 | 8 | 2.362 | 8 | 8 | 2.380 | 7 | 2.410 | 2½ | 2.400 |
| 1680 | 10 | 1.651 | 10 | 12 | 1.680 | 10 | 1.670 | 4 | 1.500 |
| 1190 | 14 | 1.168 | 14 | 16 | 1.190 | 14 | 1.200 | 5 | 1.200 |
| 840 | 20 | 0.833 | 20 | 20 | 0.840 | 18 | 0.850 | – | – |
| 590 | 28 | 0.589 | 28 | 30 | 0.590 | 25 | 0.600 | 10 | 0.600 |
| 420 | 35 | 0.417 | 35 | 40 | 0.420 | 36 | 0.420 | 14 | 0.430 |
| 297 | 48 | 0.295 | 48 | 50 | 0.297 | 52 | 0.300 | – | – |
| 250 | – | 0.246 | 60 | 60 | 0.250 | 60 | 0.252 | 24 | 0.250 |
| 210 | 65 | 0.208 | 65 | 70 | 0.210 | 72 | 0.211 | 30 | 0.200 |
| 177 | – | 0.175 | 80 | 80 | 0.177 | 85 | 0.177 | – | – |
| 149 | 100 | 0.147 | 100 | 100 | 0.149 | 100 | 0.152 | 40 | 0.150 |
| 125 | – | 0.124 | 115 | 120 | 0.125 | 120 | 0.125 | 50 | 0.120 |
| 105 | 150 | 0.104 | 150 | 140 | 0.105 | 150 | 0.105 | 60 | 0.102 |
| 88 | – | 0.088 | 170 | 170 | 0.088 | 170 | 0.088 | 70 | 0.088 |
| 74 | 200 | 0.074 | 200 | 200 | 0.074 | 200 | 0.076 | 80 | 0.075 |
| 62 | – | 0.063 | 250 | 230 | 0.062 | 240 | 0.065 | 100 | 0.060 |
| 53 | 270 | 0.053 | 270 | 270 | 0.053 | 300 | 0.053 | – | – |
| 44 | – | 0.044 | 325 | 325 | 0.044 | – | – | – | – |
| 37 | 400 | 0.037 | 400 | 400 | 0.037 | – | – | – | – |

Table 1. Testing sieve series in common use.

Different systems of sieves are used in various countries for the determination of sieve size powders. In America the Taylor or the U.S. Standard System, in U.K. mainly the B.S. System, in Germany usually the DIN System and in France the AFNOR System are widely prevalent. The various sieve scales in common use are shown in Table 1 [13].

The distribution of particles size has considerable influence in determining the flowability and apparent density as well as the final porosity of the product.

## Particle Shape

Particle shape has a pronounced effect on the packing of a powder and has an influence on its compacting and sintering properties and the mechanical strength of the sintered product. Irregularly shaped particles have reduced apparent density and flow rate, good pressing and sintering properties, while spherical particles have maximum apparent density and flow rate but reduced pressing properties and inferior sintering characteristics.

Optical or electron microscopic examination is the usual method of evaluating the particle shape.

## Apparent Density

The loose powder densities, i.e., apparent and tap densities of the powder are important characteristics of any powder. They are strongly affected by a variety of other powder characteristics as indicated in Table 2 [14]. All these characteristics affect the friction conditions prevailing in the powder.

The weight of known volume of unpacked powder is called the apparent density. The apparent density is a very important factor affecting the compression ratio that is required in order to press the powder to a given density. It is obvious that a bulky or low apparent density in the powder will require a longer compression stroke and relatively deep dies to produce a cold-pressed piece of given size and density.

## Tap Density

Tap density is the apparent density of the powder after it has been mechanically shaken down or tapped until the level of the powder no longer falls. The tap density also depends on all those variables listed in Table 2 and , in addition, on the characteristics of the tapped procedure. During tapping the particles are forced to jump according to the vibration characteristics applied, and in this way they overcome to some extent the friction forces which determine the apparent density of the powder. Tapping therefore, results in improved packing conditions with reduced particle porosity and roughness.

Table 2. Variables affecting the loose powder density.

| | |
|---|---|
| (1) | Type of material. |
| (2) | Material density. |
| (3) | Particle density. |
| (4) | Average particle size. |
| (5) | Particle size distribution. |
| (6) | Average particle shape. |
| (7) | Particle shape distribution. |
| (8) | Specific surface of the powder. |
| (9) | Oxide films. |
| (10) | Additions, such as lubricants. |
| (11) | Medium surrounding the particles. |

## Flow Rate

The flow rate is a very important characteristics of powder which measures the ability of a powder to be transferred. It is defined as the rate at which the metal powder will flow under gravity from a container through an orifice both having the specific shape and finish. A powder is required to flow uniformly, freely, and rapidly and conform to the mold cavity. If the flow is poor, it becomes necessary to slow down the process of cold pressing in order to get sufficient powder into the die. The flow rate of any powder is largely influenced by the size of the powder particles, distribution of the size, particle shape, and freedom from even minute amount of absorbed moisture.

## Pressing Properties

The pressing properties are represented by the term compressibility and compactibility. Compressibility is one of the most important characteristics of a metal powder since it affects the densification process. It is a measure of the the ability of the powders to get deformed under applied pressure and is represented by the pressure-density (or pressure-porosity) relationship. It is defined as the ratio of (a) the green density of the compact to the apparent density

of the powder, or (b) the height of the uncompacted powder in the die to the height of the pressed compact, or (c) the volume of powder poured into the die to the volume of the pressed compact. This ratio is usually termed as compression ratio.

Compactibility is indicated by the pressure-green strength relationship. Compactibility of a powder is defined as the minimum pressure required to produce a compact of given green strength.

Both these terms are dependent on particle size, shape, porosity or density and hardness, surface properties, chemical composition and previous history (e.g., hardening, annealing, etc.) of the powder.

## Green Density

In general, the green density has been found to increase with (i) the increase of compaction pressure, (ii) the increase of particle size or apparent density, (iii) the decrease of particle hardness (and strength), and (iv) the decrease of compacting speed. The general dependence of green density on several important factor is shown schematically in Figure 2 [13].

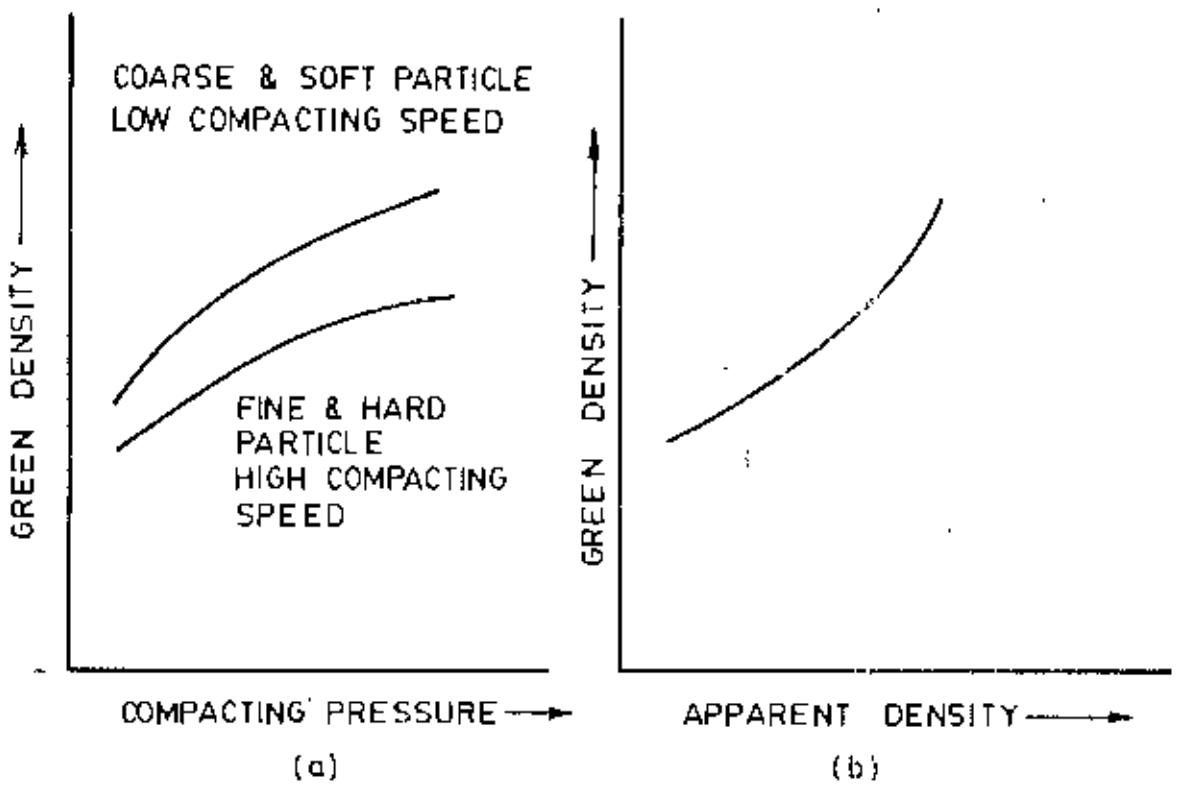



Figure 2. Schematic illustration of dependence of green density on.

(a) Particle size, hardness, compacting speed and compaction pressure.

(b) Apparent density for a given metal powder.

## Green Strength

The green strength of a powder is defined as the mechanical strength of a green compact required to withetand, without damage to sharp edges and fracture the ejection from the die, handling of the part for quality control measurements and transfer to the sintering furnace. The strength of the green compacts is preliminarily dependent on the consolidation pressure and arises mainly from cold welding and mechanical interlocking of neighboring particles. Particle shapes and structures and size distribution have a great effect upon green strength.

## Properties of the Sintered Compact

### Dimensional change during sintering

Dimensional changes always occur when a green compact is given a sintering operation. It is determined by taking the measurements of dimensions of standard specimen before and after sintering under standard conditions. It is customary to express the shrinkage (or growth) as a percentage of sintered length (particularly in the carbide industry) or of unsintered length (particularly in the industry dealing with engineering components and bearings) [13].

## Sintered density

The method used for the determination of sintered density are similar to those which have already been described for the determination of green density. The property facilitates rendering of informations on porosity of the finished product.

## Porosity

The presence of porosity has a much greater influence on tensile strength [16-21], yield strength [22-24], elongation and fractural toughness [25-33], and fatigue strength [34-37] and a rapid increase in these values is obtained with the density approaching the theoretical. Porosity acts as a stress raiser and the sintered component does not indicate truly elastic behavior, rather it appears to function in a similar manner as graphite in cast iron. It is very difficult to produce powder metallurgy parts without any porosity remaining after sintering. The total porosity present in the sintered part may be calculated from the following equation

$$P = 1 - \frac{D_p}{D_s} \qquad \text{( Ref. [13] )}$$

where P is the fractional porosity, $D_p$ the density of the sintered material and $D_s$ the density of the solid material.

## Mechanical properties of sintered parts

The mechanical properties of the sintered parts that are usually considered are hardness, elongation, and tensile and compressive strength. Hardness measurements of the sintered parts are not reliable because of the existence of considerable porosity with it. However, in the ideal case, the microhardness remains independent of porosity but where the residual porosity in the sintered part is very fine due to the use of very fine powders, it shows a dependence on porosity [13].

## Microstructure

The examination of microstructures of sintered components follows the general metallographic technique. Sintered parts possessing residual porosity should be polished and etched with extra precautions. After etching, the specimen should be throughly washed, otherwise the etchant will be absorbed in the pores and staining will appear. Metallographic examination will not only reveal the amount and distribution of porosity but also the amount and distribution of phases, grain size, inclusions and homogeneity of samples.

