# Investigative Study on High Strain Rate Powder Compaction

## M.Tech. Thesis

By

**TANUJ VISHWAKARMA**

**DISCIPLINE OF MECHANICAL ENGINEERING**

**INDIAN INSTITUTE OF TECHNOLOGY INDORE**

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# Investigative Study on High Strain Rate Powder Compaction

**A THESIS**

*Submitted in partial fulfillment of the*

*requirements for the award of the degree*

***of***

**Master of Technology**

*by*

**TANUJ VISHWAKARMA**

**DISCIPLINE OF MECHANICAL ENGINEERING**

**INDIAN INSTITUTE OF TECHNOLOGY INDORE**

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# INDIAN INSTITUTE OF TECHNOLOGY INDORE

## CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in the thesis entitled **INVESTIGATIVE STUDY ON HIGH STRAIN RATE POWDER COMPACTION** in the partial fulfilment of the requirements for the award of the degree of **MASTER OF TECHNOLOGY** and submitted in the **DISCIPLINE OF MECHANICAL ENGINEERING, Indian Institute of Technology Indore**, is an authentic record of my own work carried out during the time period from May 2022 to June 2023 under the supervision of Dr. Ashish Rajak, Assistant Professor, Department of Mechanical Engineering, Indian Institute of Technology, Indore and Dr. S. Janakiraman, Assistant Professor, Department of Mechanical Engineering, Indian Institute of Technology, Indore.

The matter presented in this thesis has not been submitted by me for the award of any other degree of this or any other institute.

**Signature of the student**
**TANUJ VISHWAKARMA**

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This is to certify that the above statement made by the candidate is correct to the best of my/our knowledge.

Signature of the Supervisor of M.Tech. thesis(1)
**DR. ASHISH RAJAK**
Date: 28-09-2023

Signature of the Supervisor of M.Tech. thesis(2)
**DR. S. JANAKIRAMAN**
Date: 28-09-2023

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**TANUJ VISHWAKARMA** has successfully given his M.Tech. Oral Examination held on September 20, 2023.

Signature(s) of Supervisor(s) of M.Tech. thesis

Date: 28-09-2023

Convener, DPGC

Date: 03/10/2023

Signature of PSPC Member #1

**Dr. Girish Verma**

Date: 28-09-2023

Signature of PSPC Member #2

**Dr. Dudekula Althaf Basha**

Date: 28-09-2023

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With Regards

Tanuj Vishwakarma

# DEDICATION

*"I dedicate this work to research that holds great significance for me. This thesis stands as a testament to my commitment to research in this field, and I hope it contributes in some small way towards its advancement."*

*"I honor the individuals and values that have played an integral part in shaping my academic aspirations. This thesis is a reflection of the gratitude I hold in my heart."*

*With heartfelt appreciation to who so ever have shown concerns with this research work,*

*Tanuj Vishwakarma*

# Abstract

The field of powder metallurgy (PM) is crucial for producing engineering components with unique properties. Powder compaction, a fundamental step in PM, influences the final product's mechanical and structural characteristics. This research investigates the high strain rate of powder compaction process compared to conventional mechanical pressing. The study involves compacting aluminium powder using electromagnetic compaction and mechanical pressing setups. Three sample sets, each with varying energy levels, were prepared for both methods. The effects of compaction technique on diameter change, hardness, microstructure, and grain characteristics were examined.

In the high strain rate process, radial compaction occurred due to the impulsive axial magnetic field, leading to Lorenz forces causing radial pressure. SEM images revealed diffused powder grain boundaries, indicating enhanced densification. Increasing energy levels led to decreased grain junctions, suggesting improved compaction. Hardness values showed slight increases from center to periphery. Optical microscopy illustrated finer, more randomized grain structures in the high strain rate process compared to directional grains in mechanical pressing.

The results underscore the benefits of high strain rate compaction in achieving enhanced densification, improved hardness, and finer microstructures. The findings contribute to advancing powder metallurgy techniques and offer valuable insights into the potential applications of high strain rate compaction in engineering components.

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# ABBREVIATIONS

| | |
|---|---|
| **EMC** | **Electro-magnetic Compaction** |
| **HVC** | **High Velocity Compaction** |
| **RMP** | **Radial Mechanical pressing** |
| **PM** | **Powder Metallurgy** |
| **SEM** | **Scanning Electron Microscope** |

# Chapter 1:

# Introduction

The field of powder metallurgy (PM) plays a crucial role in the production of various engineering components and products with unique properties and performance characteristics. Powder compaction, a fundamental step in PM, involves consolidating loose powder particles into a coherent, dense structure to form a green compact. This process significantly influences the final properties and performance of the manufactured components. In recent years, advancements in material science and engineering have led to the exploration of novel techniques for powder compaction to enhance the mechanical properties of the final products.

The traditional or conventional powder compaction methods involve applying static pressure over a prolonged period to achieve compaction. While this method has been successfully employed in numerous applications, it does have certain limitations, particularly when it comes to the mechanical properties and homogeneity of the resulting compacted materials. However, a promising alternative to conventional powder compaction is the high strain rate powder compaction process. This innovative approach involves subjecting the powder to a rapid and intense loading process using electromagnetic compaction setups.

## 1.1 Powder Metallurgy

Powder metallurgy (PM) is a versatile manufacturing process used to create components and materials from metallic and non-metallic powders. This process allows the production of complex shapes with precise dimensions and tailored properties, making it highly desirable in industries where cost-effectiveness, efficiency, and superior material performance are crucial factors. Powder metallurgy finds applications in automotive, aerospace, electronics, medical, and power generation industries, among others.5

## 1.2 Powder Compaction

Powder compaction is a fundamental step in powder metallurgy, involving the consolidation of loose powder particles into a compact, coherent structure. The process is carried out to form a green compact, which is a preliminary shape of the final product. The density and microstructure of the green compact significantly influence the mechanical properties and performance of the end product. Conventional powder compaction methods employ static pressure to achieve densification.

## 1.3 High Strain Rate Powder Compaction

High strain rate powder compaction is an innovative technique that departs from the conventional approach by subjecting the powder to rapid and intense loading using electromagnetic compaction setups. The powder experiences a dynamic force over an extremely short duration, resulting in high strain rates during the compaction process. This dynamic loading is expected to enhance densification and potentially lead to improved mechanical properties and more uniform microstructures in compacted samples.

## 1.4 Background

The concept of high strain rate compaction has been of interest to researchers and engineers due to the potential advantages it offers over conventional methods. High strain rate compaction aims to address some of the limitations associated with conventional compaction techniques, such as microstructural defects, density gradients, and variations in mechanical properties across the compacted samples. By subjecting the powder to a rapid loading rate, high strain rate compaction is expected to result in enhanced densification, improved mechanical properties, and more uniform microstructures.

## 1.5 Research Objectives

The primary objective of this M.Tech thesis is to conduct an in-depth investigative study on the high strain rate powder compaction process and compare it with the conventional compaction method. The research aims to:

- Investigate the effects of high strain rate compaction on the densification behaviour of aluminium powder.
- Compare the mechanical properties, including hardness and strength, of compacted samples using conventional and high strain rate methods.
- Analyse the microstructural characteristics of the compacted samples to understand the impact of compaction technique on material homogeneity.
- Examine the advantages of the high strain rate powder compaction process over conventional compaction in terms of final product performance.

## 1.6 Scope of the Study

To achieve the research objectives, three compacted samples will be obtained for each compaction method (conventional and high strain rate) using modified crimping fixture in attachment with hydraulic press (Mechanical radial pressing) and electromagnetic compaction setup (High stain rate process). The compaction energy levels will be varied among the samples obtained for each method. Radial compaction will be employed to measure the change in diameter of each sample as reflection of compaction, and subsequent hardness testing will be performed to assess the mechanical properties.

Microstructure analysis and scanning electron microscopy (SEM) imaging will be conducted to investigate the structural characteristics of the compacted samples. The obtained results will be compared to evaluate the advantages and limitations of the high strain rate powder compaction process in comparison to the conventional method.

## 1.7 Organization of the Thesis

This thesis is organized into several chapters to systematically present the research findings and analyses. Chapter 2 provides an extensive literature review, discussing the fundamental concepts of powder compaction, the theory behind high strain rate compaction, and previous studies related to this research area. Chapter 3 outlines the research methodology, including the experimental setup, materials, and testing procedures.

Chapter 4 presents the results and analysis of the investigation, including the densification behaviour, mechanical properties, and microstructural characteristics of the compacted samples. Chapter 5 offers a detailed discussion of the findings and compares the advantages and disadvantages of high strain rate powder compaction over the conventional method. Finally, Chapter 6 concludes the thesis with a summary of the research outcomes and proposes future research directions in this field.

In conclusion, this M.Tech thesis aims to contribute valuable insights into the high strain rate powder compaction process and its potential benefits in enhancing the properties and performance of compacted materials. The findings of this study will not only advance the knowledge in powder metallurgy but also hold practical significance for various engineering applications, where the mechanical properties of the materials are of utmost importance.

# Chapter 2:

# Fundamental Concept and Literature Survey

## 2.1 Introduction to High strain rate process in Powder metallurgy

Powder metallurgy (PM) is a highly advanced method of manufacturing with the ability to produce near net shape, high strength, and durable compacts at a low cost. It involves consolidating powder particles together by compressing it in a product-shaped die and sintering it if required, to directly produce a finished product with minimum material lost in its production. Apart from this, it also provides many other advantages over its competing Metal forming technology, which also makes it fit to be used in various automobile, aerospace, and structural applications.

One of the steps involved in PM is powder compaction, which is a crucial step as it largely determines the final properties and strength of the product, and needs to be studied well so as to pick up optimum process parameters and precise powder morphological requirements to create a product with the property as close to that generated from its competing processes, which is not achieved till date but day by day with the extensive study's going on, it is very likely to be achieved, and perhaps can go even better than that, so choices we make in every step is to be chosen wisely to achieve optimum results.

For example, depending on the rate at which powder is compacted, the mechanism of adhesion between particles differs. Compaction at a lower rate strain rate, such as that done in the case of conventional methods like isostatic pressing and die compaction, particle undergoes plastic deformation, due to which mechanical interlocking takes place, which further requires sintering to achieve maximum strength but in case of doing the same compaction at High strain rate, like that in case of hydraulic impact, explosives, magnetic or spring-loaded hammers technic allows no time for heat to flow out, and that trapped heat eventually melts the metal at powder particle interface which leads to welding of particle together at their interface itself eradicating the need for sintering. Some of the melts also occupy the void between powder particle hence reducing porosity, increasing strength, and all that produces a denser product, with the increase in density, everything improves as the tread suggests, hence Compaction at a High strain rate turn out to be advantageous therefore preferred, and that is also the reason why there was a shift of research interest toward dynamic Compaction that can be seen in its timeline.

Power Compaction is itself a complex phenomenon and its dynamic elements add more elements to it. Here one needs to deal with the preprocessing factors, such as powder material and morphological properties, processing parameters like strain rate, pressure and temperature characteristics and post processing parameters like sintering temperature, all in one set such that gives out density, strength, hardness homogeneity, porosity, inclusion, cost as output, which needs to be tailored to our needs by picking up the right optimum parameter to be executed. Researchers have come up with various Theories and relations depicting the governing of process, some of which are also included in this literature content.

Different attempts have been made to understand the cause and effect of varying parameters on the results obtained and, through this literature, it's been tried to compile some of these findings and their justifications to generate a good understanding of High Strain rate compaction or High Velocity Compaction (HVC) or Explosive compaction process.

## 2.2 Dynamic Compaction Set up.

There can be many ways through which powder can be compacted, within which also setup arrangement can differ and modified accordingly as per requirements and convenience. It is not possible to list out all but for illustration purposes, some of the most common variants of hydraulic, electromagnetic, and gas explosives methods are discussed below.

### 2.2.1 Impact Press

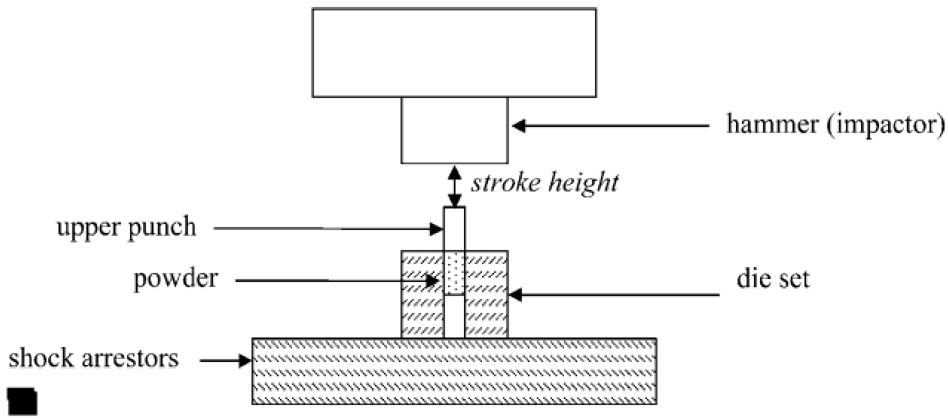



*Figure 1. Schematic of high-velocity compaction via Impact Press [13].*

In this setup, a heavy hammer weighing in Tons is dropped on a punch fixated to a die filled with powder that needs to be compacted. The hammer strikes a punch with an Impact velocity and the whole momentum is transferred to punch to the compact the powder.

### 2.2.2 Gas Gun

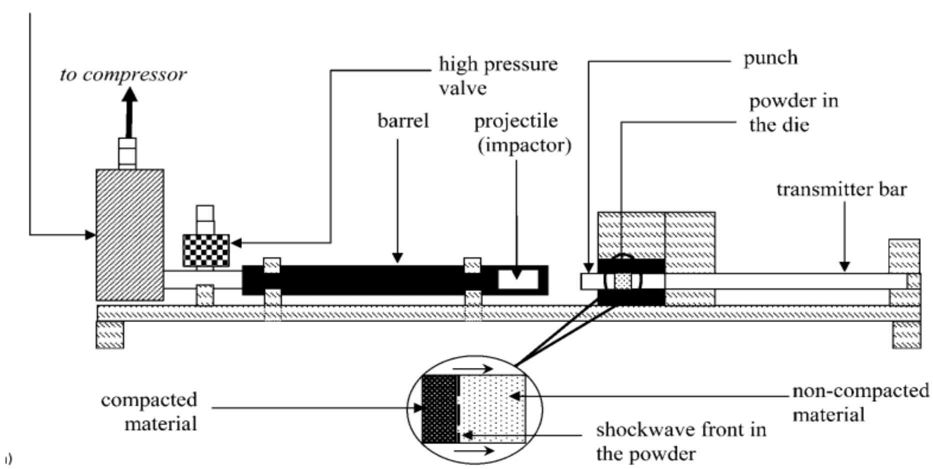



*Figure 2. Schematic of high velocity compaction using a gas gun [13].*

In a gas gun set up, compressed air is used to fire a projectile from a barrel targeting punch fixed to a die containing powder. When a projectile hit a punch momentum transfer takes which is utilized to compress the powder in a die.

## 2.2.3 Electromagnetic Powder Compaction

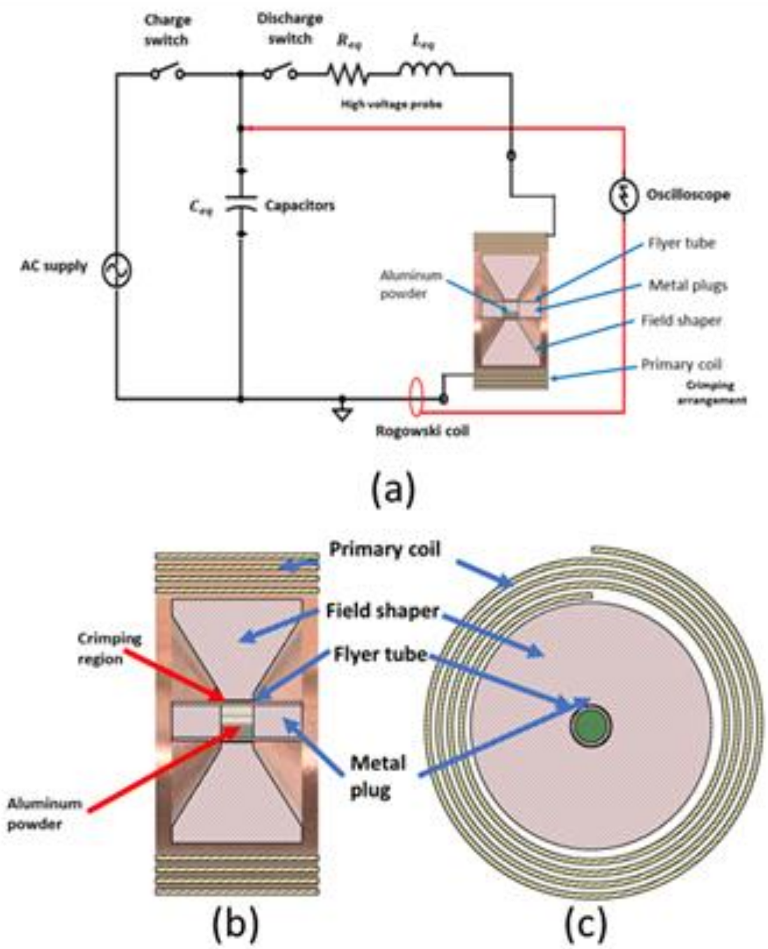



*Figure 3. Schematic of high velocity compaction using Electromagnetics Compaction Technique, (a) Circuit diagram, (b) side, and (c) front cross-sectional view of primary coil assembly [1].*

This process utilizes Lorenz force generated through electromagnetism phenomena for compacting power, one such set up for it is shown in Fig 3. Here powder is filled in easily deformable ductile material like an aluminium tube and packed with mild steel corks at the end of the tube, and this is further placed inside field shaper for strengthening the magnetic field surrounded by a primary coil connected to the circuitry. When the primary coil is powered, fluctuating magnetic fields are set up inducing currents on the surface of the conductor placed inside the coil, and due to its repealing nature generates a magnetic pressure on the aluminium tube which deforms it in the radial direction, compacting powder inside.

## 2.3. Compaction Phenomena

### 2.3.1 Compaction Stages

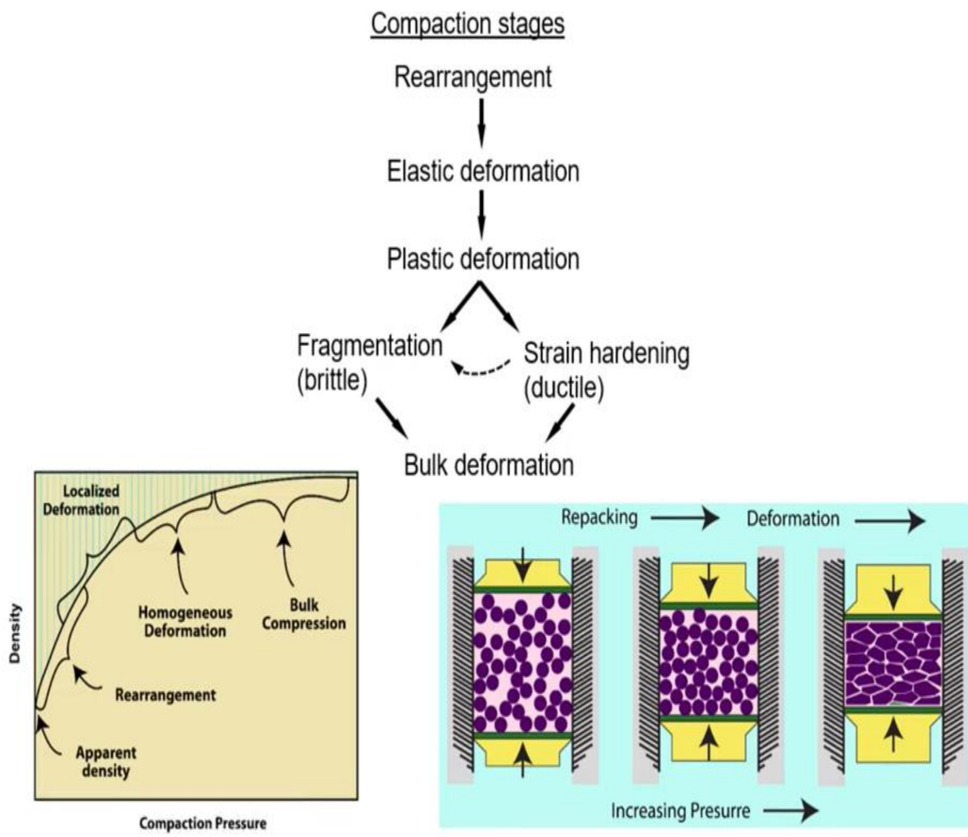
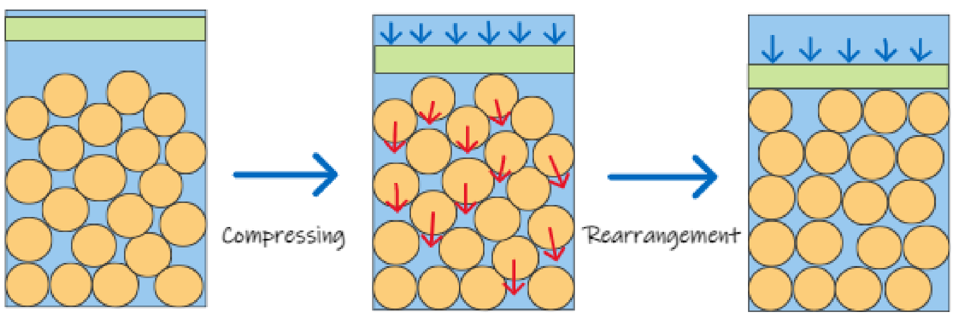



*Figure 4. Stages of Compaction.*

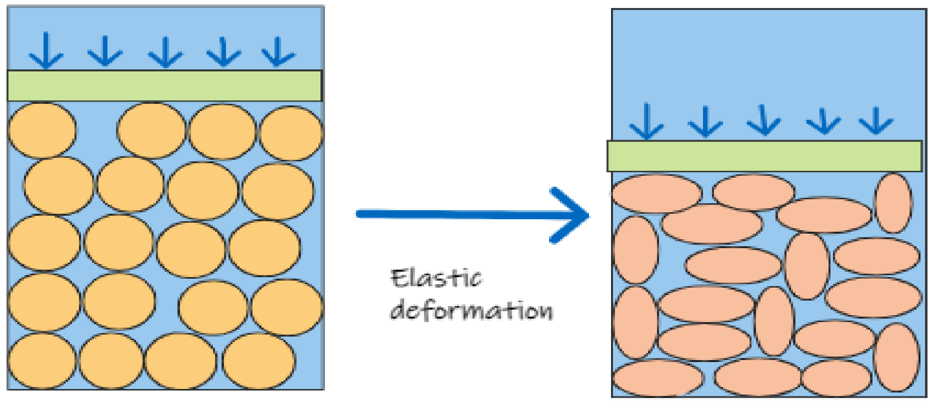
### 2.3.2 General Compaction Mechanisms

Initially, when the powder is just put in a container, it is in the stage where one can decrease the bulk volume just by shaking it, this will lead to the rearrangement of powder particles where the powder is set in other mechanical equilibrium configuration which is more compact, this happens due to slipping and adjusting of powder grain into the spacings which is bigger enough to occupy powder grains but closed earlier to provide entrance to powder particle but by shaking temporary gaps are generated between particle through which other particle can slip into that void spacings, this will lead to increase in coordination number of particles and density of powder bulk. The amount of final densification obtained is also dependent on the initial density by which the compaction process has started so thereby also dependent on amount of initial densification [2].

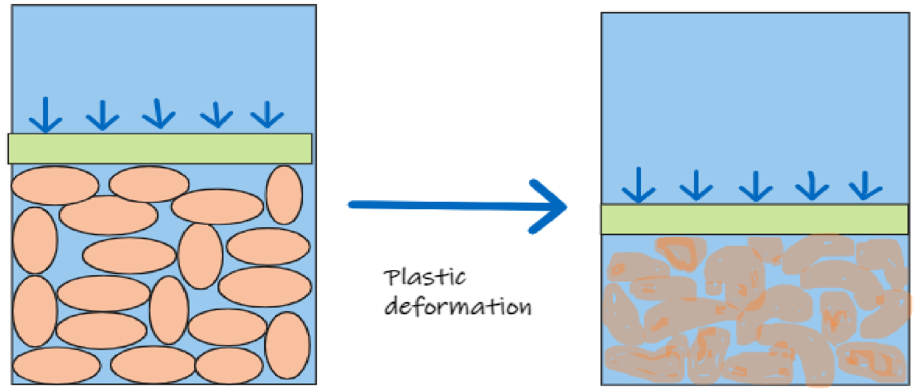
Further, at the start of compaction, there will be more rearrangement but this time some powder particle is pressed at the junction of two particles in contact, leading to side pushing of two particles, inserting third particle in between if there is space available for that. This will further increase the density.




After nearly all of the spacing is filled and there is no more room left for rearrangement of particles, elastic deformation of particle begins and powder grains will be compressed from sides where they are in contact with surrounding powder grains but simultaneously expand towards sides where it is free to expand i.e in the void spaces and that along with volumetric compression of powder particles also leads to partially filling up of void spaces leading to further densification, perhaps this process should not to be stopped here otherwise there will be spring back effect which will lead to decrease of density as we are still in elastic zone, and sometimes density obtain could be less than that what achieved before compaction in elastic zone. If we successfully cross the elastic zone then comes the plastic zone, where power grains will undergo plastic deformation. Note that it is possible that while one grain is undergoing plastic deformation mean while another powder grain at some other location in compact might be still undergoing elastic deformation as the distribution of pressure intensity is generally not uniform.

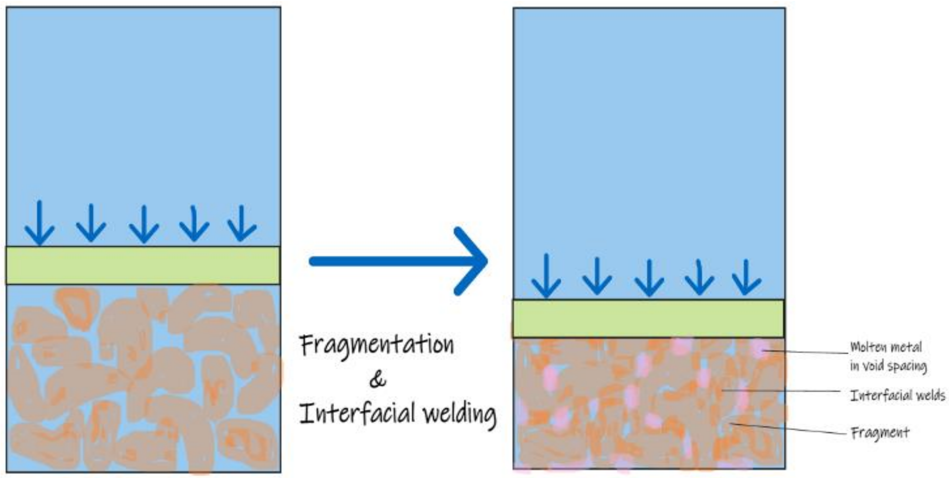



Plastic deformation gives the same results of densification by further filling up void spacings as that in case of elastic deformation but here that took place in an irreversible manner as there is no risk of spring back effect.

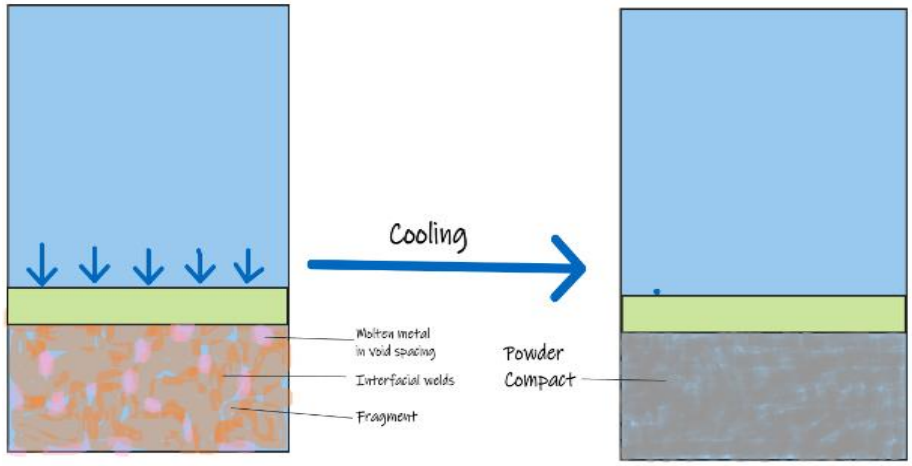



When Grains run out of option of ways to adjust with compaction, it undergoes Fragmentation or strain hardening depending on where it is made of brittle or ductile material. Sometimes even ductile material can behave as brittle if the compaction process is happening at a very high strain rate or at a very low temperature [14] so that is also needed to be accounted.

In the overall process, the powder is flowing and grains are slide slipping each other generating heat due to friction, Also as energy is supplied, and due to the adiabatic nature of high strain rate power compaction this energy apart from getting stored in as a deformation, will also appear as heat which will raise the bulk temperature sufficient enough to cause interface melting and softening [3], which leads to welding at the interface of powder particles and some of the melt will also fill up void spacing bringing down porosity [4] hence enhancing densification leading enhanced strength of green compact [5].




After this, the compact is going to be cooling down, and depending on the rate of cooling governed by thermal properties of materials, and environmental conditions, change in microstructure may be observed at powder grain interface conforming partial melting giving different hardness and microstructure for different locations in the compact [6], after removal of load some spring back effect can be observed due to release of residual stress induce during loading [7].