## 2.4 Powder Conditioning

The metal powder just after production may not possesses favorable physical or chemical characteristics for subsequent processes. To obtain of such properties is of prime importance from the view point of both manufacturer and user. Powder conditioning, which involves mechanical, thermal or chemical treatments or alloying of powders, is a very important processing step of Powder Metallurgy. In general, the powder should be free from impurities and possess uniform properties favorable for compacting and sintering in order to produce powder compacts of high density and reproducible properties. Impure, wet, or defective powder may be washed, dried or softened and purified by annealing in a reducing atmosphere. Its size, size distribution and shape may be varied by sieving, mixing or milling for optimum condition.

Preliminary heat treatment before mixing or blending shpuld be carried out in a reducing atmosphere in order to eliminates work hardening, reduces the oxides and to alter the apparent density of the metal powder.

Blending or mixing is extremely desirable before pressing to secure uniformity in the pressed compact. Particularly all powders have lubricants added in the blending operation to reduce die wall friction and to aid in the ejection. Various types of blenders and mills

such as ball mills, rod mills, double cone mixer etc. are employed for mixing.

Immediately after the preparation of powder mix, it is transferred to press hopper stored under air, vacuum, or liquid in sealed containers.

## 2.5 Powder Compaction

Compacting the powder is an important step in the Powder Metallurgy method. In addition to producing the required shape, the compacting operation also influences the subsequent sintering operation, and governs, to a large extent, the properties of the final product. Several of the most important effects of compacting are :

1. To reduce voids between powder particles and increase density of the compact.

2. To produce adhesion and cold welding of the powder and sufficient green strength.

3. To plastically deform the powder to allow recrystallization during subsequent sintering.

4. To plastically deform the powder to increase the contact areas between the powder particles, increasing green strength and facilitating subsequent sintering.

Although there are various methods of powder compaction, only a few of them are widely employed commercially. It is convenient to group the various methods into the following classification: (i) pressure-less shaping technique, (ii) cold pressure shaping technique, and (iii) pressure shaping technique with heat.

The pressure-less shaping methods are those in which a required shape is given to a powder mass prior to sintering it without applying any external pressure. The methods which fall into this group are loose sintering, slip sintering, slurry casting, clay type molding and high velocity projection; and of these only loose sintering has importance in the Powder Metallurgy field.

The cold pressure shaping techniques have the largest scope for shaping metal powder. Included in this class are: (a) cold die compaction, (b) isostatic pressing, (c) explosive forming, (d) high energy rate forming, (e) powder rolling, (f) cyclic compacting, (g) vibratory compacting, (h) centrifugal compaction, and (i) powder extrusion.

Pressure forming with heat include (a) hot pressing, (b) hot working, e.g., forging, hot extrusion, hot rolling, (c) hot isostatic pressing, (d) spark sintering, and (e) hot coining.

Of all these shaping methods listed above, cold die compaction, which is considered as the conventional technique, is simple and the most widely used method because of the ease of automation of this technique, mass production of powder-metallurgy compacts, allowing

more latitude iu the selection of lubricants, and improved surface appearance by the elimination of oxidation at room temperature. Other major compaction techniques which have been developed are commonly utilized to overcome some of the drawbacks of die compaction and to provide for an improved consolidation process.

Following the compacting operation, the relatively fragile but coherent mass of metal powder must be ejected from the die without injury, and transferred to a furnace for sintering.

## 2.6 Sintering

### Introduction

The welding together and growth of contact area between two or more initially distinct particles at temperatures below the melting point, but above one-half of the melting point in $^{o}K$ is known as sintering. Since the sintering process is a surfacial phenomenon and the rate of sintering is greater with smaller than with larger particles the process is most important with powders, as in powder metallurgy.

Although sintering does occur in loose powders, it is greatly enhanced by compacting the powder, and most commercial sintering is done on compacts. Compacting is generally done at room temperature, and the resulting compact is subsequently sintered at elevated temperature without application of pressure. For special applications, the powders may be compacted at elevated temperatures and therefore simultaneously pressed and sintered. This is called hot pressing or sintering under pressure.

The sintering process is the most important step in Powder Metallurgy by which a strong bonding between particles is attained. The force responsible for sintering are the same as those which hold atoms together in metallic lattices. Inside metals, equilibrium exists between forces of attraction and repulsion. On the surface of metal, forces are not balanced; therefore, if another atom of same substance is brought in close enough proximity, they will be attached and can become part of the parent lattice. For the bond to become stronger (more general) requires improved mating of the surfaces; this enhanced by heat and/or pressure. Thus, in a powdered mass, some sintering or cold-welding may be achieved during cold-pressing in a die and bonding completed at elevated temperatures. Simultaneous application of pressure and heat accelerate the whole process and is especially advantageous with hard powders.

## Mechanism of Sintering

The driving force in sintering is surface energy, which is decreased because of the total surface area decreases as sintering proceeds. When two spheres originally in tangential contact sinter, the area of contact between the spheres increases and a neck is formed. In amorphous materials such as glasses, the process causing neck formation is viscous flow (as when two drops of water coalesce to form one). This type of viscous flow is not possible in crystalline solids. Here the most important material transport process is self-diffusion. Because the material in the neck surface has a highly convex curvature and the number of defects in its crystal structure (vacant lattice sites) is considerably higher than on a flat or concave surface,these defects move by self-diffusion from the convex neck surface to the adjacent flat surface, which means the material moves in the opposite direction, that is, the neck growth (Figure 3a). Instead of coming from the adjacent flat surface, the material forming the neck may also mova by self-diffusion from the grain boundary between the two spheres to the convex neck surface (Figure 3b). This latter type of movement explains why compact shrinks, because in this case the centers of the spheres approach each other during sintering. During grain growth the grain boundaries, which are the source of the material which is transported into the convex neck surface, that is, into the pores of the compact, are swept out of the compact. [38]

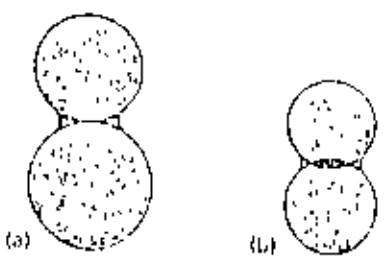



Figure 3. Neck formation.

(a) Neck growth movement of defects from the neck surface to the adjacent flate surface.
(b) Movement of neck-forming material from the grain boundary to the neck surface.

The mechanism of liquid-phase sintering is more complicated. It involves viscous flow of the liquid phase, but also solution of the solid phase in the liquid phase and its reprecipitation in such a way so as to make the compact more dense. As in solid-phase sintering, the driving force in liquid-phase sintering is a decrease in surface energy.

## Sintering Practice

The sintering of components requires a sintering furnace, close control and regulation of temperature, heating time, heating rate and sintering atmosphere.

Sintering may be carried out in batches or continuously in furnaces similar to those used for conventional heat treatment. For laboratory or experimental work the batch-type furnace is most appropriate, but for production work continuous furnaces are often more suitable. In nearly all cases a controlled atmosphere is necessary. Partly burned fuel gas, hydrogen, mixture of hydrogen and nitrogen, inert gases, or even vacuum are used in commercial powder-metallurgy practice. The atmosphere surrounding the work should be capable of preventing oxidation of the powder surfaces and should reduce any surface oxides that are present.

Table 3. The Temperature and Time of Sintering of some important powders.

| Type of powder | Temperature | Time |
|---|---|---|
| Al and Al alloys | 370°C to 500°C | upto 24 hours |
| Cu and Cu alloys | | |
| Brass | 800°C | 30 minutes |
| Bronze | 900°C | 30 minutes |
| Iron alloys | 1100°C | 2 hours |

The sintering temperature and time vary with the compressive load, the type of metal powders and the strength required in the finished part. The temperatures and time of sintering of some important powders are shown in Table 3 [39].

## 2.7 Finishing Operations

After sintering, the article must be cooled slowly in a protective atmosphere to reduce distortion which would be produced by rapid cooling. Then the cooled article is finally processed in order to use it in the specific purposes. The finishing operations usually given to the sintered articles are coining or repressing, surface treatment, heat treatment, impregnation treatment, surface coating, machining, and joining.

# Chapter Three

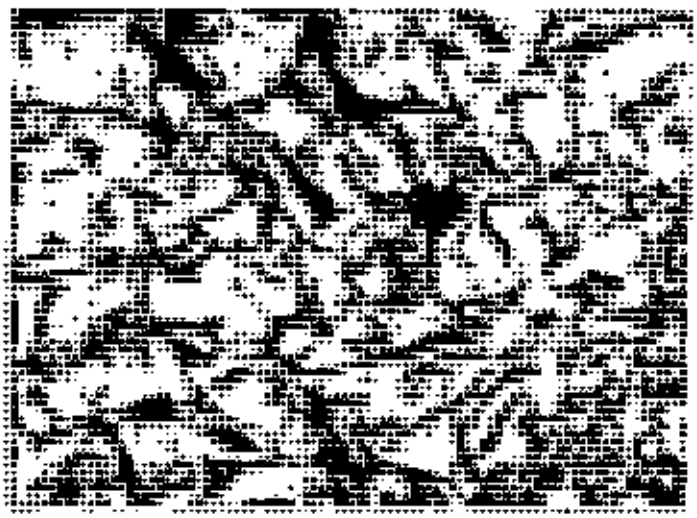
## EXPERIMENTAL PROCEDURE

## 3.1 Preparation of Cast Iron Powder

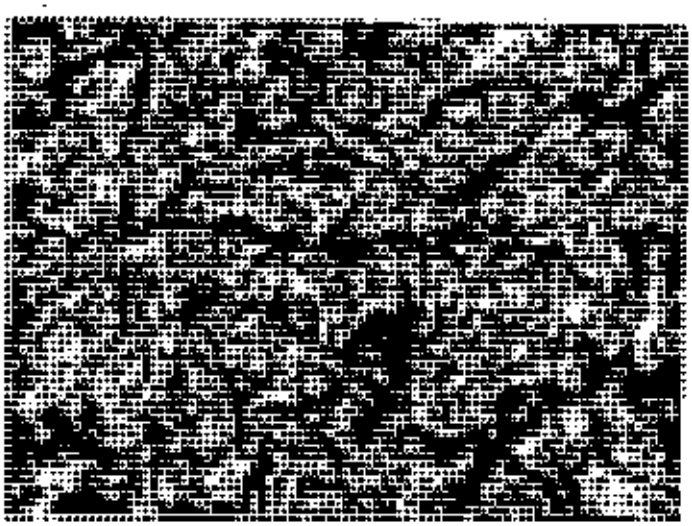
Gray cast iron machined swarf from the Bangladesh Machine Tools Factory, Joydevpur, was used for the present work. Initial size of the swarf was about +30 mesh. In the beginning of the experiment to identify the nature of cast iron, the microstructure as well as the chemical composition of the starting material were determined (Figure 4 and Table 4).

To generate iron powders the mechanical process of producing metallic powder was used. The mini-ball mill (Figure 5) of the Departmental Laboratory was used for this purpose.

The milled powder was first separated into various sieve fractions. During pulverization a lot of free graphite was liberated. The percentage of cast iron powder and free carbon (graphite) in different sieve fractions were determined by washing away the free graphite. The difference in specific gravity between the graphite flakes and the iron particles is great, which facilitates the extraction of carbon from cast iron powder. A mechanical stirrer is used to agitates the powder in the water and the free graphite floats up. Washing and decanting were continued until the washed water remained clear after which the powder was dried. The sieve analysis of the washed powder was made and the finer fractions of the sieve ( -100 mesh) was used for further work.



(a)



(b)

Figure 4. Optical micrograph of as-sampled gray cast iron swarf showing (a) fine graphite flakes in the matrix in the unetched condition, and (b) fine graphite flakes, ferrite and pearlite in the etched condition, x400.