Green strength of material is directly related to final density achieved after compaction [8] so more and more attempts are being made to obtain parameters which can take us to achieve density as close as to that of pure metal with near to zero porosity or inclusion.

### 2.3.3 Multifurcation of mechanisms under different conditions.

A major part of densification occurs during the dynamic compaction of powder. Dynamic compaction is associated with shockwave propagation which will only happen when the velocity of compaction is greater than the velocity of sound in powder, thus mechanisms differ for low and high compaction rates. At a low loading rate, mechanisms are governed by arrangement and friction dominating effect whereas at higher loading rates, mechanisms will be taken over by interparticle melting and strengthening mechanism.

| region/curve | description |
|---|---|
| A | pressing in absence of shock wave |
| B | particle deformation close to static, inspite of the shockwave character |
| C | strength loss and plastic flow of the softened volume |
| D | localization of energy and melting of interfaces |
| E, F, G | similar to B-D respectively; incomplete densification |
| 2 | separation of plastic flow & incipient melting |
| 3 | intensified plastic flow linked with loss of strength |
| 4 | time of pressure impulse |

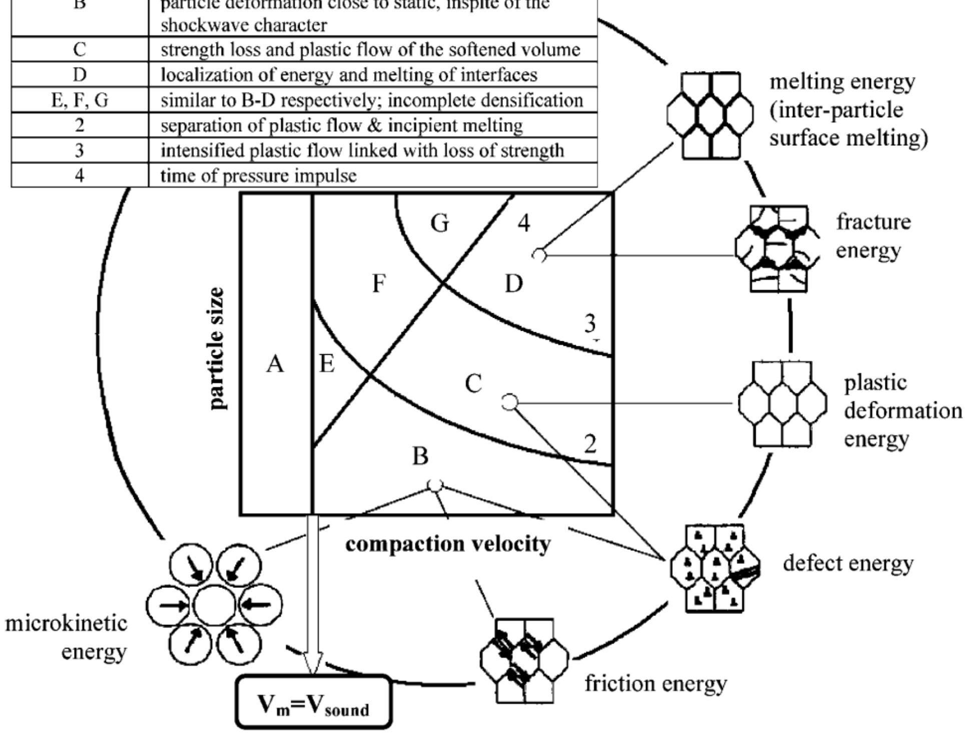



*Figure 5. Major densification mechanisms occurring during dynamic compaction [49-50].*

Fig 5 describes the various densification phenomena happening during dynamic compaction under a set of particle size and compaction velocity. It can be observed from Fig 5 that controlling phenomena of dynamic compaction changes from region from microkinetic energy to interparticle surface melting as particle size increases.

In Region A, compaction velocity is less than the velocity of sound therefore no generation of shock wave and follows regular quasistatic compaction. At the boundary line of Region, A, the material speed of the powder is equal to the velocity of sound in the powder and this line differentiates quasistatic compaction from Dynamic compaction, therefore acting as a starting line of dynamic compaction [22].

As we enter Region B with lower particle size, but greater compaction velocity than the sound velocity in powder, there is the generation of the shock wave, but its presence doesn’t make much of a change and the process behaves much like in quasistatic compaction in Region A. This happens due to poor packing of smaller size particles causing high dispersion of compressive stress waves and much of wave energy is dissipated in overcoming interfacial friction between particles.

As the Particle size increases from Region B to Region C and to Region D in a higher compaction velocity region, greater compaction Energy is input, this leads to plastic deformation and work hardening of material for moderately size particles without thermal softening whereas, for larger particle size in Region D, the effect of thermal softening is also observed along with greater Plastic deformation and work hardening mechanism.

The softening was caused in Region D by the localized temperature rise in heat trap zones due to the adiabatic nature of the process and this localized temperature rise is much greater in the particle contact interface, sufficient enough to melt the material at the interface, that further leads to welding at powder grain interface. Some of this molten state also flows into porous void spacings improving density and strength. This molten metal after solidification transforms into different phases than the parent metal, microstructural analysis of which suggested that this molten phase could go up as high as to 15% to 20%, thus serving as evidence of mechanism. Thermal softening and melting of particles cause it to bond with each other, leading to enhancement of the compact strength.

The controlling phenomena are put into a partition by drawing curves 2,3, and 4 in Figure each representing change in mechanisms of compaction. As one goes across curve 2 from Region B to C, densification mechanisms make a sudden change from microkinetic energy to plastic deformation mechanisms However, this transition is smooth across curve 3, where the influence of thermal softening gradually increased to limits where it should be considered.

Curve 4 in Fig 5 is the situation where particle deformation time plus freezing time of interparticle melting is equal to the time duration of acting pressure and is represented by a straight line as deformation time is directly proportional to particle size and inversely proportional to speed. The positions of all three curves depend on the thermal properties, density, and hardness of the particles.

## 2.4. Role of Powder Characteristics

Powder attributes like powder material, powder bulk property, powder shape and size morphology, process parameters, and part geometry are all going to play a key role in steering the path of the process to land on point with certain properties at the end of compaction. If one wants a process to land on the desired set of properties then one needs to know how the process behaves under what set of parameters, to control and direct it to yield the desired results. Some of the behaviors that have been found by various researchers under specific parameters are described below to illustrate the dependence of the process on such parameters.

### 2.4.1 Powder Material Properties

The basic material properties that affect the compression process in dynamic compaction are:

**(i) Yield, Tensile and Fracture Strength of powder material**

**(ii) Strain Hardening Behavior**

**(iii)Strain, Strain Rate and Temperature sensitivity** (from Johnson cook equation)

**(iv) Thermal Properties (**Such as specific heat, thermal conductivity, diffusivity, latent heat of fusion and melting temperature)

**(v) Crystal structure**

**(vi) Ductility/ Brittleness Behavior**

Compressibility is inversely proportional to yield strength, tensile strength, strain hardening and strain sensitivity, and directly proportional to temperature sensitivity [9][13].

The deformation behavior of the materials is also affected by the crystal structure because the dislocation behavior is dependent on the same [10-13]. Strain hardening of body-centered cubic (BCC) metals is usually much more sensitive to strain rate than face-centered cubic (FCC) metals which remain ductile over a wide range of strain rates. Body-centered cubic metals tend to lose their ductility with increasing strain rates and generally undergo a brittle transition [13-14].

Thermal diffusivity accounts for the different thermal properties affecting the process as these determine Temperature rise on interface of powder grains and extent of interfacial melting taking place for welding between power particles and amount of melt generated to fill up voids spacing in powder.

For brittle materials like metal-oxide and ceramic materials, limited dislocation mobility increases the threshold for yielding, promoting the fracture of individual grains during densification. Therefore, the mechanisms controlling consolidation in brittle materials can be quite different from ductile materials like metals where greater plastic deformation is allowed before fracture.

### 2.4.2 Powder Bulk Properties

**2.4.2.1 Velocity of sound in powder material** High strain rate compaction is generated by creation of shock, for that compaction velocity should be greater than equal to velocity of sound in powder to establish shock waves in the powder. This shock wave propagates and compacts powder along its way. The velocity of sound in a powdered material is at least a hundred orders of magnitude lower than its corresponding velocity in the solid form (or the bulk sound velocity) therefore an important parameter to be considered. This velocity is independent of the powder morphology and size but is dependent on the internal lubricant amount, in addition to material properties such as young modulus [13], [15-17].

**2.4.2.2 Powder apparent density** The ranges of sound velocity in powder are based on the corresponding relative apparent density of the powder and change with time as the experiment progresses.

**2.4.2.3 Average coordination number of powder grain in bulk**

The coordination number is the number of grains with which one grain is in direct contact. In a bulk it's taken on an average for bulk and density will increase as the coordination number increases [18].

**2.4.2.4 Interfacial and wall friction** The compact possesses non-uniform density distribution, which is mainly due to friction among the particles and the mold wall [19]. Analyzing the friction coefficient curve of the iron powder under different pressures, it was found that friction coefficient increases with the increasing compressing force at the beginning of the compression. With the increase of the compact density and the gradual stability of the contact interface, the friction coefficient asymptotically decreases [20]. Improving the friction conditions can reduce the loss of compaction force.

**2.4.2.5 Void space and packing fraction** As powder mixture consist of particle of all shape and size and overall arrangement can’t be free of space voids therefore apparent density of powder is less than that of pure constituents of powder and depends on powder size and roundness distribution.

**2.4.2.6 Powder fill** The amount of powder filled in the die plays a critical role in the transference of the shock wave through the powder. The specific energy (compaction energy per unit mass) follows a parabolic trend with powder fill height to achieve the same density in hydraulic press setup for powder compaction [21].

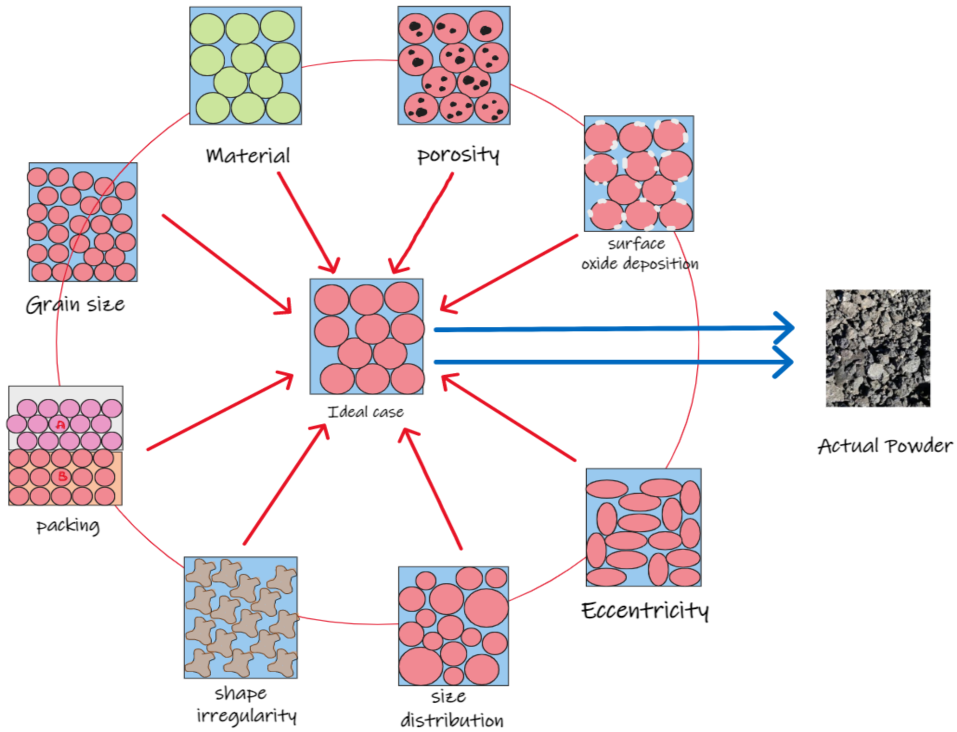



*Figure 6. Describes different powder attributes as an ingredient to depict actual powder.*

### 2.4.3 Powder Size, Morphology and Porosity

#### 2.4.3.1 Particle Size Distribution

Study shows significant influence of the particle size distribution on the mechanical behavior in powder compaction. A smaller sized powder fraction will result in a uniform energy distribution over the volume at high pressure, but that can also lead to de-compaction of the compact due to the relief or unloading waves. A larger size particle will result in higher adiabaticity, but that may only lead to partially deformation of powder particle leaving scope of porosity and weak mechanical bonding. A powder can consist of a particle having a range of size varying from very stepper to greatly humped distribution and this will have effect on deciding process parameters to set up for optimum quality and needed to be taken care of.

#### 2.4.3.2 Particle Morphology Distribution

The study suggested that irregular powder (air atomized) suffers greater bending stresses and has greater points of stress concentration (energy deposition is more) which causes enhanced localized thermal modifications (loss of strength), and hence lead to better densification than spherical powders (inert gas atomized) [22]. Also, after localized plastic deformation stage, thermal softening stage occurs due to the adiabatic nature of process. This stage occurs earlier in irregular shaped particles powder as compared to regular shaped particle powder. Irregular particles suffer more straining and bending moments leading to generation of larger number of thermal softening points supporting densification and strengthening compact [23].

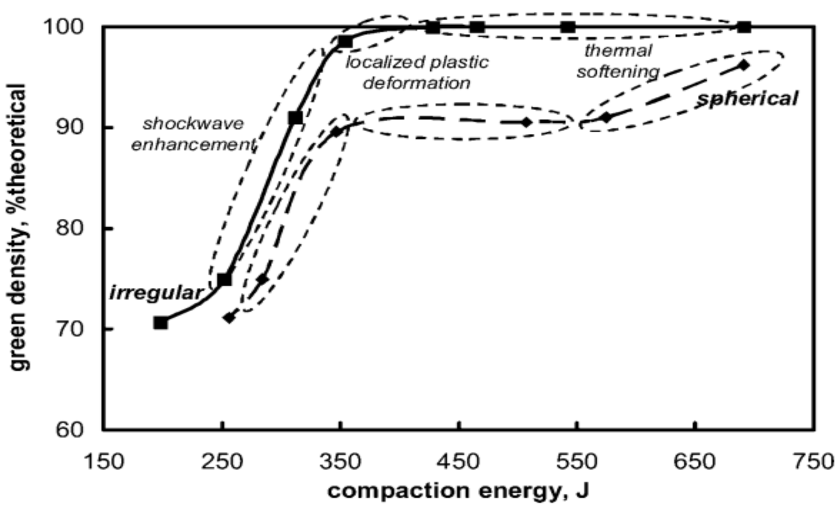



*Figure 7. Effect of powder shape, irregular and spherical in Al alloy powder [23].*

### 2.4.3.3 Purity in the powder particle

The Powder produced from different processes has different levels of purity and porosity, for example, The sponge powder which is made from the atomic spraying technic possesses less purity than one produced from Electrolytic methods, and in experiments, it was found that Electrolytic iron powder is more compressible than sponge iron powder, hence increasing purity can lead to higher densification [24].