Table 4. Chemical composition of the as-sampled cast iron swarf.

| | Chemical Composition, wt.% |
|---|---|
| C | 3.050 |
| Si | 2.260 |
| Mn | 0.450 |
| S | 0.005 |
| P | 0.140 |
| Fe | Balance |

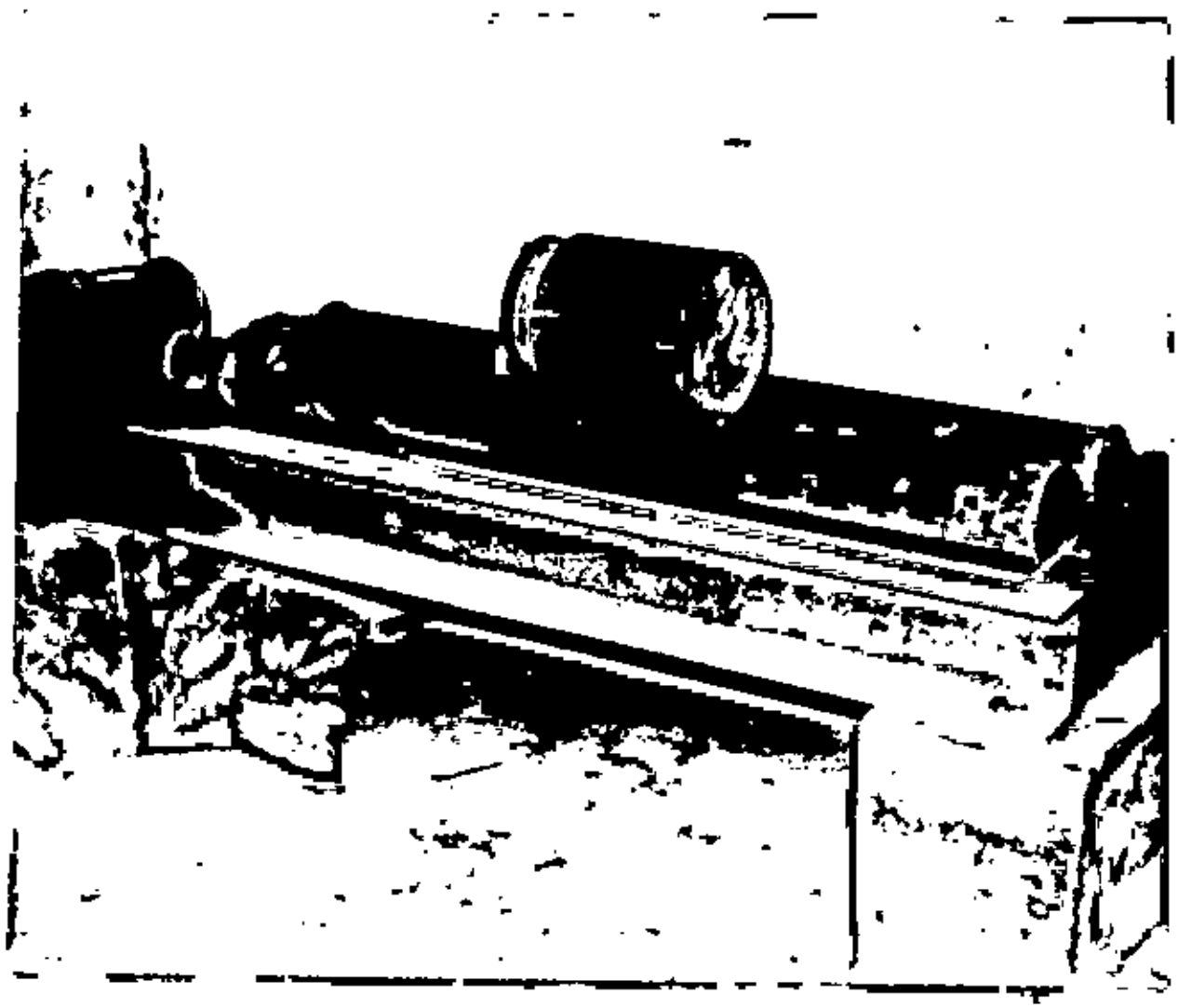


Figure 5. The Ball Mill

To reduce the carbon content of the washed powder, the powder is decarburized in an oxidizing atmosphere produced by the addition of iron oxide ($Fe_2O_3$) powder in the temperature range of 800-1000$^{o}$C. The amount of iron oxide needed to mix with 100 gm of washed powder was calculated to be 35 gm as shown in the Appendix A. and then the mix was placed in a heating furnace using a mild steel pan. To select the appropriate temperature for decarburization, a trial and error was made using temperatures between 800-1000 $^{o}$C. At temperatures lower than 900$^{o}$C the red iron oxide remained distinctly visible thus giving the idea that the cast iron powder was not fully decarburized. Decarburization at temperatures above 900$^{o}$C still showed some redness but at the same time produced sintering between the powders and adhering the powder with the pan. So for the next stage of the experiment, the steel pan was avoided and a porcelain crucible was used. Using the porcelain crucible decarburization was again carried out at temperatures between 800-1000$^{o}$C and after examining the decarburized product the temperature 900$^{o}$C was finally been selected. A four hour holding time was used in all the decarburizing experiments. The decarburized powder was milled again and then subsequently sieved.

The chemical composition and the powder characteristics such as apparent density, tap density and flow rate were evaluated, using standard methods [40] at various stages of processing including those after blending with 0.5 wt. percent nickel powder with the decarburized powder.

## 3.2 Compaction of the Prepared Powder

Compaction in the metal die was performed in the present work as it is one of the most important and commercial method for shaping metal powders. The mild steel die (Figure 6) used by the Magnetic Materials Division, Bangladesh Atomic Energy Commission, Dhaka was used in this project. Since the die was not heat treated, compaction could not be made at a pressure higher than 25 MPa (Mega Pascal). A single action hydraulic press of about 35000 KN capacity was used for compacting the powder (Figure 7).

The compacting behavior of the powders at different stages was studied by pressing the powders in the die with a cavity of 100 x 17 sq.mm. under the press. The powder lubricant polyvinyl alcohol was premixed into the decarburized cast iron powder, while the cast iron powder containing free graphite was compacted without the addition of lubricant since the graphite acts as a self-lubricating agent.

About 1-2 gm. of polyvinyl alcohol was dissolved in hot water and then mixed with powder in appropriate amount and stirring for long time. For each compact an approximate 80 gms of blended powder was used. Specimens having a dimension of about 100x17x15 cu.mm. were made by varying the compacting pressure from 5 to 20 MPa. For the easy withdrawal of the compact from the die, the die cavity was lubricated with oil after each ejection of the compact.