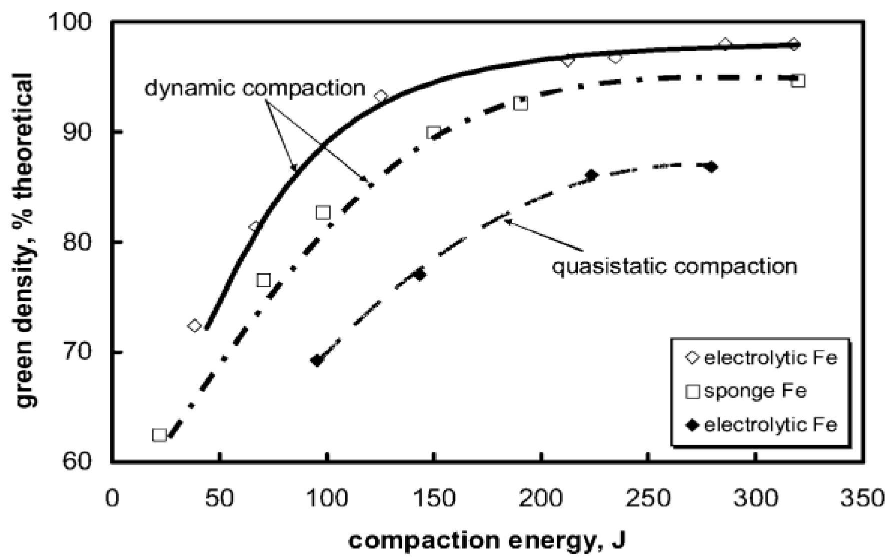



*Figure 8. Green density of different powder types of iron powder, which are dynamically and quasi-statically compacted [51].*

### 2.4.3.4 Surface Condition

Usually, in the atomic spraying technic, molten drops at higher temperatures undergo surface oxide formation, therefore surface oxide is inherently there on the powder surface which is less in case of powder prepared from electrolytic process. In the progress of the compaction process also there is generation of oxide film which is comparatively less when Electromagnetic compaction is opted [2]. This oxide layer's formation mainly depends on the compaction pressures, i.e., compaction energy. The oxide layer breaks due to mechanical friction interaction at the interface at a higher energy compaction process, therefore, the oxide layer doesn't appear at higher compaction pressure [25] and the extent and nature of this surface oxide describes adhesion interaction of particles from one another contributing its effect on strength of compact produced.

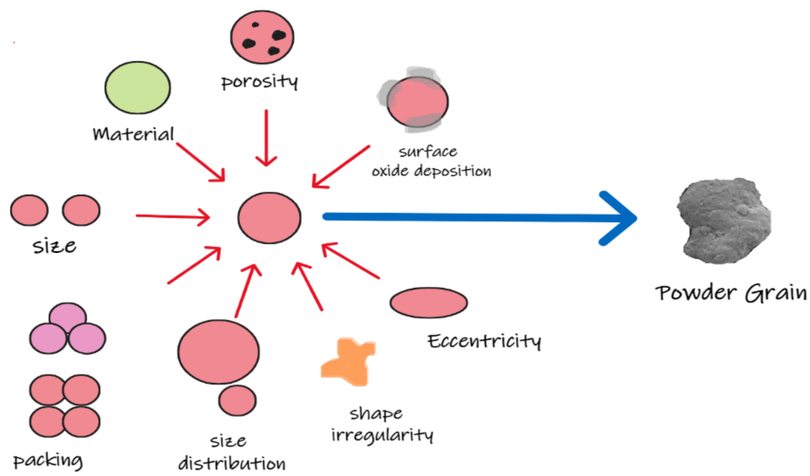



*Figure 9. Describes different powder attributes as an ingredient to depict actual powder particles.*

### 2.4.4 Role of Process Parameters

#### 2.4.4.1 Compaction pressure builds up characteristics.

The compaction pressure is usually measured using a pressure transducer placed in the die and this pressure builds up varies with location and time as the dynamic compaction happens and the Shock wavefront flows away from the compaction end. The more compaction energy you put in for a shorter period, the higher pressure rise peak will be observed in general which could have a positive impact of getting higher compact density [26].

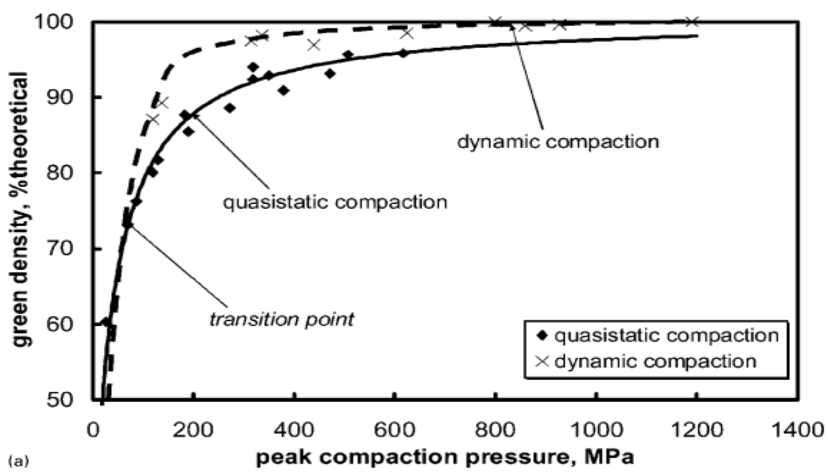



*Figure 10. The curve depicts the dependence of green density achieved to peak pressure noticed for Iron powder (a) [26].*

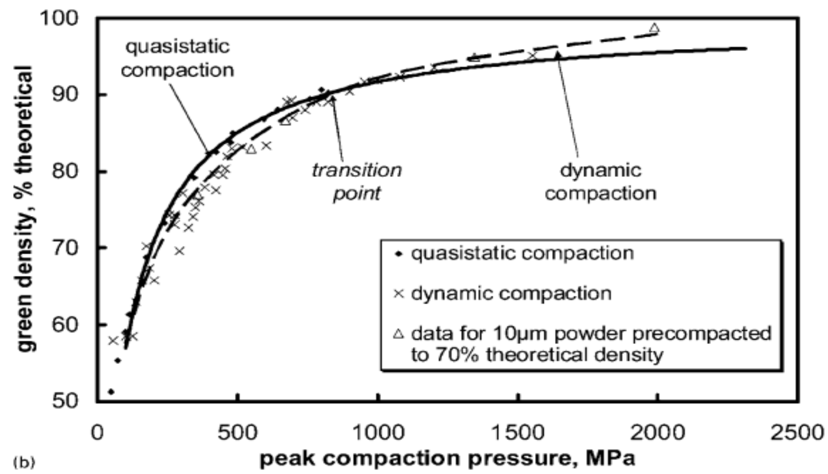



*Figure 11. The curve depicts the dependence of green density achieved to peak pressure noticed for Aluminium powder (b) [26].*

### 2.4.4.2 Compaction Energy supplied.

Compaction energy in dynamic compaction per unit mass of powder plays a critical role in framing the properties of powder compact, For Iron, Aluminium, and copper powder it is observed that the greater the compaction energy per unit mass of powder added in the process, the greater the green density it achieved at the end of compaction [26-27] due to greater melting state of powder particle appearing in process available to fill the void spacing between particles, but that effect dissipates as we move closer to achieve maximum theoretical possible density and nature of curve goes asymptotically towards maximum theoretical possible density.

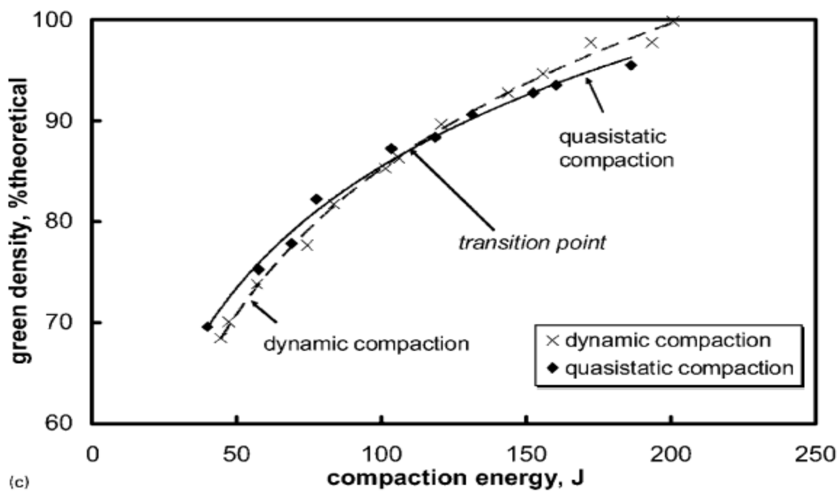



*Figure 12. E–D (energy–density) curves for copper powder [27].*

### 2.4.4.3 Loading Rate

As the shock waves lead the compaction end, the powder between those two has been compacted by both pressing effect and due to shock wave whereas powder in front of has only been compressed by pressing, so the rate of compaction coupled with velocity and location of shock will decide the nature of nature of compaction and green density achieve [27-28].

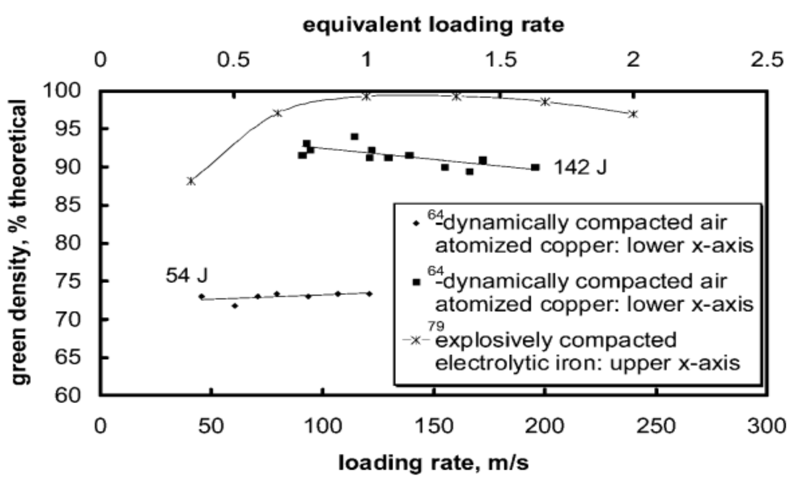



*Figure 13. Effect of loading rate at constant energy in air-atomized copper powder and explosively compacted pure electrolytic iron powder [27-28].*

### 2.4.4.4 Part geometry and dimensions of the container

It has come to notice that the geometry and dimension of the container used for the containment of powder also play a role (mainly height to diameter ratio in the case of cylindrical geometry) as pressure distribution suggests an exponential decline of pressure with height with dependence on height to diameter ratio of the compact of powder, The lower height-diameter ratio makes the transfer effect of compaction force better. Also, the specific energy (compaction energy per unit mass) follows a parabolic trend with powder fill height to achieve the same density in hydraulic press setup for powder compaction [13].

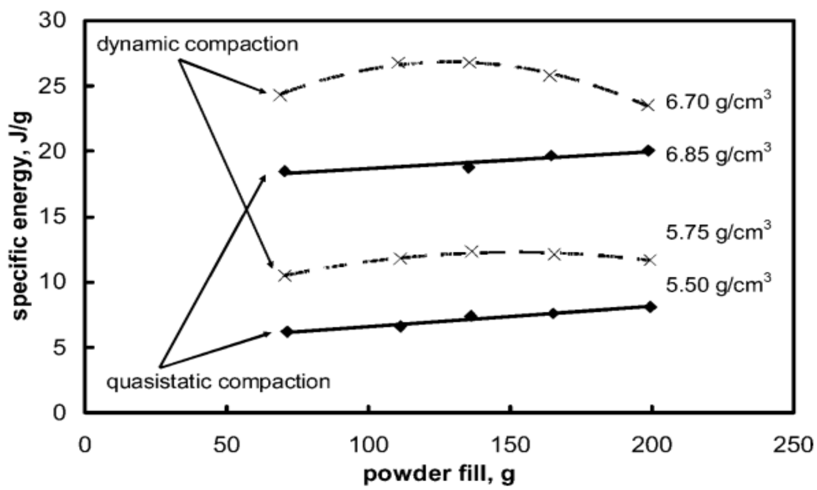



*Figure 14. Specific energy required to produce the same density with different powder fills (fill heights) in quasi-static and dynamic compaction for iron powder [21].*

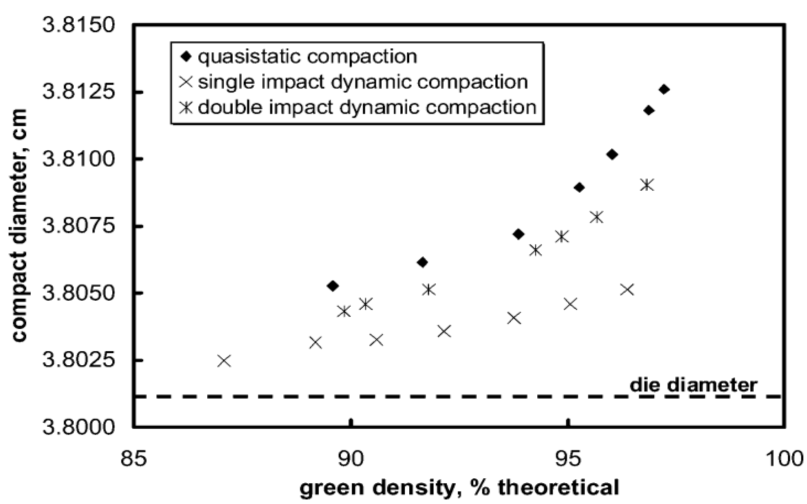



*Figure 15. Dimensional control in dynamic and quasi-static compaction [13] [52].*

### 2.4.4.5 Lubrication effect

The increase in temperature can improve the lubricating performance of the lubricant, reduce the frictional resistance between the inner wall of the mold and the powder particles, and facilitate the displacement and deformation of the powder particles but larger amount of internal lubricant hinders the densification at higher compaction pressures. In quasi-static compaction, the limitation is due to the space occupied by the internal lubricant. This must also apply to dynamic compaction and is also detrimental to wave propagation through the powder [29].

## 2.5. Theoretical basis of High velocity compaction (HVC)

The high-velocity compaction process is a complex phenomenon, analysis of which includes nonlinearity problems such as material, geometric and boundary conditions nonlinearity, powder deformation and flow, friction considerations, localized-welding, inertia effect, stress wave propagation, rheological characteristics, and thermomechanical couplings. Based on their research work, scholars have put forward various theoretical analysis methods, all of which describe it approximately and not exactly under some range of conditions. Two such theories are described below.