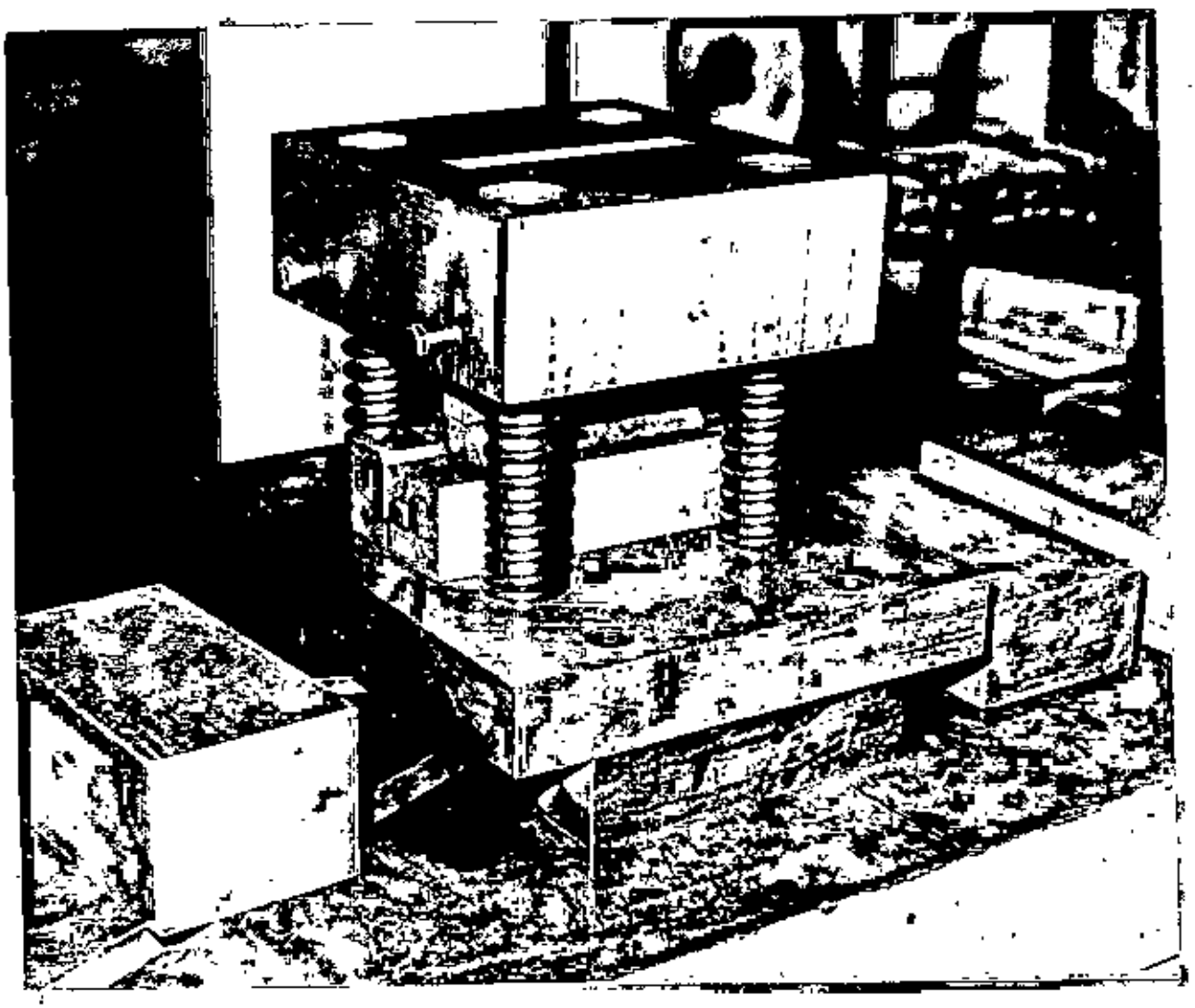


Figure 6. The Die

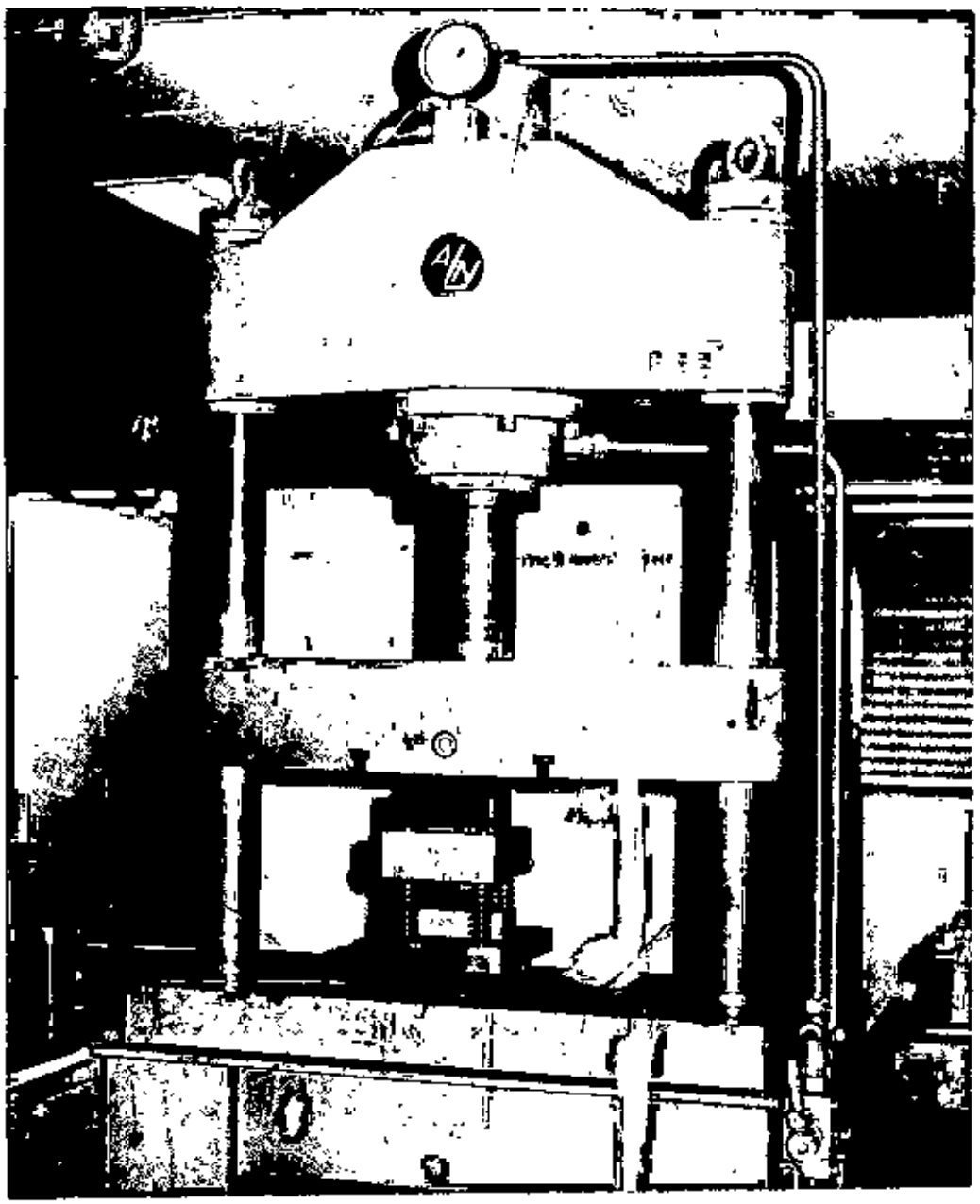


Figure 7. The Hydraulic Press

Since the particles had gone through repeated plastic deformation and fracture resulting in work hardening, the compacting characteristics of these particles such as green density were determined.

## 3.3 Sintering the Green Compact

Compacts of the powders of different stages that have been pressed at a pressure between 5 to 20 MPa were sintered in a sintering furnace for 4 to 10 hours at various temperatures in the range 900-1150$^{o}$C. The sintering furnace priliminary selected was a high vacuum furnace with capacity of controlling the atmosphere. Few tests were made in this furnace using hydrogen atmosphere to reduce the oxide present in the powder. But soon the furnace went out of order and no further experiments could be made in this furnace.

Then the work was carried out in an electrically heated heat treatment furnace with no provision for atmosphere control (Figure 8). To prevent further oxidation the green product was well covered with insulating material.

Tests for determining the properties like sintered density and hardness, were made after the sintering treatment and the macrostructures of the fractured surfaces were observed.

Figure 9 shows the products at the various stages of the processing to the the cast iron swarf to the final sintered product.

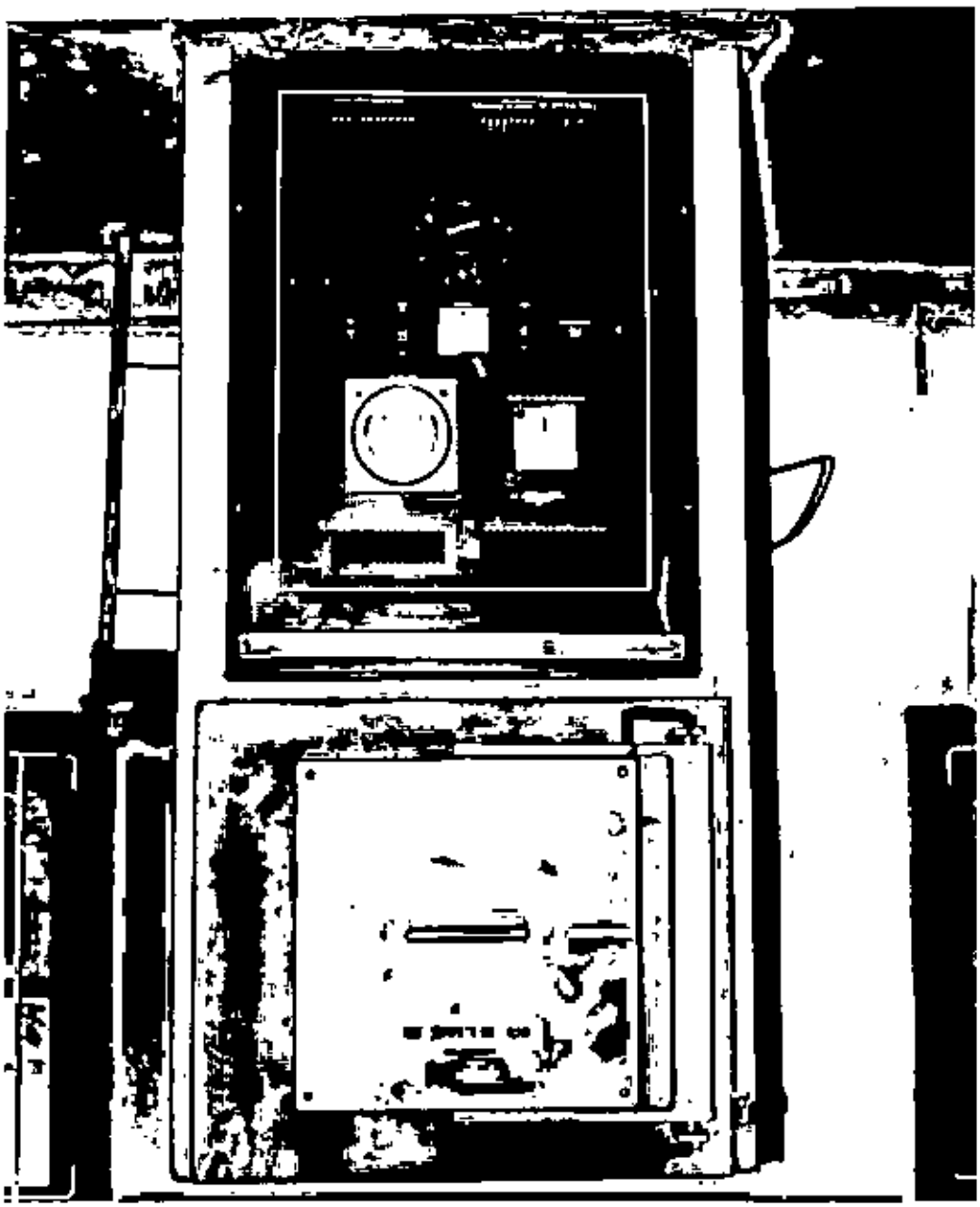


Figure 8. The Sintering Furnace

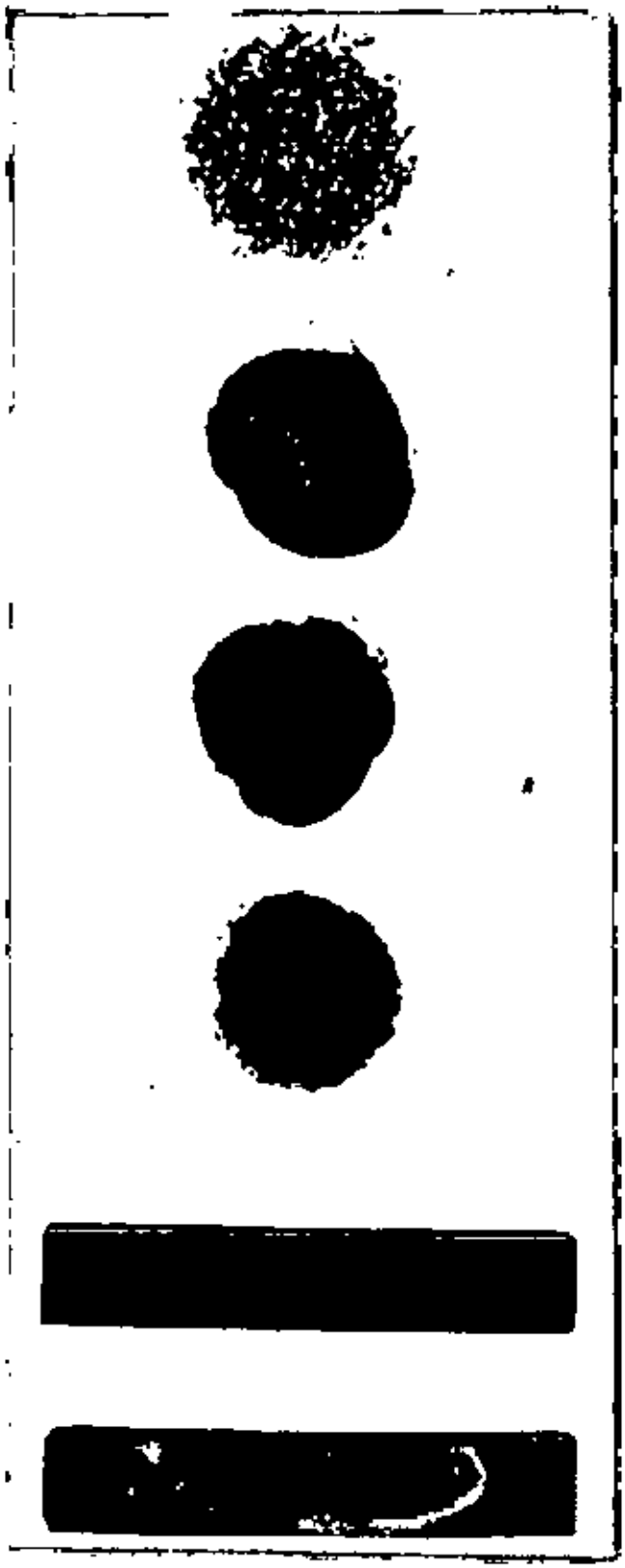



Figure 9. Photograph of the products at various stages of processing of cast iron swarf.

# Chapter Four

## RESULTS AND DISCUSSIONS

## 4.1 Characteristics of the Cast Iron Powder

The carbon content of the as-sampled cast iron swarf was 3.05% (Table 4) and the optical microscopy revealed fine graphite flakes, ferrite and pearlite in the etched sample (Figure 4). Hence the swarf was definitely of gray cast iron.

Tables 4 and 5 show the chemical composition of the cast iron swarf at various stages of processing. The carbon content of the cast iron swarf was substantially reduced from a fair amount of 3.05% to 2.65% in the milled powder after washing away the free graphite. The carbon content was further reduced to 0.09% after decarburization by reducing in an oxidizing atmosphere produced by the addition of iron oxide ($Fe_2O_3$). Thus the harmful effect of carbon in cast iron could be reduced. The amount of silicon and manganese were also reduced due to oxidation. However, the amount of sulphur showed a marked increase in the decarburized sample. This might have come from the iron oxide powder which was used for decarburization.

One of the most important physical characteristics of the metal powder, the mesh size distribution of as-ground powder and the percentage of cast iron powder in each sieve fraction that is retained after washing away the free graphite is shown in Table 6. According to this table the bulk portion of the powder charged is retained between

Table 5. Chemical composition of the cast iron swarf at various stages of the process.

| Cast Iron Powder | Chemical Composition, wt.% | | | | | |
|---|---|---|---|---|---|---|
| | C | Si | Mn | S | P | Fe |
| After washing | 2.65 | 2.35 | 0.48 | 0.006 | 0.16 | Bal. |
| After decarburized | 0.09 | 1.49 | 0.19 | 0.023 | 0.16 | Bal. |

Table 6. Sieve analysis of the as-ground powder and percentage of cast iron powder retained in each sieve fraction.

| Mesh Size | Weight of Powder (gm) | | Per cent Cast Iron powder retained |
|---|---|---|---|
| | Before washing | After washing | |
| + 12 | 1.3 | 1.28 | 98.46 |
| - 12 + 30 | 1.9 | 1.86 | 97.89 |
| - 30 + 40 | 14.7 | 14.55 | 98.98 |
| - 40 + 60 | 147.3 | 138.57 | 94.07 |
| - 60 + 70 | 124.2 | 115.36 | 92.88 |
| - 70 + 100 | 86.9 | 76.78 | 88.35 |
| - 100 + 140 | 43.9 | 40.13 | 91.41 |
| - 140 + 200 | 22.5 | 17.55 | 78.00 |
| - 200 + 270 | 12.5 | 7.00 | 56.00 |
| - 270 (Pan) | 44.8 | 8.50 | 18.97 |
| | 500.0 | 421.58 | 84.32 |

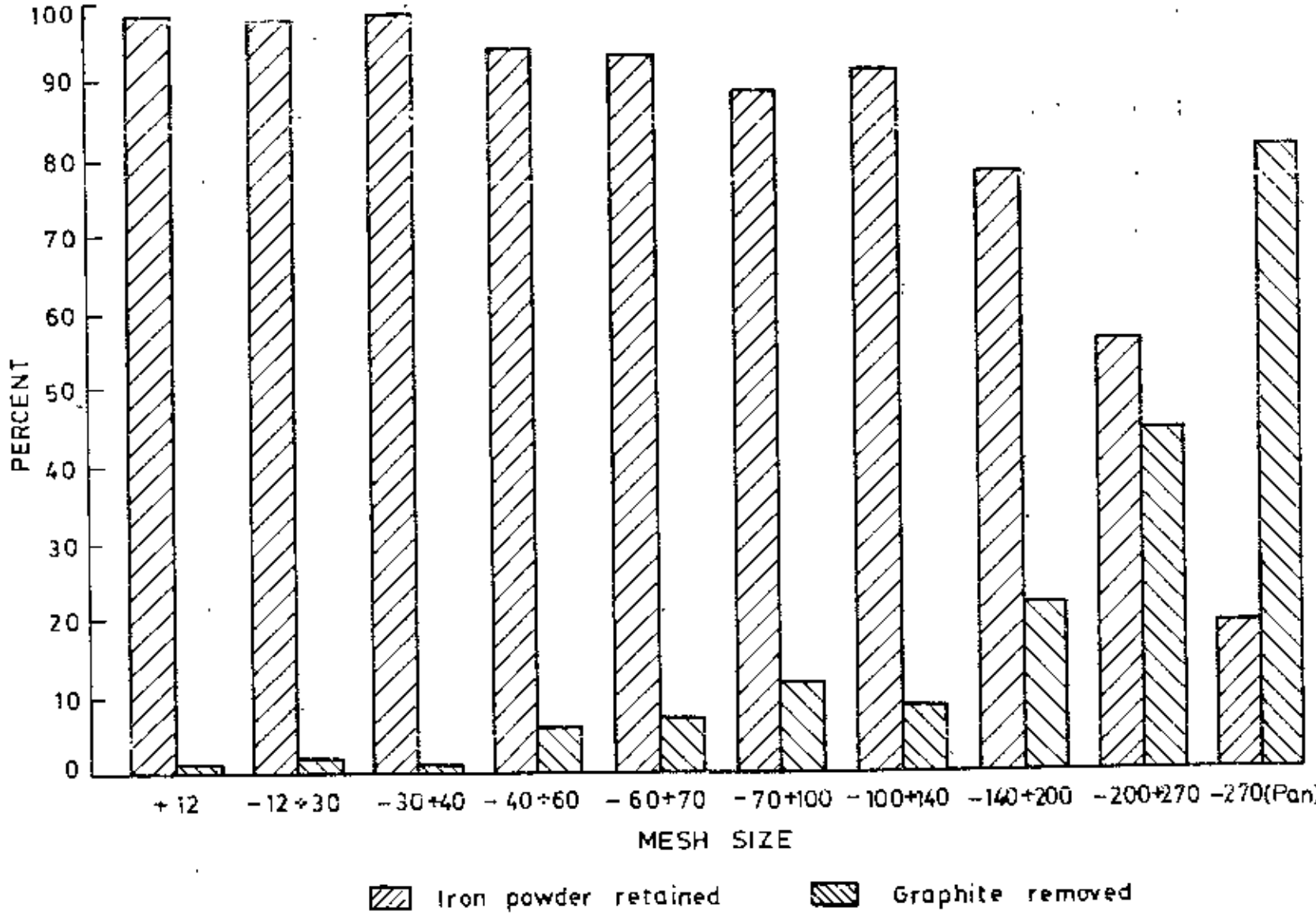



Figure 10. Percentage of cast iron powder retained and graphite removed after washing in each sieve fraction.

-40 to +100 mesh sieve and the finer (-270 mesh) fraction consists of only a little amount of cast iron powder. So it is apparent that the efficiency of the milling operation is not very satisfactory to produce finer grade of cast iron powders for Powder Metallurgy purposes. The work of P. Ramakrishnan and others [10] also support this finding.

The percentage of cast iron powder retained in each sieve fraction is decreased and, alternately, the free graphite removed is increased with increasing mesh size. This is shown in Figure 10.

During decarburization the particles coagulated, so they were further pulverized. It produced much finer particles and the efficiency of milling was considerably increased. This indicates that at the end of the decarburization process the particles acquire much more brittleness and surface irregularity due to oxidation.

For the rest of the work, powders having a fineness between -100 to +270 mesh were used. Thus, though the fineness of the particles was not good enough as -325 mesh is required for Powder Metallurgy application it gave a particle size distribution which would produce lesser porosity and greater density in the ultimate compact.

The shape of the particles which was shown in Figure 11 had round and smooth surfaces. Hence the mechanical interlocking among the particles during compaction became much more difficult as compared to the particles having irregular surfaces with several sharp protrudes resulting in easier mechanical interlocking.

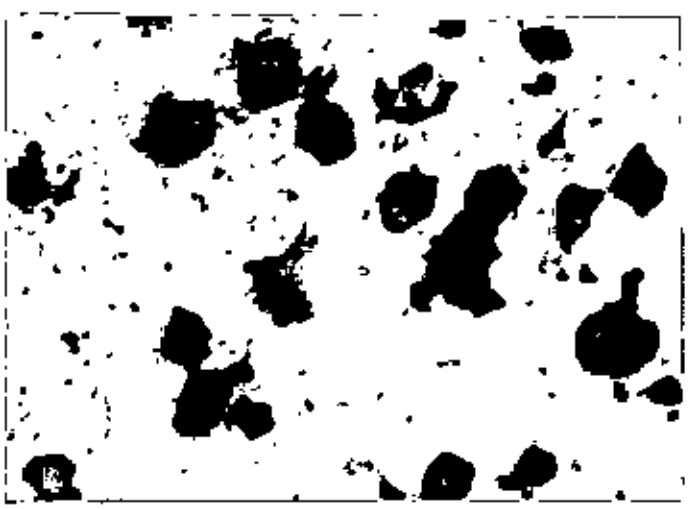
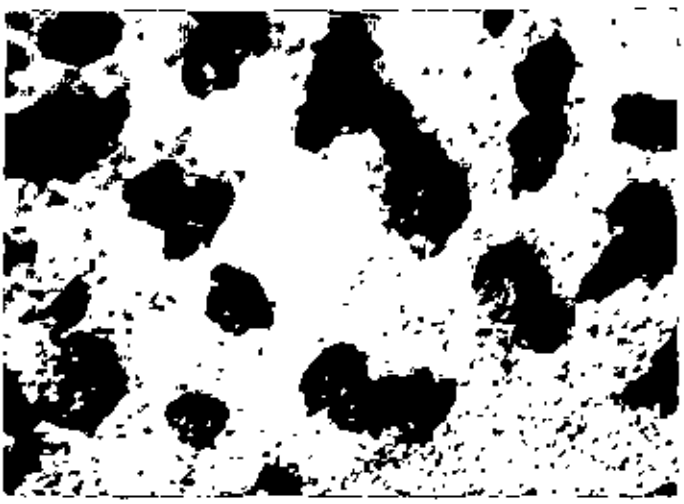
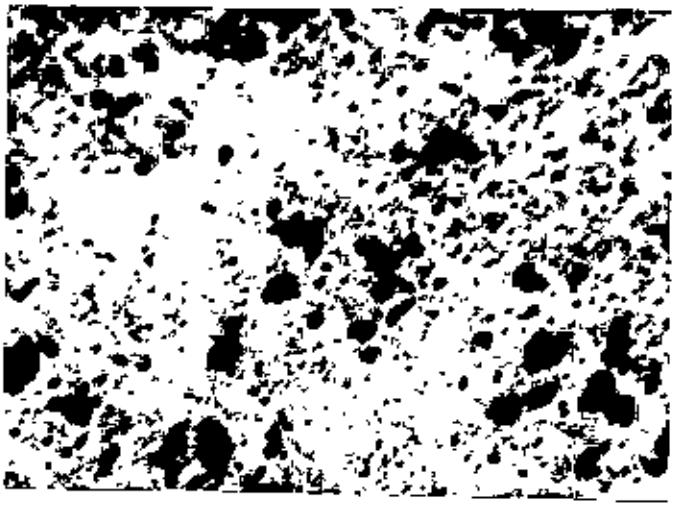


Figure 11. Photomacrograph of the cast iron swarf showing round shape of the particles, X100.



(a)
As-sampled



(b)
After
decarburization

Figure 12. Photomacrograph of the cast iron swarf showing the reduction of particle size after decarburization, x100.

The fineness of the particle was considerably increased after decarburization (FIgure 12). The particles acquired much more brittleness during decarburization and a further milling crushed them to finer powders.

The apparent and tap densities of the powder at various stages of processing have been shown in Figure 13 and Figure 14 respectively. It has been shown that the apparent and tap densities of the particles were considerably increased after washing and decarburization because of the reduction of free graphite and the uniformity of size distribution. Thus it gave a positive attitude towards recycling the cast iron swarf by powder metallurgy technique.

The flow-rate of the powder which measures the flowability of the metal powder under gravity has been shown in Figure 15. It is apparent from the figure that the flow-rate of the powder decreased slightly after washing and then increased after decarburization. This was due to the fact that during washing the free graphite was decreased and thus the friction between the particles was increased. Since after decarburization the powder was further pulverized and became much finer and the powder having a particle size between -100 to +270 mesh was used, the size distribution of the particles and hence the flow-rate of the decarburized particle were increased.