### 2.5.1 High velocity compaction equation.

A high-velocity compaction equation is an Experimental Approximation equation obtained by fitting in Experimental results by regression and is valid on the specific range of conditions. It is a quantitative analysis derived considering the densification mechanism which can be used to improve the theoretical models. Table-1 depicts various equation fittings under mentioned conditions.

**Table 1:** High Velocity Compaction Equation

| **Name of Equation** | **Scope of application** | **Theoretical Characteristics** | **Conclusion Formula** |
|---|---|---|---|
| Kawakita's compaction | Suitable for soft metal | It considers the plastic | $C = \frac{abP}{1 + bP}$ |

| | | | |
|---|---|---|---|
| equation [38] | powder under small pressing force. | deformation and yield limit of powder particles, and is often used as the compression curve of various pharmaceutical powders | |
| Bal'shin equation [39] | Only suitable to calculate the medium hardness green body density in the range of hard powder or medium compaction pressure. | It regards the powder as an ideal elastomer, and does not consider the influence of work hardening and friction, pressing time and fluidity | $\log\left(\frac{P_{max}}{P}\right) = L(\beta - 1)$ |
| Heckel suppression equation [40] | It is used to describe the plastic deformation of metal powder and its stress ''Hardening Effect' | It is summarized after experiments on a large number of metal powders. | $\log\left(\frac{\epsilon_o}{\epsilon}\right) = KP$ |
| Huang Peiyun suppression | It is suitable for soft and hard powders | It adopts the concept of natural strain, | |

| | | | |
|---|---|---|---|
| equation [41] | at low, medium and high pressures | considering factors such as stress and strain relaxation during powder compaction, work hardening agent, large degree of strain, etc. | $$\frac{\left(\frac{d_m}{d}-1\right)}{\left(\frac{d_m}{d_o}-1\right)} = e^{\frac{P^n}{M}}$$ |
| Johnson-Cook constitutive equation [42] | In view of the large strain, high strain rate and high temperature of ductile materials, it is proposed to describe the behavior characteristics of metallic materials at high deformation rate and high temperature. | It is an empirical equation describing the thermal-viscous plastic constitutive relationship. The material parameters have clear physical meaning and relatively simple, easy to fit experimental data, and have strong versatility. It is usually used as a material constitutive model for numerical calculations. | $$\sigma = \alpha \times \beta \times \gamma$$ Where: $$\alpha = A + B\epsilon^n$$ $$\beta = 1 + C\ln(\epsilon^*)$$ $$\gamma = 1 - \frac{T - T_t}{T - T_m}$$ |

| | | | |
|---|---|---|---|
| Thermal softening shear densification mechanism [43] | After pre-compaction, the powder is struck again by an impact hammer, resulting in instantaneous local high-temperature welding. | It is assumed that the green density is related to the amount of heat softening zone and that the shear zone temperature increases exponentially with the applied impact energy. | $\ln(\varphi) = \frac{K_{1\,\Delta}H_L}{e^{K_2\left(1-\frac{P}{\Delta H_L}\right)}+c}$ |

**2.5.2 Classical theory of high velocity compaction.**

Classical theories of high-velocity compaction are set of theories valid under a different set of conditions, as it is a relatively complicated process, with branching out phenomena so there is no single compaction theory depicting its governing path. Some of those theories which have tried to describe the phenomena are presented in Table 2.

**Table 2.** Classical theory of high velocity compaction.

| **Suppression theory** | **Model Hypothesis** | **Theoretical Basis** | **Theoretical Characteristics** |
|---|---|---|---|
| Impact molding theory [44] | The density of dynamic compaction does not depend on the impact kinetic energy, but on the maximum impact force and impact | When the impact kinetic energy is constant, if the hammer mass, powder material, particle deformation and initial loose density are | The compaction effect of a hammer with certain kinetic energy can be seen as the superposition of smaller impact force and longer |

| | | | |
|---|---|---|---|
| | time. | different, the impact stress and action time in different States will be produced, and the corresponding compact density will be completely different. | stroke, or the superposition of larger impact force and shorter stroke. |
| Inertia effect [44] | Powder particles have inertia in the process of high velocity compaction molding. | The green body starts from the state where the initial velocity is zero and reaches the impact velocity and completes the deformation in a very short time. A high acceleration will be generated in the green body, and then inertia will appear. | There are three inertia effects: global inertia, strain inertia and internal inertia |
| Stress wave theory [45][46] | Real stress wave form | All solid materials have inertia and deformability, and the deflection caused by external load gradually propagates from near to far in the | The stress wave has a sawtooth waveform, and its duration is affected by the loading rate. Each loading waveform has |

| | | | |
|---|---|---|---|
| | | medium to form stress waves. | several extreme points, which will cause tensile stress after being reflected by the free end surface, resulting in delamination and spalling of the green body surface |
| Rheology theory [47][48] | Nonlinear viscoelastic model, plastic model | It regards powder as rheological fluid and considers the influence of time on powder compression process. | It has rheological properties such as strain delay, stress relaxation, compression creep, elastic aftereffect and powder internal friction. |

## 2.6. Simulation-Based Study and Experimental Validations

The numerical simulation of HVC has gained a lot of attention and gained research focus in the field of Powder compaction. As in this case, a complete experimental setup requires a lot more investment of time and resources, and a large number of such experiments are needed to be carried out to investigate conditional insights of phenomena, in this case conducting a numerical simulation run for matching the expectations using already known knowledge makes sense very much. Some of such attempts are described below.

During simulation studies, it is vital to have knowledge of which model gives closer results with experimental results thus in the simulation study for comparisons between using 2D or 3D MPFEM Simulations in Modeling Uniaxial High-Velocity Compaction behaviors of Ti-6Al-4V Powder ,it is was observed that 3D MPFEM model generate closer results than 2D model in following the experimental green density achieved at the end of the compaction and its relationship with true strain and Energy per unit mass ($E_m$) [31].

Zheng Zhou-shun et al applied the Discrete Element Method to powder compaction processes to establish a contact model of particle and formulate an equation of motion of each particle. The process of powder flow and density distribution during HVC is stimulated based on computing software PFC-2D. The result obtained for density distribution appears to follow a certain law in which density decreases from top to bottom. The Highest density is achieved at the top surface while the lowest density is achieved at the bottom corner. Also, by keeping the height to diameter ratio minimal the difference of density on different parts reduces and hence becomes more uniform in density [32].

In order to illuminate the effect of particle grain size and its distribution on force transmission through powder grain contact points, Zhang Wei et al utilized the Concept of Force chain, and here in counting the length, and directional deviation of these force chain was reported for various range of particle size and it was found out that when the particle size distribution range is small, force chain distribution is more uniform, and the anisotropy is not significant, but as the range spreads keeping lower bound same then the fraction of larger size grain increase, and with that fluidity of particle also increases [33]. Analysis of Force such chain formation and its distributions are only possible through simulation only.

Another Simulation-based study was conducted by David J. Benson attempting to calculate shock velocity – Particle relation, where hundreds of discrete particles were analyzed with Eulerian finite element program and based on a comparison by least square fitting of experimental data, a reasonably accurate relation for shock velocity and particle relation was established using the model [34].

Numerical simulation turns up to be a reasonable and effective way for investigations, which can largely reduce the experimental cost and time investment in high-velocity compression, with the only limitations being that it is based on a theoretical framework carrying assumptions that might not apply exactly to the real-life world, and what is obtained is an approximate numerical solution, and not the exact one, therefore cannot completely replace the experiment procedure and validation methods but still possess a lot of potentials to sort out directions.

## 2.7. Process limitations and problems in development.

The high-velocity compaction process is successfully use in applications in automobile, aerospace, and structural applications, but there are still some limitations to overcome and Challenges to tackle to make best use of technic, some of known ones is described below.

(1) There are still a larger number of contradictory views among scholars about the densification mechanisms which is been followed. For example, many scholars [35] have raised their doubt about the existence of the stress wave phenomenon. Lack of concrete and convincing evidence is still missing in the knowledge of HVC and needs to be addressed.

(2) The parts produced by the high compaction process still lag to deliver properties such as strength, wear resistance, and fatigue life over the competing metal forming process, so extensive work is still needed to be done to uplift its shortcomings to achieve the best possible results.

(3) So far Reacher's have mainly focused on the development and experimentation on mainly Convectional materials like iron, aluminium, titanium powder so that need to change, and new material should also be introduced and tested for the process.

(4) Maturity of setup and need for dedicated Molds used for the experiments have been noticed, as high energy and high frequency impact characteristics of high velocity compaction cannot be noted using conventional compaction molds, therefore need for smartly designed mold and setup dedicated for the purpose must be produced to extract more and more incites on process.

(5) Due to the complexity of the process many experimental observations are required to investigate the phenomena, but most colleges, universities, and enterprises do not have the dedicated setup for conducting HVC which slows down its development progress and could take longer time to make it fully mature for use extensively.

## 2.8. New development trends

New development trends and application prospects of high velocity compaction have emerged, some of it is described here.

1) Peng Ni et al proposed a new method of powder compaction using laser shock for compaction of powder in small die for creating small parts using powder metallurgy. The compact size of $\Phi$ 2.5 × 0.5 mm of aluminium powder using 1800 mJ laser energy is achieved. Here in 99.72% of green compact density is reached and the Microhardness between 50 and 60 HV with an increase of 60% is found with this method [53].

2) While performing experimentation with the Electromagnetic powder compaction method on Aluminium 6061 Aloy powder, it was found out that the result of density variation with input Voltage and Compaction energy per unit mass need was coming out to be in good agreement with the simulation study performed by them with less the 2% error [54]. Thus, in some cases like this simulation study not only turns out to be cost-effective but also possesses border reach for implementation of Sophisticated new age processes like Electromagnetic powder compaction.

3) K. Sajun Prasad et al in their paper presented a new and rapid throughput experimental setup to do impulsive and shock physics

experiments. Setup involves accelerating projectile mass to a very high velocity using plasma pressure. This plasma is generated by instant vaporization of Aluminium foil with the passage of a current of around 200 KA via capacitor discharge. Using this method CP-Ti Powder was successfully compacted. Along with that shock, velocity can be evaluated using a free surface velocity of the compact loaded barrel [56].

## 2.9. Conclusion from Literature survey

High velocity compaction (HVC) technology is a key technology to realize high density, high precision, high performance, and low cost for P/M parts. High velocity compaction involves propagation of a compressive stress wave through a powder to cause its densification. Its densification starts with rearrangement, followed by elastic and plastic deformation and melting and welding. This melting and welding are due to its adiabatic nature of process, which causes heat trap localized melting zone in the regions at high stress concentration zones which leads to welding of particle together at their interface providing strength to compact. Some of the melts also occupy the void between powder particles hence reduces porosity, increasing strength. Mechanisms through which it occurs are greatly governed by powder character statics and process parameters.

The factors such as material parameters, part shape, molding equipment and process conditions play a role that is discussed in this literature. This also showed that the selection of different pre-processing and process parameters is critical for a high-performance dynamic compaction system is essential. Due to its own technical characteristics, high-velocity compaction has found the optimal solution between the performance and cost of powder metallurgy parts.

Based on their research work, scholars have put forward various theoretical analysis methods, which describe governing's of process approximately if not exactly under some range of conditions. In this various Simulation approach has also been put up results of which is quite consistent with experimental hence proving potential for the Simulation approaches.

High Velocity Compaction technology also has the advantages of energy saving, environmental protection, high efficiency and so on, and is widely applied in the field of powder metallurgy industry. However, there are also some problems that cannot be ignored, such as large volume of high velocity compaction molding equipment, high precision requirements for processing and installation, high cost, and low popularity rate, missing knowledge and knowns of unknowns.

# Chapter 3:

# Research Methodology

## 3.1 Experimental Setup

Two different setups were used to radially compact aluminium powder packed in an aluminium tube cartridge. The first setup is Mechanical press powder mimicking Quasistatic compaction (RMP) whereas the Second setup utilises an Electromagnetic setup to create a high stain rate compaction (EMC). A detailed description of the two setups is discussed below.

### 3.1.1 Hydraulic press coupled with modified mechanical crimping accessory for RMP.


*Figure 16. Components of Mechanical Radial Compression Setup (RMP).*

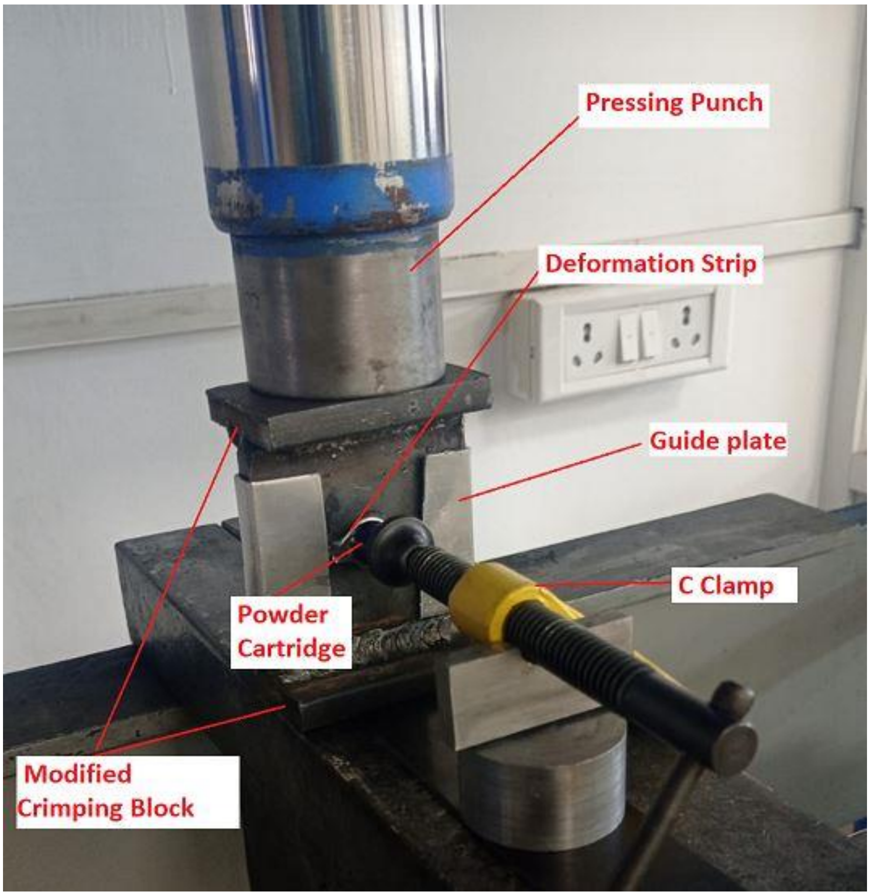



*Figure 17. Experimental Set up for RMP.*

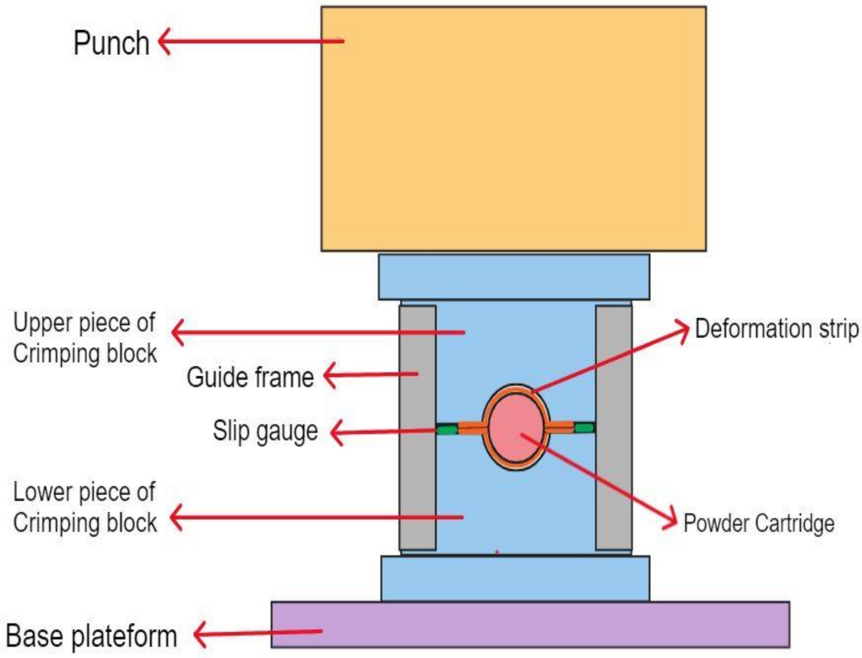



*Figure 18. Schematic of Front View of RMP Setup.*

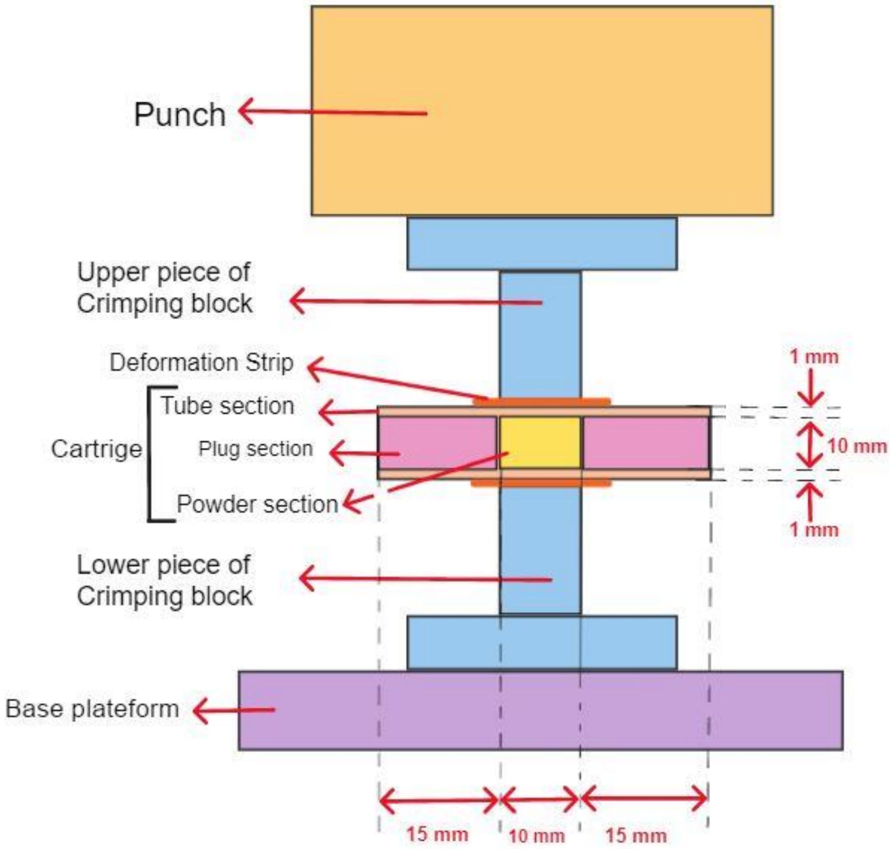



*Figure 19. Schematic of Side View of RMP Setup.*

### 3.1.2 Electro-Magnetic Setup and its Working

#### (I) Components and Schematics of Electro-Magn etic Setup


*Figure 20. Shows Front and Side View of Electro-Magnetic Forming/Crimping/Compacting Machine.*

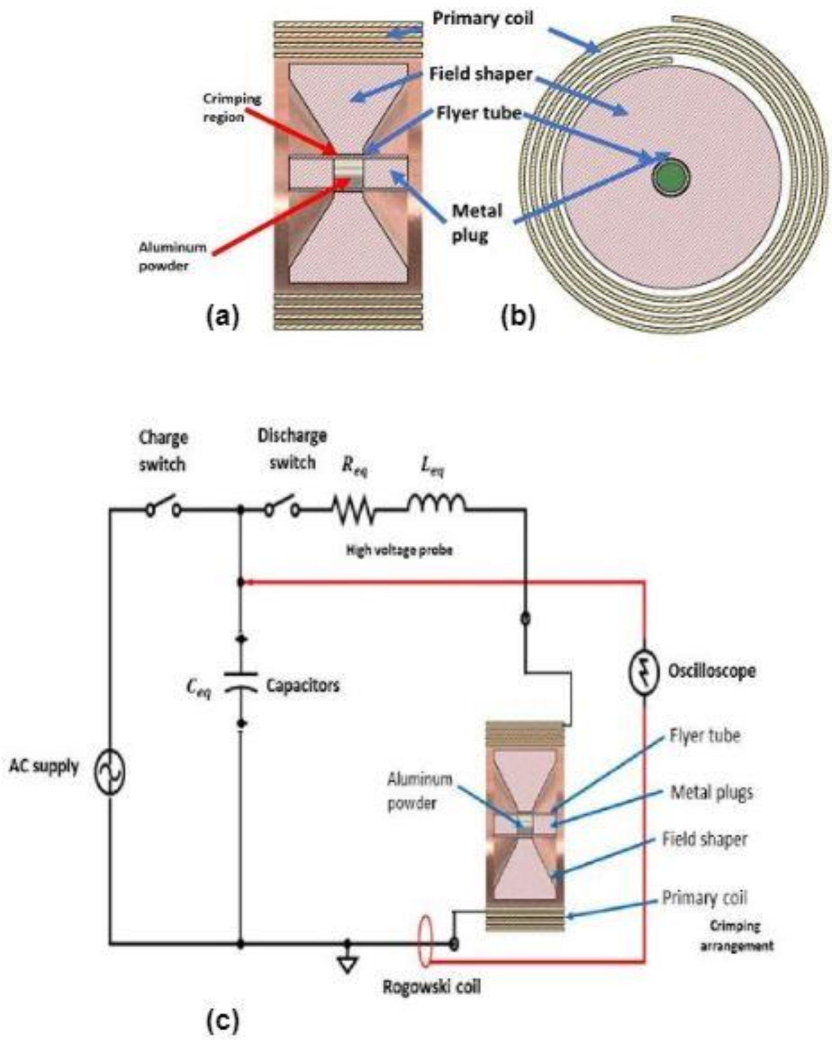



*Figure 21. Schematic of high velocity compaction using Electromagnetic Compaction Technique. (a) side cross-sectional view field shaper and coil assembly (b) front view of field shaper and coil assembly ( c) Circuit Diagram of EMC setup.*


*Figure 22. Electro-Magnetic Setup and Assembly.*

**(II) Working principle of EMC Machine**

In electromagnetic powder compaction, the process hinges on harnessing the force of electromagnetic fields to consolidate loose powder particles swiftly and effectively. The primary working mechanism revolves around the rapid discharge of a capacitor bank through a coil. This discharge generates a powerful and transient magnetic field. This magnetic field, in turn, interacts with the conductive powder material placed within the coil.

The magic occurs when the magnetic field is induced within the powder bed. This induces eddy currents within the conductive particles, and as per Lenz's law, these currents create their own magnetic fields that oppose the original magnetic field. Consequently, the powder particles experience a series of Lorenz forces, resulting in their rapid movement and simultaneous collision. This dynamic action leads to the compaction of the powder, causing it to densify into a coherent and dense structure.

The beauty of electromagnetic compaction lies in its ability to provide exceptionally high strain rates, far beyond what traditional static compaction methods can achieve. This rapid loading rate is pivotal in enhancing the mechanical properties of the compacted material, as it minimizes the chances of microstructural defects, density gradients, and variations in mechanical properties across the sample.

**(III) Design and Significance of Field Shapers**

The field shaper is an integral component in electromagnetic powder compaction, responsible for shaping and directing the magnetic field to ensure precise compaction. Its design and placement are critical in achieving uniform and controlled densification. By carefully engineering the field shaper's geometry and positioning, it becomes possible to focus the magnetic flux precisely onto the desired powder zone. This precision is paramount in avoiding undesirable variations in compaction across the sample, resulting in enhanced material homogeneity. The significance of the field shaper lies in its ability to maximize the efficiency and effectiveness of the compaction process, leading to improved mechanical properties and microstructural uniformity in the final product.

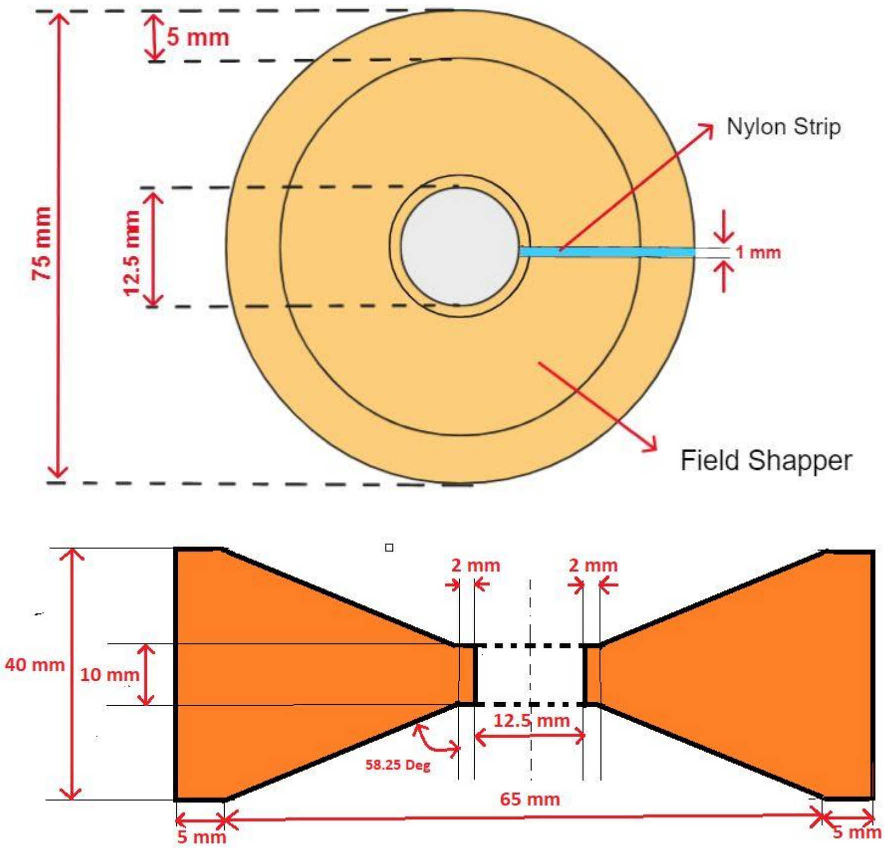



*Figure 23. Top and side cross-sectional schematic view of field shaper.*

## 3.2 Materials and Consumables

### 3.2.1 Powder Material

99% Pure Aluminium Micro powder with an irregular grain Structure is used as working material for powder Compaction. Powder Material Description is given below.

Material: Aluminium

Powder type: Irregular shaped Grains

Purity: 99%

Atomic Particle Size: 50-80 micron

Chemical Composition:

**Table 3:** Shows Elemental constituents and their composition in Aluminium powder.

| **S.no** | **Element** | **Concentration** |
|---|---|---|
| 1 | Al | 99% |
| 2 | Ca | 0.123% |
| 3 | Ni | 0.100% |
| 4 | Si | 0.205% |
| 5 | Mg | 0.188% |
| 6 | Fe | 0.202% |
| 7 | Cu | 100.0 ppm |
| 8 | Se | 116.6 ppm |
| 9 | Cr | 108.5 ppm |
| 10 | others | <5000 ppm |

### 3.2.2 Process Consumables

Powder was Contained in 40 mm length Tubes and fitted with 15 mm cylindrical plugs at two ends leaving 10 mm space in the middle of tube for powder to be compacted thus creating power cartridge.

| | |
|---|---|
| Tube: Material – Al-1050<br>Dimensions- 12 mm OD, 10 mm ID, 40 mm length<br><br>Plug: Cylindrical Rod with tapered edge<br>Material – Al-6061<br>Dimensions – Diameter – 10 mm, length- 15 mm |  |

### 3.2.3 Fixture and assembly elements

**Table 4:** shows Fixtures and components used in Setup assembly.

| **Element** | **Material** | **Purpose** | **Picture** |
|---|---|---|---|
| Field Shaper | Copper | To concentrate Magnetic field in a location |  |
| Cartage Fixture (3D printed) | PLA | Hold Powder cartridge inside Field shaper |  |
| End Capes | Teflon | Position Filed shaper in machine |  |
| Insulation Band | Nylon | To insulate field shaper from Machine body. |  |
| Kapton Tap | Polyimide | Rapped on cartridge body to insulate contact with field shaper |  |

| | | | |
|---|---|---|---|
| Crimping Acessory | Hardened Steel | For radial Mechanical pressing using Hydraulic Press |  |

## 3.3 Experimental Procedure

### 3.3.1 Cartridge Fabrication and Assembly

The cartridge was prepared by fabricating a cylindrical body using Al-6061 tubes and Al-1050 rods. The Al-6061 tube, with an outer diameter of 12mm and inner diameter of 10mm, was cut into 40mm length pieces. Cylindrical plugs, 15mm in length, were also cut from Al-1050 rods with a diameter of 10mm. The cartridge assembly involved inserting the bottom plug into the tube, adding 1.57 grams of aluminium powder, and then inserting the top plug. After the plugs were in place, crimping was done to firmly secure the plugs to the tube, ensuring the stable confinement of the aluminium powder within the middle section of the tube.

The crimping process added an extra layer of reinforcement, preventing any movement of the plugs and powder during the subsequent powder compaction process.