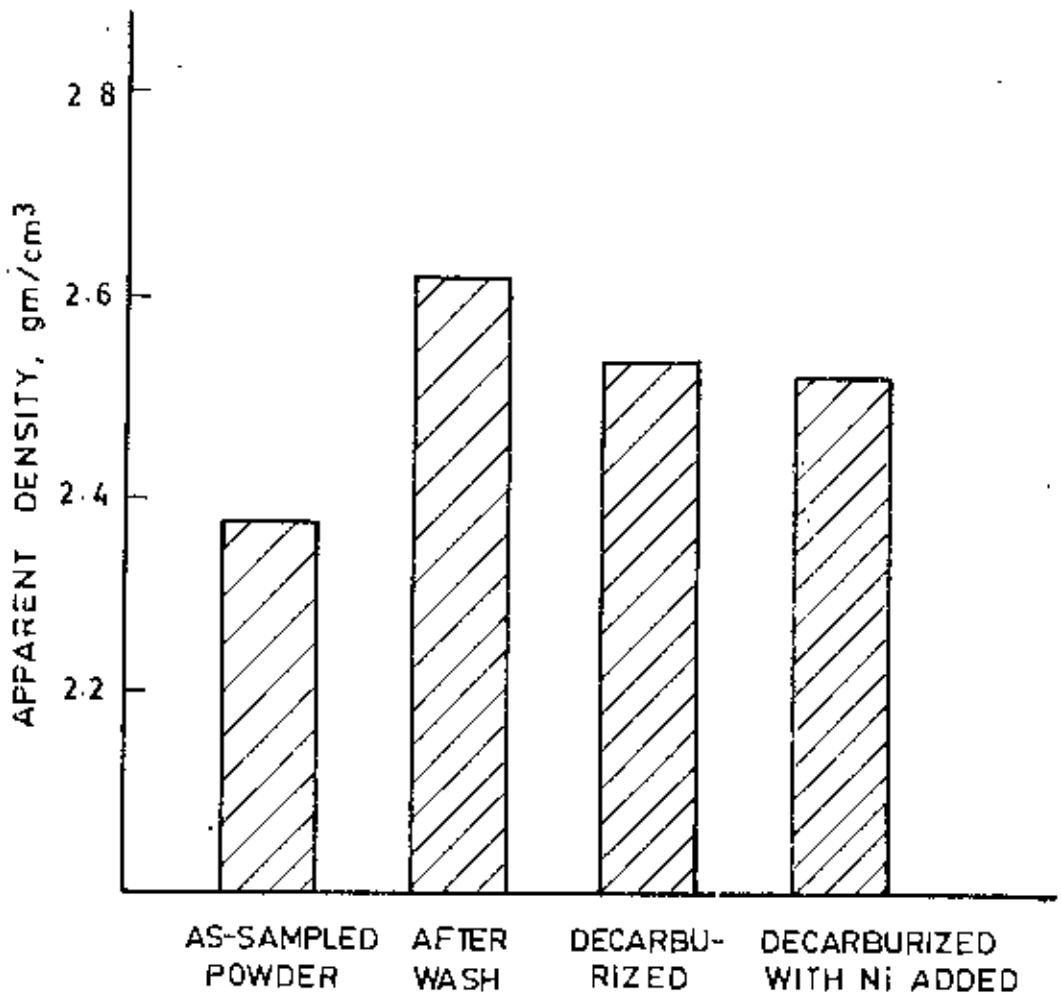



Figure 13. The apparent density of the powder at various stages of processing.

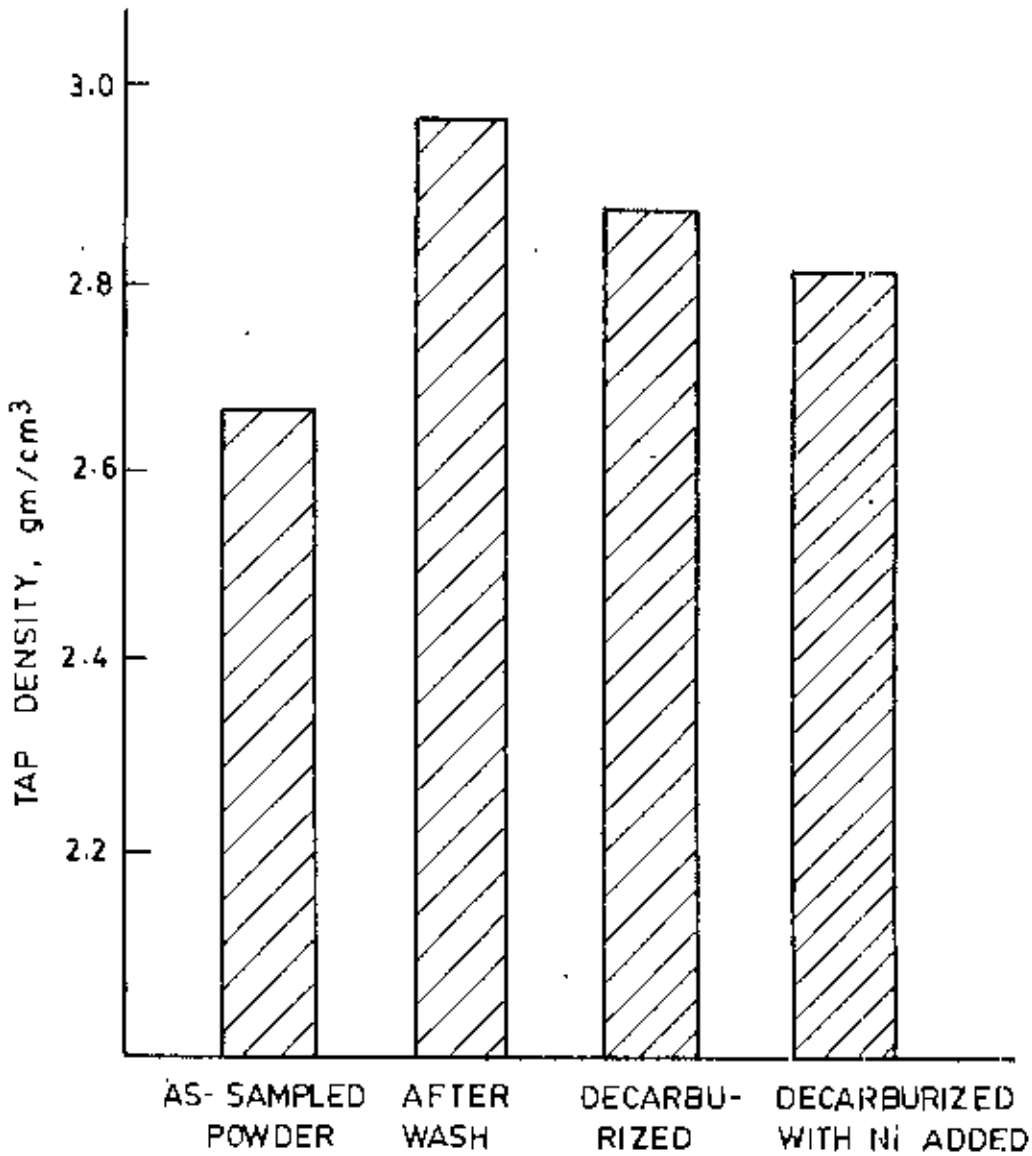



Figure 14. The tap density of the powder at various stages of processing.

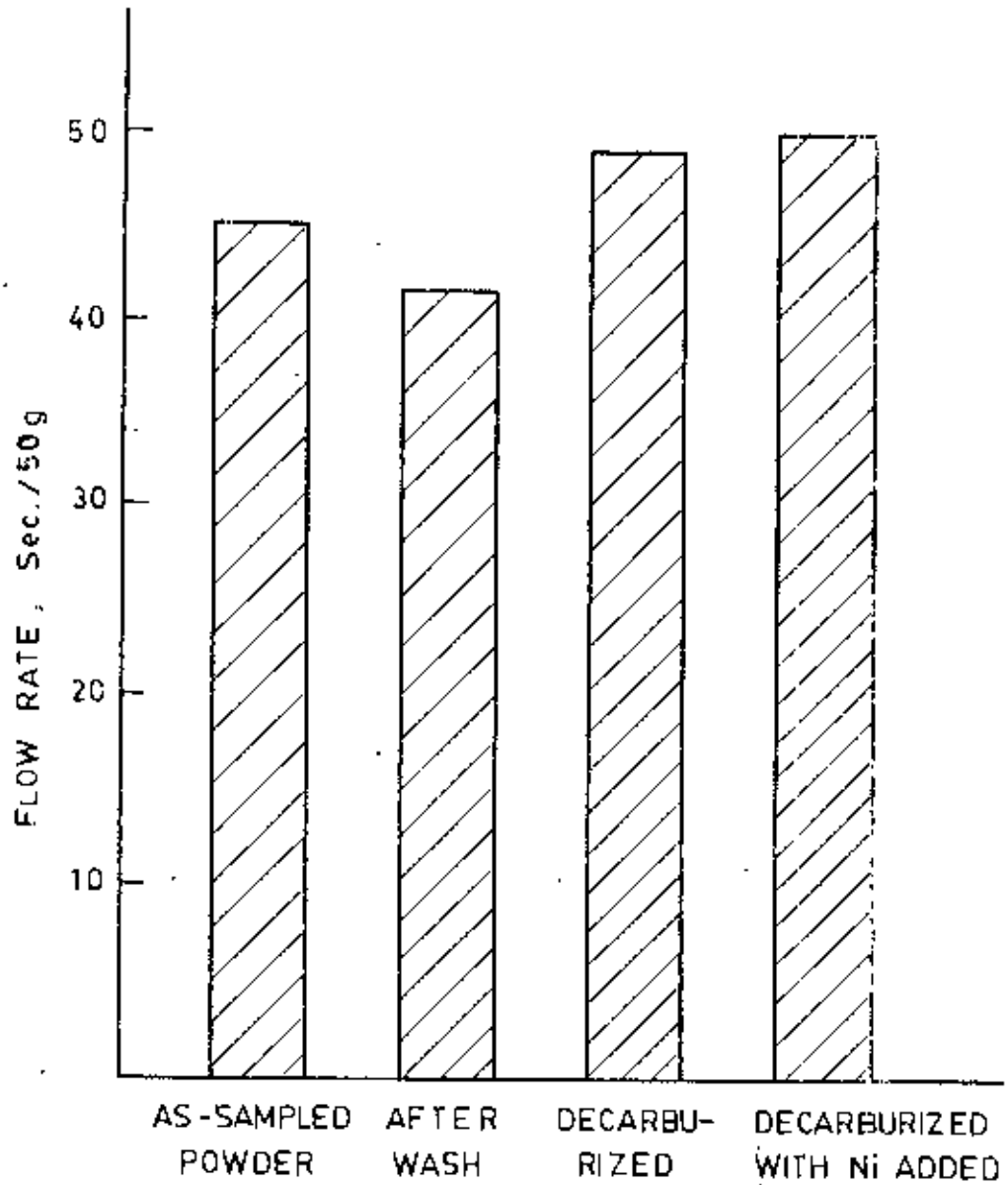



Figure 15. The flow-rate of the powder at various stages of processing.

## 4.2 Decarburization of the Washed Powder

The overall carbon percentage of the ground powder after washing was about 2.65 per cent. Since decarburization produces a remarkable increase in tensile strength and reduction in shrinkage [5,6], the washed cast iron powder was decarburized. Decarburization of these powder could either be done in a hydrogen atmosphere in the temperature range 900-950$^{o}$C or in an oxidizing atmosphere produced by the addition of iron oxide in the temperature range 950-1000$^{o}$C. Since the latter process is much more efficient and could bring down the carbon level to around 0.30 wt. per cent in eight hour [10], reduction of carbon by iron oxide powder was selected. It was found that the carbon level in the sample was reduced to only 0.09 per cent which falls in the range of low carbon steel. It gives a good opportunity to compare the properties of Powder Metallurgy product with those of steels.

To select the correct temperature for decarburization, a number of experiments was performed in the temperature range 800-1000$^{o}$C. It was found that the powder decarburized below 900$^{o}$C contained the red iron powder ($Fe_2O_3$) which indicated incomplete decarburization. On the other hand, the powder decarburized at temperatures above 900$^{o}$C showed the sintering of the powder. Henceforth, the temperature 900$^{o}$C was selected for deacrburization. The use of steel pan to hold the

powder, after few experiments, was omitted and a porcelain crucible was selected because of the fusing tendency of the powder with the pan. The decarburizing time was held constant (4 hours) in all experiments.

## 4.3 Compaction Characteristics of the Powder

The compacting characteristics of the powders at different stages of the process are shown in Figure 16. By analyzing the results a major effect was found to be of compacting pressure on the green density in all cases. An increasing pressure increases the green density. The decrease in compactibility after washing was most likely due to the removal of free graphite which might otherwise have been acting as a lubricant. The improved compactibility of the decarburized powder could be the combined result of the lower carbon level and their favorable morphological characteristics such as improved fineness, better grain size distribution, etc. There was a slight decrease in compactibility after the addition of nickel which may be due to the work-hardening effect caused by the ball-milling used for the blending.