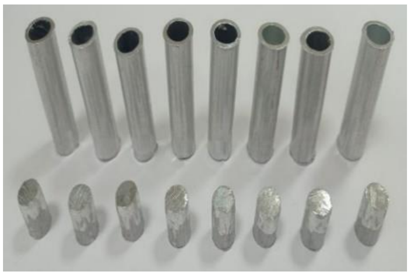


*Figure 24. Tubes and Plugs.*

*Figure 25. Powder filled Cartridges.*

### 3.3.2 Electromagnetic Compaction

**(I) Sample Preparation**

**(1) Cartridge Insertion:** The first phase of the experimental study involved the electromagnetic compaction of samples. For this purpose, three sets of samples were prepared. Each set consisted of four cartridges, two of which were powder-filled samples, while the other two were empty cartridges serving as controls.

**(2) Sample Duplicity:** To ensure the reliability of the results, the inclusion of sample duplicity was essential. The two powder-filled cartridges and two empty cartridges within each set were intended to confirm the consistency and accuracy of the obtained results.

**(3) Significance of Empty Tube:** The experiments with empty tubes were conducted primarily to isolate and eliminate the influence of the tube as a powder container. Since the core focus of the research was on powder compaction, these experiments allowed us to filter out any effects attributed to the presence of the tube itself, providing a purer understanding of the powder compaction process.

**(II) Electromagnetic Compaction Process**

(**1) Operating Parameters:** The electromagnetic compaction machine was operated at three different energy levels, corresponding to 65%, 70%, and 75% of its rated value. The specific parameters for each set were as follows:

- Set 1: Operating at 65% rated energy (Discharge Voltage, V = 9.75 kV, Energy supplied, E = 4.70 kJ).
- Set 2: Operating at 70% rated energy (Discharge Voltage, V = 10.5 kV, Energy supplied, E = 5.51 kJ).
- Set 3: Operating at 75% rated energy (Discharge Voltage, V = 11.25 kV, Energy supplied, E = 6.27 kJ).

**(2) Magnetic Field Activation:** The electromagnetic compaction setup was initiated to generate an impulsive magnetic field in the axial direction. The Lorenz Forces acting on the tube surface because of the impulsive magnetic field led to radial pressure, resulting in radial compaction of the aluminium powder within the cartridges.

**(III) Sample Collection**

3.1 Set-wise Sample Collection: After completing the electromagnetic compaction process, the samples were collected from each set, consisting of both the powder-filled and empty cartridges.

**(IV) Data Analysis**

4.1 Measurements and Observations: The key parameter measured for analysis was the change in diameter of the compacted region in the powder-filled samples. This data was recorded for each set.

**(V) Comparative Analysis:** The results obtained from the powder-filled samples were compared across the three sets, considering the different energy levels used for electromagnetic compaction. The analysis aimed to identify the effects of varying energy levels on the radial densification behaviour and properties of the entire compaction region within the cartridge.

### 3.3.3 Mechanical Pressing

**(I) Sample Preparation**

(1) Cartridge Insertion: Like the electromagnetic compaction process, the cartridge, consisting of the aluminium tube filled with powder and

securely crimped plugs, was inserted into the Radial mechanical pressing (RMP) setup.

**(2) Sample Duplicity:** To ensure the accuracy of the results, each set of samples included four cartridges. Among these, two cartridges were powder-filled samples, while the other two were empty cartridges used as controls.

**(II) Radial Mechanical Pressing Process (RMP)**

**(1) Cartridge Sandwiching:** In the RMP setup, the prepared cartridge was placed in a crimping block. This cartridge was then sandwiched between two flat aluminium strips capable of deformation at the powder-located zone, ensuring uniform pressure distribution during compaction.

**(2) Radial Compression:** The crimping block was modified to enable the generation of radial compression of the cartridge specifically at the powder zone. A hydraulic press was used to apply load, leading to the reduction of the diameter of the cartridge at the powder zone, matching the diameter obtained during high strain rate compaction through electromagnetic compaction.

**(3) Limiting Compaction:** To ensure that the compaction process achieved the desired diameter matching the high strain rate compaction sets, a combination of slip gauges was carefully placed on the crimping block's approaching surface. These slip gauges acted as mechanical stops, limiting the compaction process to a specific point, thus matching the diameter obtained through high strain rate compaction.

**(III) Date Collection**

**(1) Load Measurement:** During the RMP, the load applied using the hydraulic press can be computed by noting down reading on the Pressure indicator mounted in the hydraulic press.

In our hydraulic press, considering the dimensions of the hydraulic cylinder 1 Kcs pressure results in 0.1 Tons or 1 kN of Force.

**(2) Energy Consumption Computation:** The energy consumption during mechanical pressing can be computed using general laws of physics of work done and work-energy equation.

**(IV) Comparative Analysis**

Comparison with High Strain Rate Compaction: Once the mechanical pressing process was completed, the data obtained, including load requirement, energy consumption, and mechanical properties such as hardness, homogeneity, and microstructure, was compared with the corresponding data from the high strain rate compaction process using electromagnetic compaction.

The comparative analysis aimed to understand the differences in the compaction behaviours and resulting properties between the two processes-high strain rate compaction using electromagnetic compaction and low strain rate compaction through mechanical pressing.

### 3.3.4 Post processing of samples

**(I) Sintering**

**(1) Sintering process:**

The samples were carefully arranged inside an electrical oven to ensure uniform heating and consistent sintering across all specimens. During the sintering process, the elevated temperature promoted atomic diffusion, allowing metal particles within the samples to bond together, resulting in a denser and stronger structure.

**(2) Sintering parameter:**

Temperature: The sintering temperature employed for both sets of samples was set at 450 ℃.

Duration: The samples were sintered for a specific duration of one and a half hours (1.5 hours) at the predetermined temperature of 450 ℃.

Process Details: Time and duration were decided collectively from literature reading and self-judgement from experience of assessment of previous attempts. Compacted Samples from both processes i.e., RMP and EMC including both the sets were concurrently kept in the Induction Furnace which was already preheated to 350 ℃. From 350 ℃, temperature raise to 450 ℃ following exponentially decaying raising rate Characteristics. Once it reached to 450 ℃, the Temperature was Dwelled there for 1.5 hours was Sintering, on completion of which the Furnace was allowed to be cooled down to 350 ℃ again following an exponential decaying rate trend till the Sample where finally taken out from the furnace and kept in ambient where it further cooled down to ambient temperature.

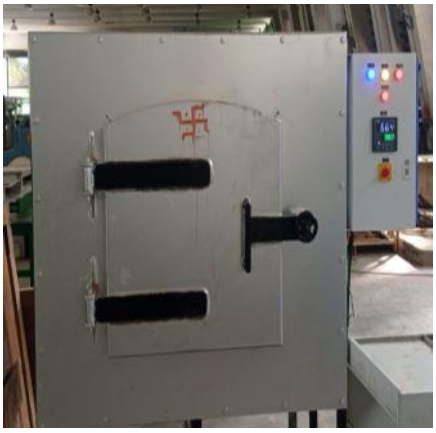


*Figure 26. Induction Furnace.*

**(II) Operations**

**(1) Cutting:** samples were cut using hand saw from section to remove end plug.

(**2) Rough Polish**: sample after cutting were rough polished to expose section at mid length.

**(3) Moulding:** Samples were cold moulded for flatting and holding ease for polishing.

**(4) Polish**: Polishing of each sample was done for 5 mins on each paper from 80, 180, 320, 600, 1000, 1500, 2000, 2500 grade Silicon carbide polishing paper, followed by diamond polishing from 1.5 and 5 micro diamond paste.

**(5) Etching:** Weck's etchant used for the etching of the samples. Its composition includes mixture of 4 gm KMnO4 and 1 gm NaOH in 100 ml distilled water. Sample was immersed for 15 seconds in etchant after which it was cleaned immediately from cotton and acetone.

### 3.3.5 Mechanical Testing and Characterization

**(I) Extent of Compaction:** A Digital microscope was used to take the image and mark the diameter of compacted samples and residual tube thickness. With original diameter being know change in diameter. After compaction, thereafter relative increase in density under different operating parameter can calculated and compared.


*Figure 27. Digital Microscope.*

Instrument Name:
Digital Microscope
Model:
Celestron Handheld Digital Microscope Pro
Used for:
Imaging and Dimensioning

**(II) Hardness Testing:** The sintered samples underwent hardness testing to assess their mechanical strength and resistance to indentation. Vickers hardness tests is conducted on samples with indent on centre, 1/3rd of radius and 2/3rd of radius on each sample and result wear recorded.


*Figure 28. Hardness Tester.*

Instrument Name:
Hardness Tester
Model:
Chennaimetco
Micro Vickers VH- 1MDX
Used for:
Measuring Vicker Hardness

(**III) Microstructure Analysis:** Optical microscopy was employed to examine the microstructure of the sintered samples. Grain size, porosity, and other microstructural characteristics were observed and analysed.

| | |
|---|---|
| <br>*Figure 29. Optical Microscope.* | Instrument Name:<br>Optical Microscope<br>Model:<br>Radiso Engineering and Marketing<br>Model: RMI-1000PA<br>Used for:<br>Capturing Microstructure |

**(IV) Scanning Electron Microscopy (SEM):** SEM imaging provided high-resolution images of the sintered samples' microstructure, allowing for detailed analysis of particle bonding.

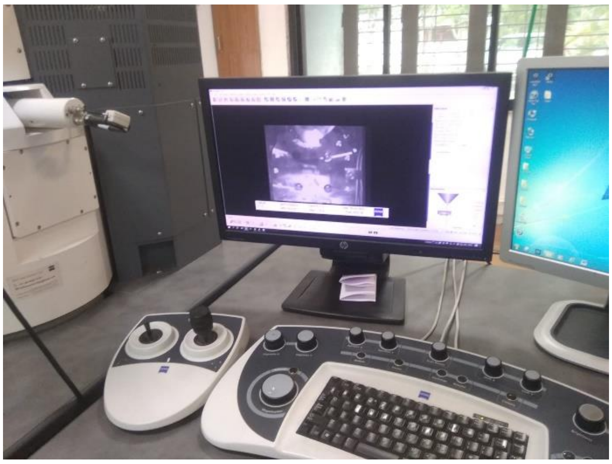


*Figure 30. SEM Machine and Desktop.*

# Chapter 4:

# Experimental Results

## 4.1 Introduction

In this chapter, the experimental results and findings from both the high strain rate powder compaction using electromagnetic compaction (EMC) and the conventional radial mechanical pressing (RMP) processes are presented. The chapter provides a comprehensive overview of the data, images, and findings acquired during the experimental process.

## 4.2 Images of Compacted Samples


*Figure 31. Showing Compacted Sample Specimen*

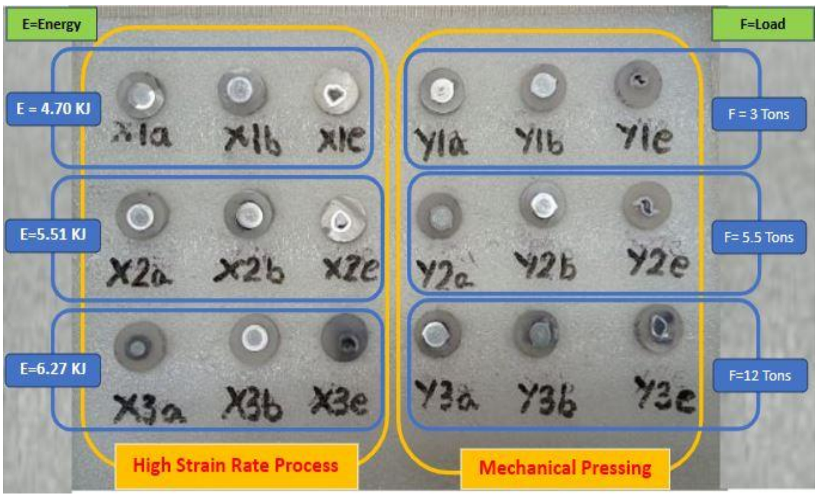



*Figure 32. Showing Cut molded and Polished sample.*

## 4.3 Scanning Electron Microscope (SEM) Images

### 4.3.1 Powder SEM Images and observations

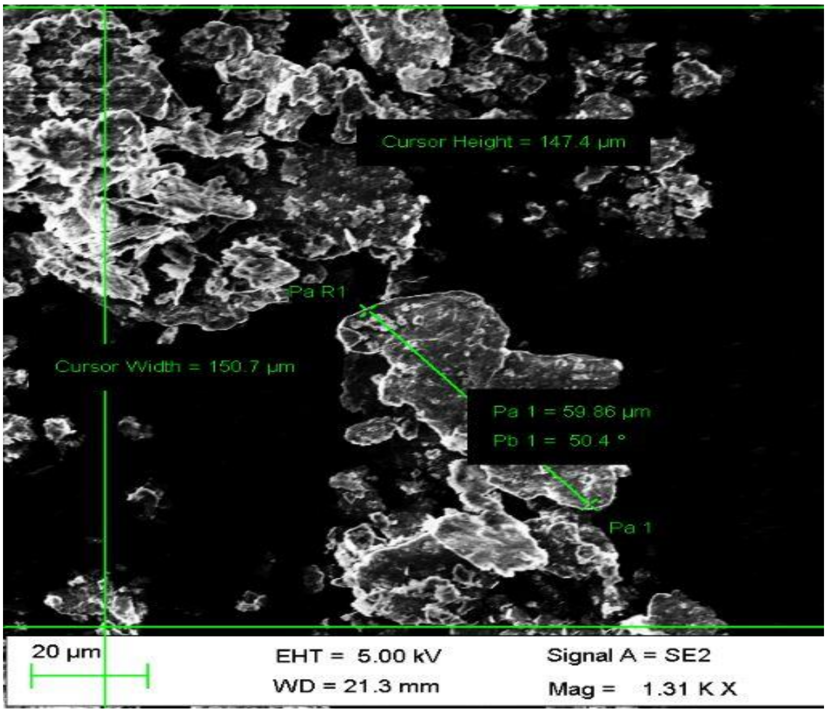



*Figure 33. Represents Conformation of sizes of powder grains in powder.*

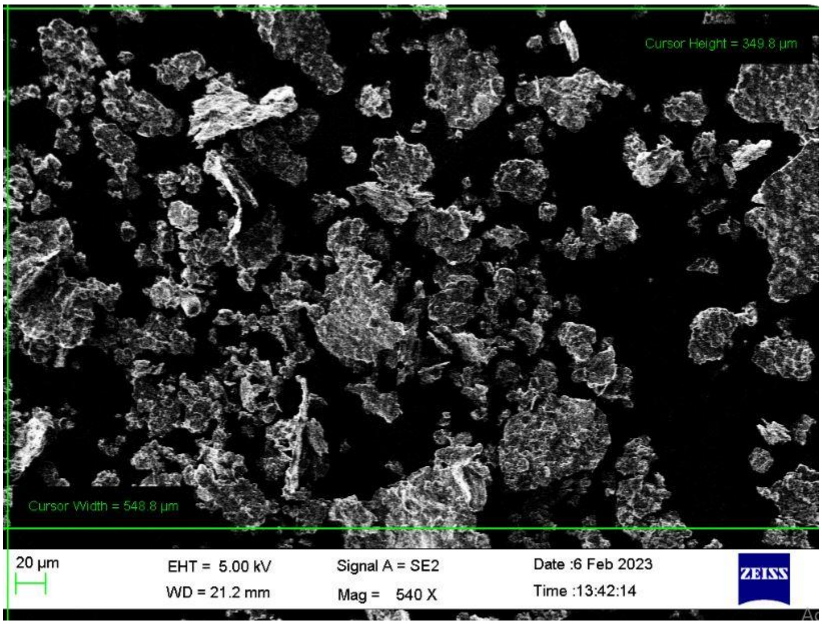



*Figure 34. Represent Conformation of Irregular Morphology of Selected powder for compaction.*

Power SEM image is taken to make conformation on powder description supplied by the powder manufacture.