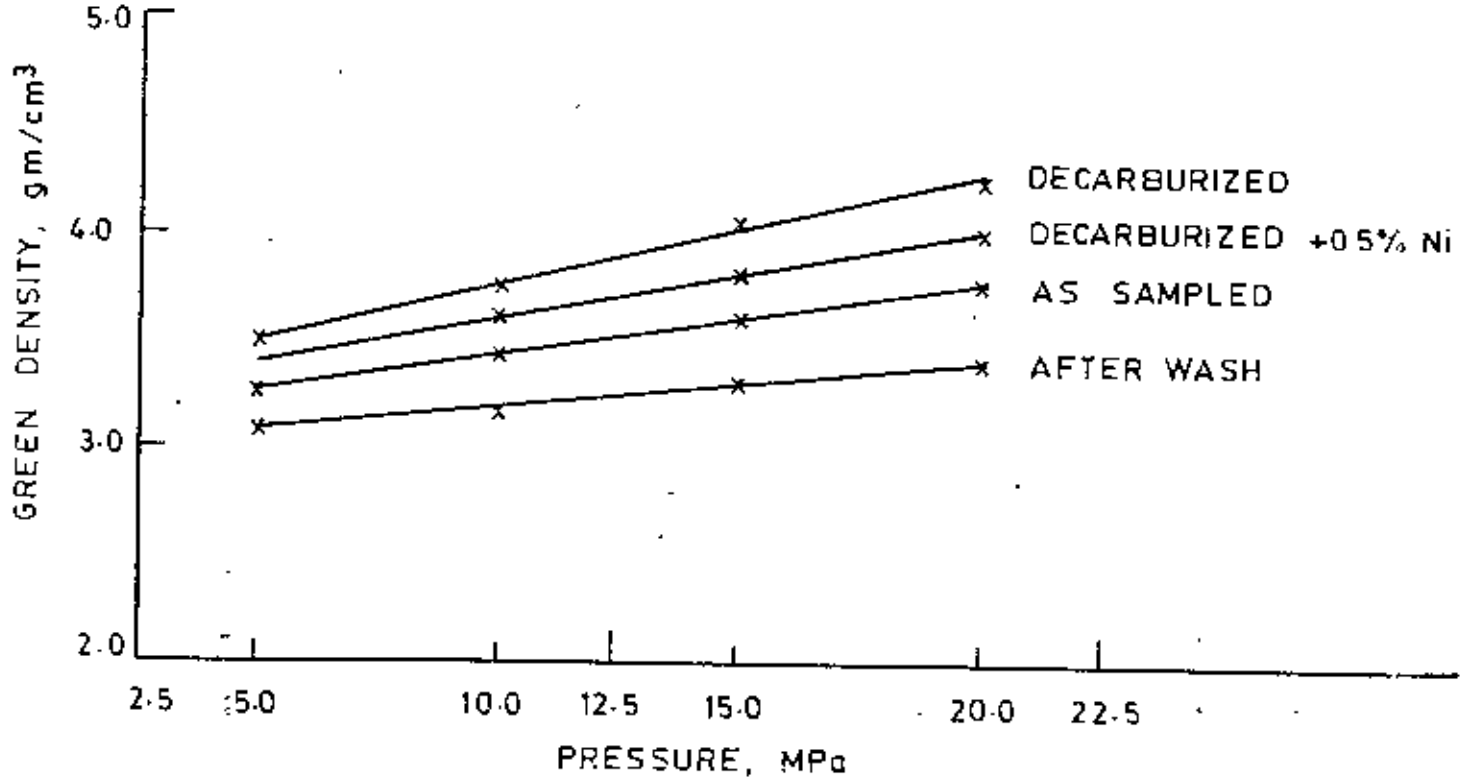



Figure 16 The green density of the compacts mode of different powders with pressure at various stages of the process.

## 4.4 Sintering Behaviour of the Powder

Sintering is the ultimate and decisive stage of all Powder Metallurgy processes. However, as stated earlier, sintering was performed in an ordinary heat treatment furnace due to the failure of vacuum furnace and the resultant product of all sintering experiments did not show proper bonding between the particles. Since the bonding between the particles during sintering depends on the temperature and time of sintering, both time and temperature were varied between wider limits in order to produce a sound product. But satisfactory result could not be obtained.

After examining all the macrostructures of the fractured surface of the samples, it was considered that the insufficient bonding created by the cold-welding during compaction was the prime reason of this failure. To identify the source, one sintered sample was ground to fine powder and an X-Ray diffraction pattern was taken (Figure 17). It showed no traces of iron powder in the sample; all of the particles of the powder or at least the surface of all particles were oxidized to form iron oxide ($\alpha$-$Fe_2O_3$). Another x-ray pattern recorded from the decarburized powder showed the same result.

So it was confirmed that the oxidation of the particles during decarburization was the prime reason for getting a product with insufficient bonding. Oxidation was caused as a result of using a furnace without atmospheric control. The brittle nature the oxide

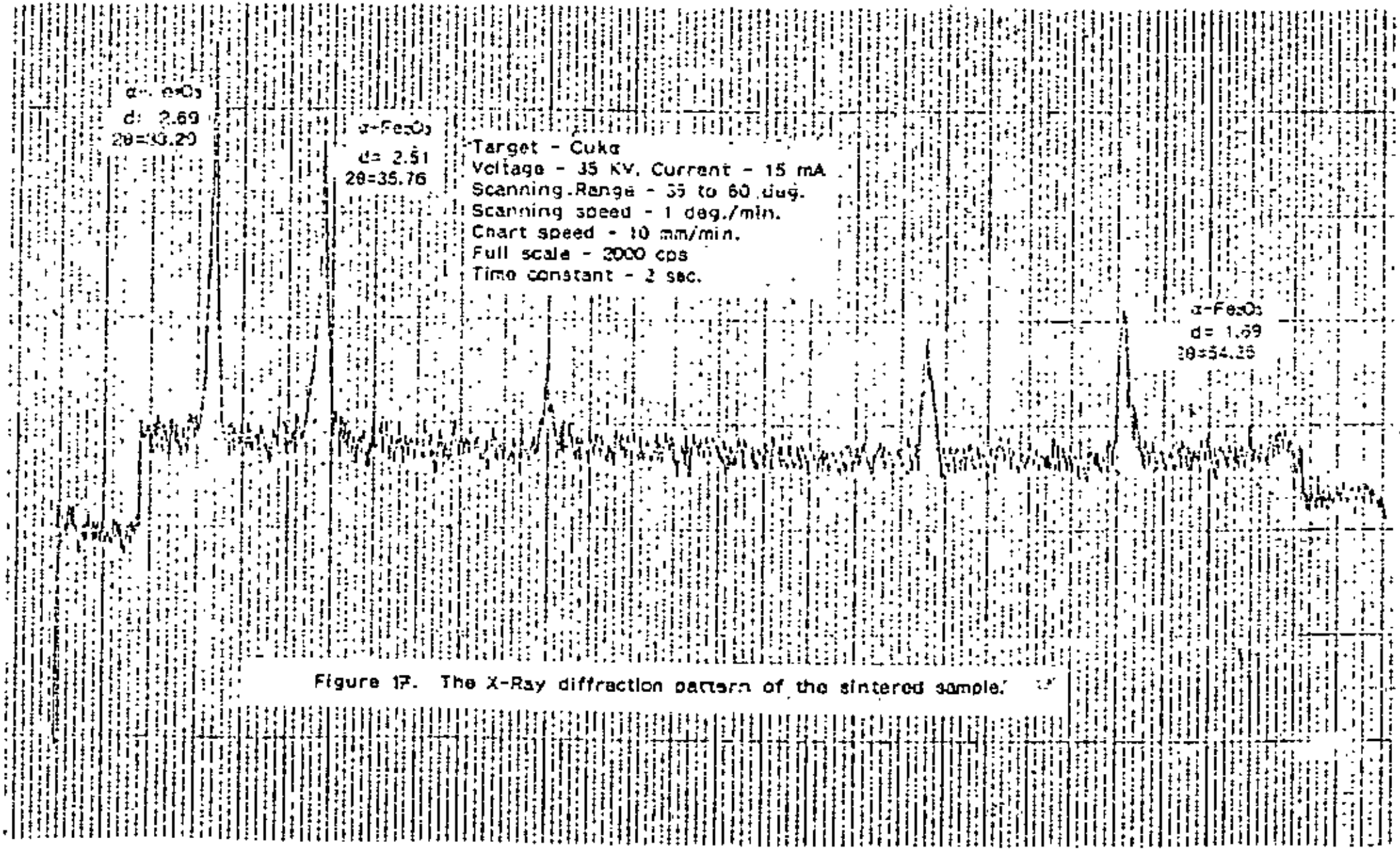



Figure 17. The X-Ray diffraction pattern of the sintered sample.

particle or the oxide layer surrounding the particles prevented sound bonding.

The other reasons behind the failure might be insufficient fineness of the powder and low pressure of compaction. The better the particle fineness with better size distribution and the higher pressure of compaction, the better is the bonding between the particles during compacting and sintering. Majority of metal powders employed in powder metallurgy industry vary in size from only 4 to 44 microns (i.e., -325 mesh). However, the ball mill and the sieving machine used for milling the cast iron swarf limits particle size to only 50 to 150 microns (i.e., -100 to +270 mesh). On the other hand, the usual pressure to compact the metallic powder should fall in the range 800-1500 MPa and compaction at pressures higher than usual offers considerably less difficulties to obtain ferrous PM materials with high-density and high-strength [41]. But a maximum pressure of only 20 MPa could be used. This was due to the limited capacity of the press and the non-heat treated mild steel die.

So due to the failure of obtaining a sound sintered product, the sintering characteristics of the powder, like hardness and tensile strength could not be studied. However, it could be seen that the sintered density of the sample did increase with the increasing pressure and temperature (Figures 18 and 19). The smoothness of the fractured surface was seen to be improved with increasing pressure and temperature (Figure 20). This showed a positive inclination towards the the desirable properties.

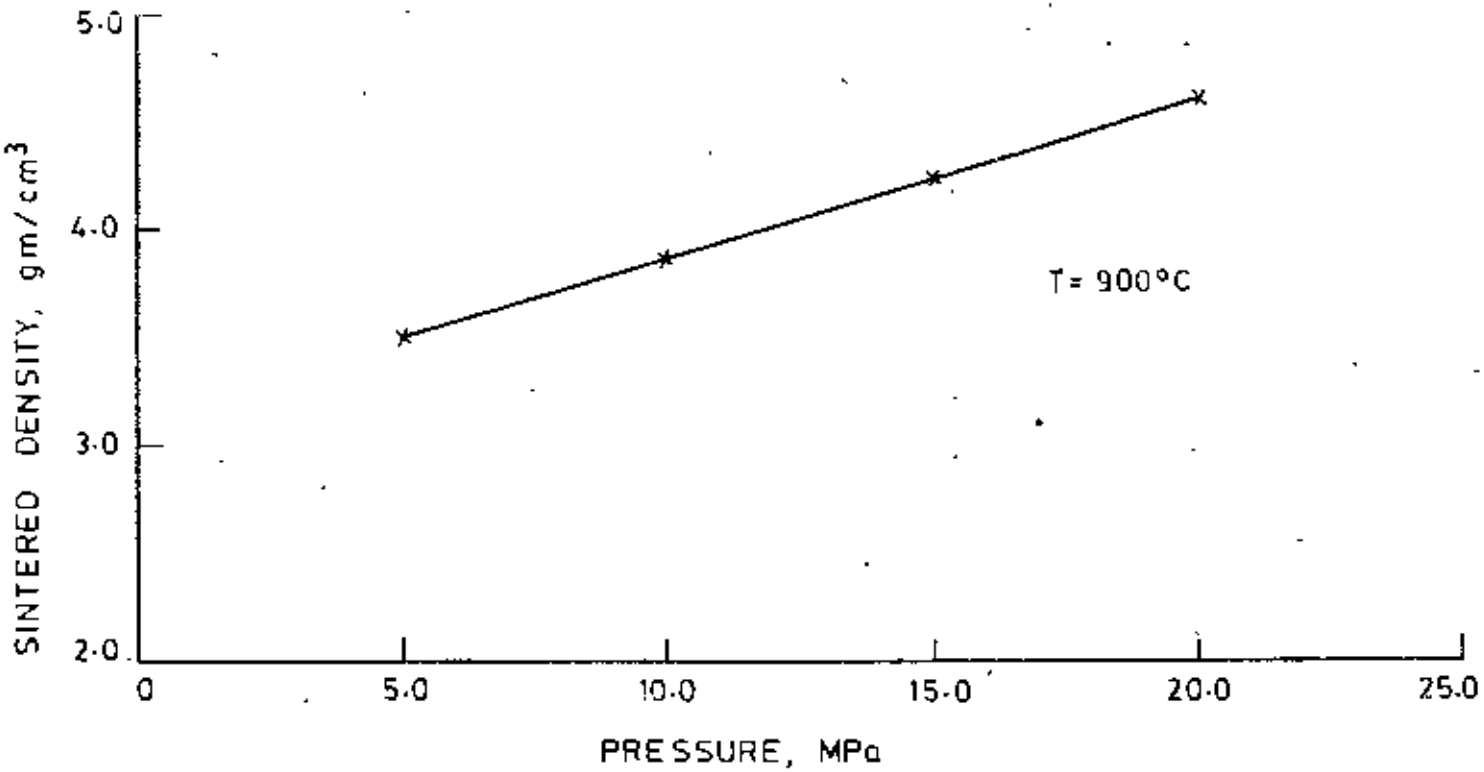



Figure 18. The sintered density of different powders with increasing pressure.

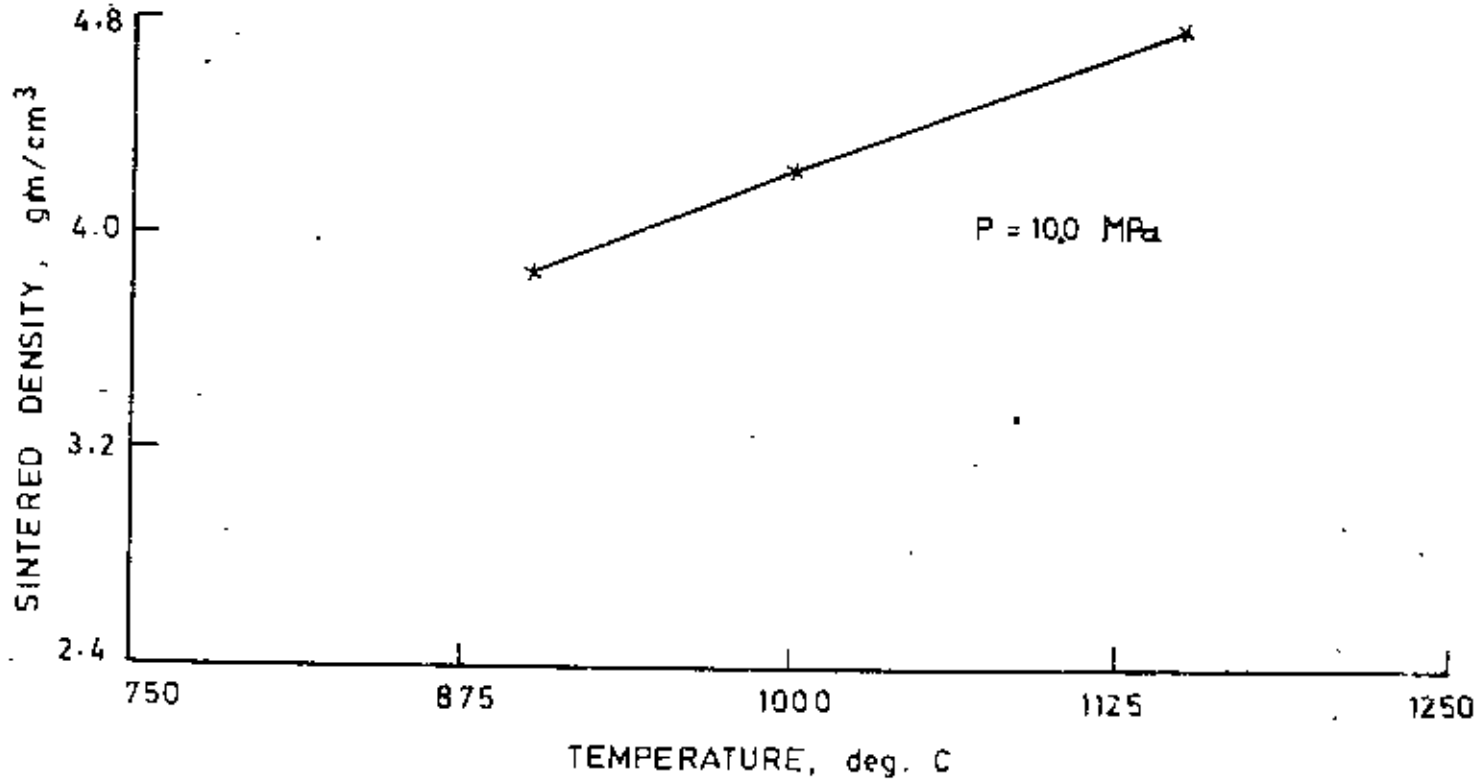
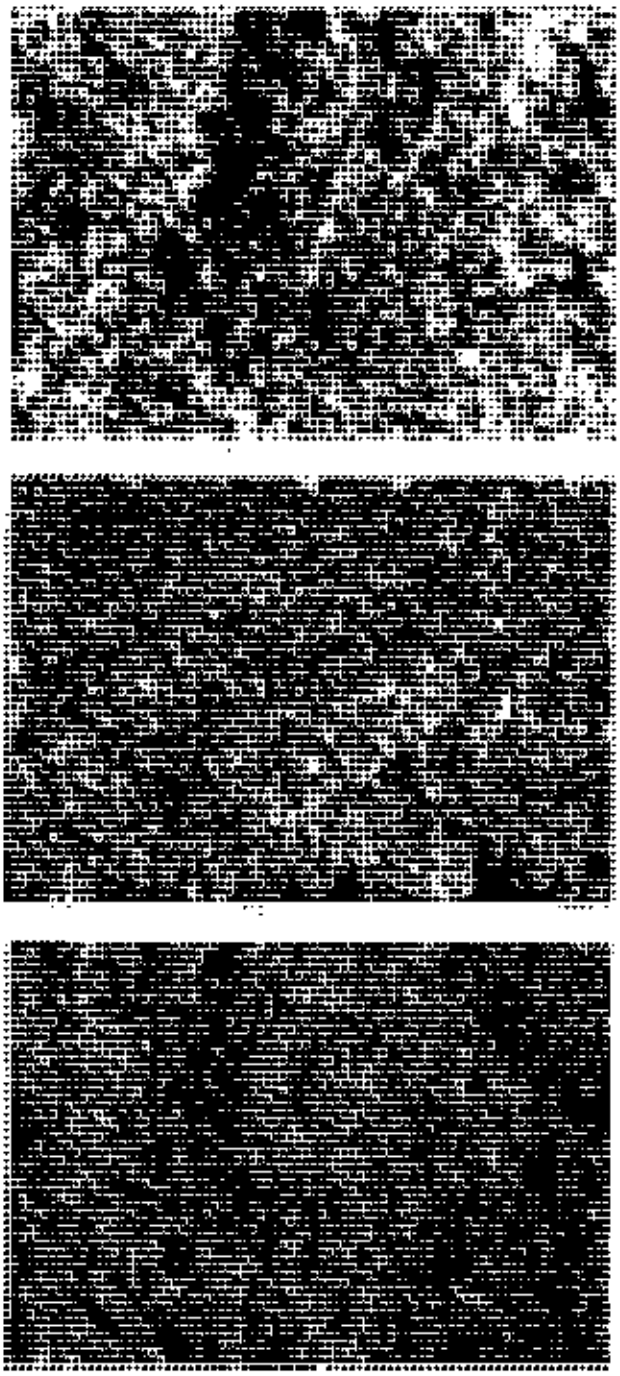



Figure 19. The sintered density of different powders with increasing temperature.



(a)
T=900°C

(b)
T=1000°C

(c)
T=1150°C

Figure 20. The photomacrographs showing the smoothness of the fractured surfaces of the sintered sample at various sintering temperatures.

## 4.5 Suggestions for Future Work

As this was a pioneering work about Powder Metallurgy, a number of problems crept up and a sound sintered product could not be produced. Even then it showed a great promise to recycle the cast iron swarf through powder metallurgy technique.

The problems faced during this work could be solved by using suitable equipments. Decarburization of the cast iron powder could be done by reduction either by hydrogen or by iron oxide. But if iron oxide is used, the compact must be sintered in a reducing atmosphere in order to deoxidize the iron oxide produced during decarburization and to prevent further oxidation during sintering. So irrespective of the processes used, a heating furnace with controlled atmosphere is a must.

High pressures are necessary to produce metallic compact by powder metallurgy technique and therefore, a press having the capacity of giving pressure of about 800-1500 MPa should be used. The die used must be made of proper die material (for example, cemented carbides, hardened high speed steel, etc.) in order to withstand the high pressures and the stresses imposed during pressing.

The particle size of the pulverized powder should be much finer and optimum grain size distribution must be obtained by proper blending of a number of various mesh fractions produced during sieving.

# Chapter Five

## CONCLUSIONS

## 5.1 Conclusions

1. The cast iron machining swarf can easily be pulverized in a ball mill. But it produces less finer particles needed for powder metallurgy applications and the rate of production of fines, that is the efficiency of milling, is not satisfactory.

2. Separation of graphite from the cast iron powder was easily and economically achieved by washing with a mechanical stirrer and by utilizing the difference of specific gravity between graphite flakes and iron powder particles.

3. The carbon level can be reduced considerably to a level of about 0.09 per cent by the reduction in an oxidizing atmosphere produced by the addition of iron oxide. The silicon and manganese were also reduced during decarburization.

4. The apparent and tap densities of the particles were increased after washing and decarburization. The flow-rate of the powder was decreased slightly after washing and then increased after decarburization.

5. The green densities of the cast iron powder were decreased with pressure. The decarburized powder showed a better compactibility than those of as-sampled and washed powders.

6. The sintered densities of the powder were also increased with pressure and temperature.

7. A better fineness of the grains with increasing compacting pressure and sintering temperature was observed.

8. Decarburizing the cast iron powder by iron oxide must be followed by sintering in a reducing atmosphere. Otherwise the sintered product will not show sufficient bonding between the particles due to the presence of iron oxide.

9. A slight decrease in compactibility after the addition of nickel powder was found.

Though proper bonding did not occur in the sintered sample, other results showed a positive response towards the recycling of cast iron swarf through powder metallurgy technique.

# APPENDIX A

# Calculation of Iron Oxide

To reduce the carbon content in an oxidizing atmosphere, pure iron oxide ($Fe_2O_3$) powder was used. The amount of iron oxide needed to mix with 100 gms.of washed cast iron powder was calculated as follows :

The carbon presents in the washed cast iron powder would react with iron oxide to form carbon dioxide ($CO_2$) since the atmosphere was oxidizing. Hence the chemical reaction would be

$$3\ C + 2\ Fe_2O_3 = 4\ Fe + 3\ CO_2$$

$3 \times 12 \qquad 2 \times 160$

Hence 36 gms of carbon $\equiv$ 320 gms of iron oxide.

The washed cast iron powder contained 2.65wt% of carbon. So for complete decarburization, 2.65 gms of carbon would require $2.65 \times (320/36)$ i.e. 23.56 gms of iron oxide.

During decarburization silicon, manganese, and some iron along with carbon would also oxidize.

So for efficient removal of carbon 35 gms of pure iron oxide was mixed with 100 gms of washed cast iron powder.

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