Fig 30 and Fig 31 images suggest it to have powder grain size ranging from 50 to 80 micron and have irregular morphology.

### 4.3.2 SEM Images of compacted sample through Mechanical Pressing and High Strain Rate Process with their comparative observation.

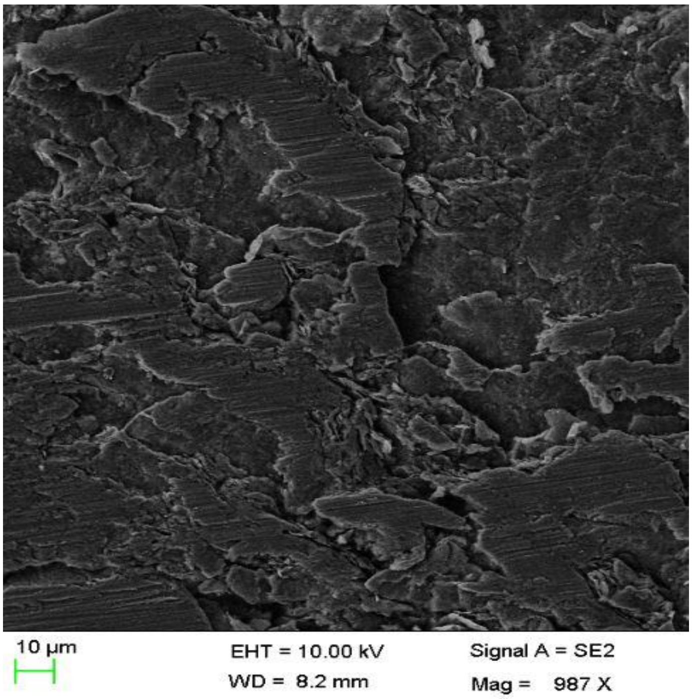



*Figure 35. SEM Images of powder compacted sample Obtained through Mechanical pressing setup.*

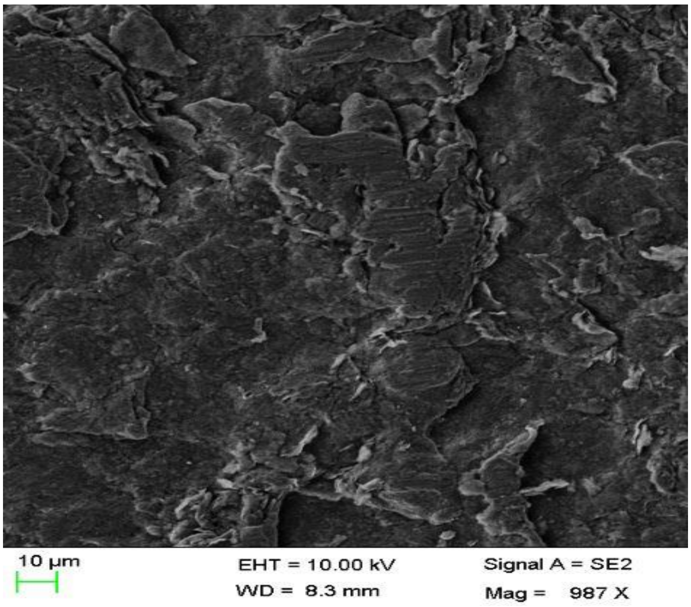



*Figure 36. SEM Images of powder compacted sample Obtained through High strain rate process setup.*

On making close observation to Fig 32 and Fig 33, surface boundary of powder grains is more diffused to one another in case of EMC process as compared to RMP process.

### 4.3.3 High Strain Rate Process at Different Energy Levels

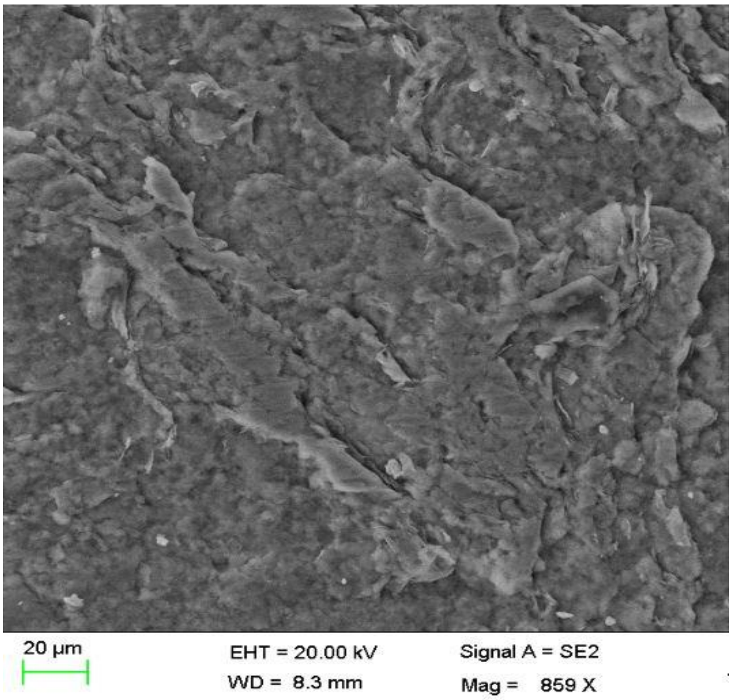



*Figure 37. Shows a SEM image of sample supplied with 4.70 KJ of energy through capacitor discharge.*

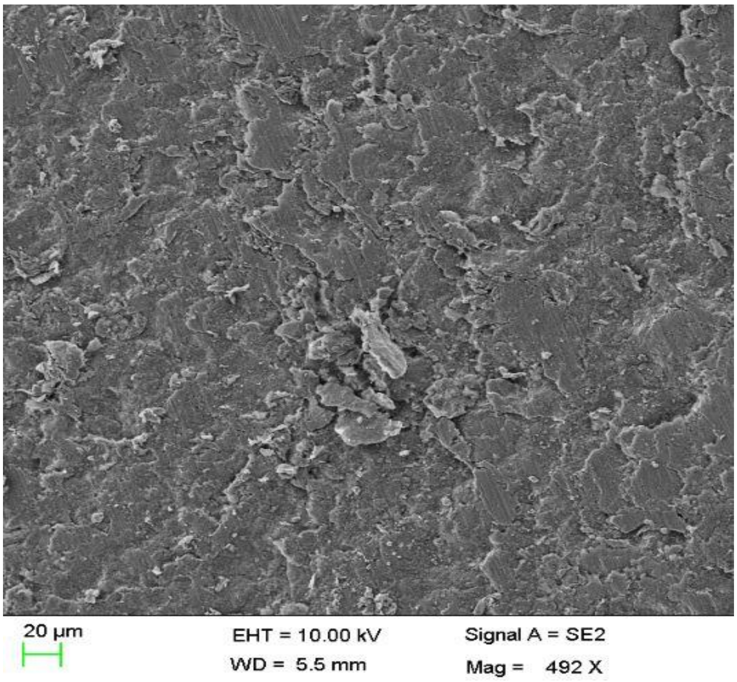



*Figure 38. SEM image of sample supplied with 5.51 KJ of energy through capacitor discharge.*

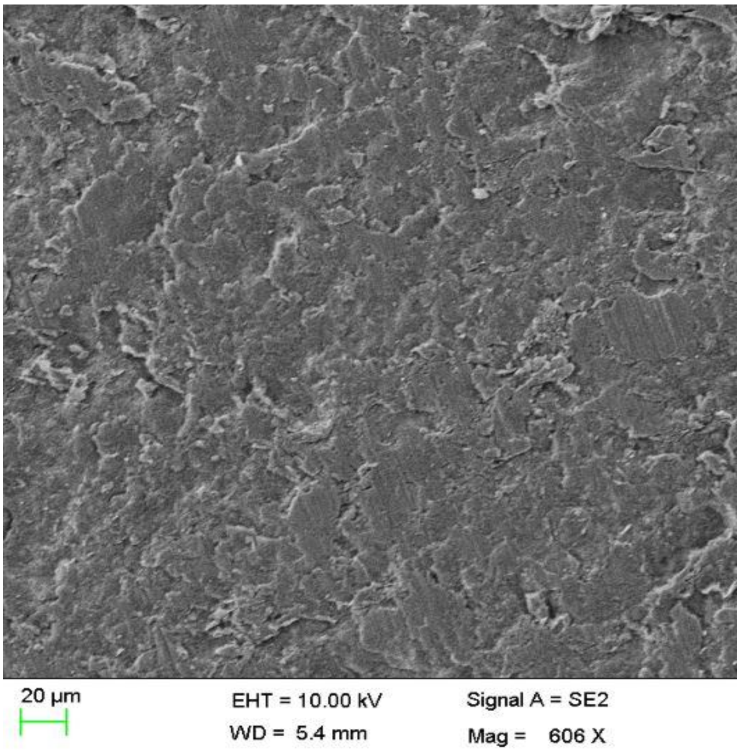



*Figure 39. SEM image of sample supplied with 6.27 KJ of energy through capacitor discharge.*

On making close observation to Fig 34, Fig 35, and Fig 36, it is observed that as the compaction energy supplied through capacitive discharge increases, the powder grain junctions appearing on the surface keeps on decreasing, that implies boundary of powder grains are more diffused to one another in Higher supplied energy sample as compared to lower energy supplied samples.

## 4.4 Compact Diameter Measurement

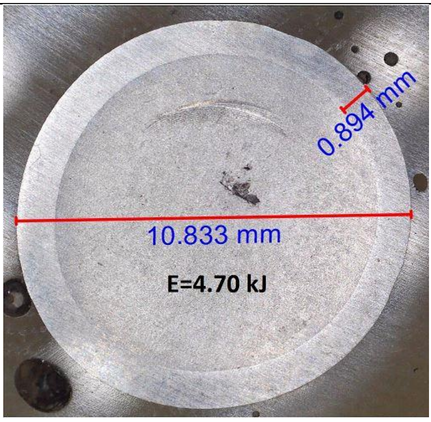
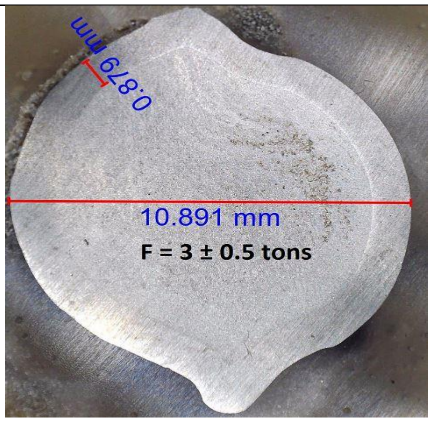
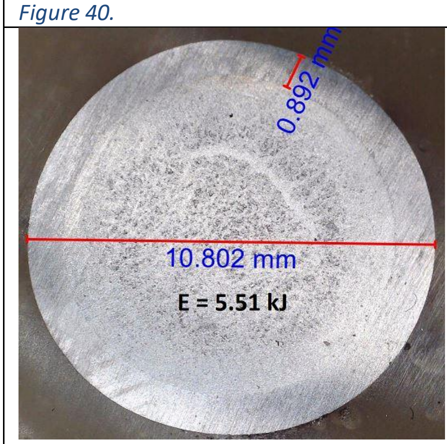
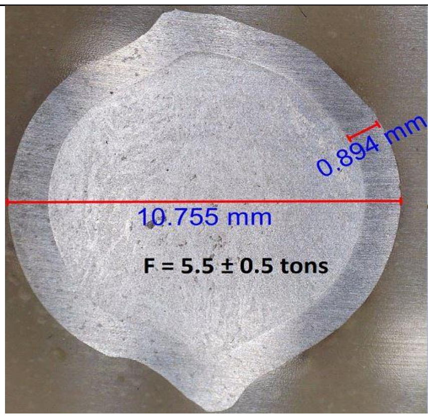
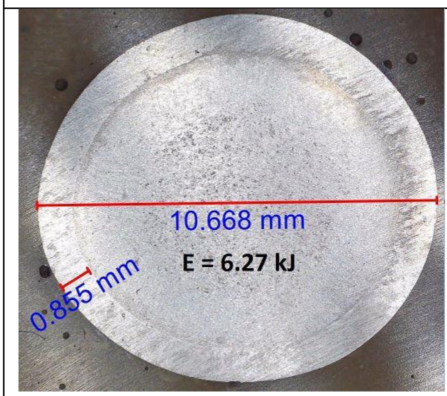
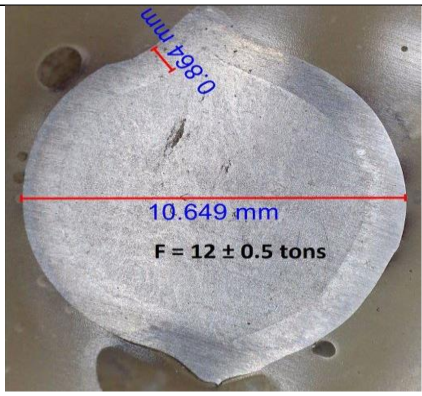
| EMC Samples | RMP Samples |
|---|---|
|  <br>*Figure 40.* |   |
|   |   |
|   |   |

*Figure 40 Table of Images Captured by Digital Microscope for purpose of Compacted Diameter and final tube thickness measurement.*

**Table 5** Compacted diameter and tube thickness achieved by High Strain Rate Process (EMC) at different Capacitor Discharge energy.

| **EMC** | **Set-a** | | **Set-b** | |
|---|---|---|---|---|
| **Energy (in kJ)** | **Average Outer Diameter After compaction (in mm)** | **Average Tube thickness After compaction (in mm)** | **Average Outer Diameter After compaction (in mm)** | **Average Tube thickness After compaction (in mm)** |
| **4.70** | 10.84 | 0.87 | 10.87 | 0.89 |
| **5.51** | 10.86 | 0.81 | 10.79 | 0.88 |
| **6.27** | 10.44 | 0.83 | 10.65 | 0.84 |
| **RMP** | **Set-a** | | **Set-b** | |
| **Load (in tons)** | **Average Outer Diameter After compaction (in mm)** | **Average Tube thickness After compaction (in mm)** | **Average Outer Diameter After compaction (in mm)** | **Average Tube thickness After compaction (in mm)** |
| **3 ± 0.5** | 10.82 | 0.87 | 10.92 | 0.87 |
| **5.5 ± 0.5** | 10.87 | 0.81 | 10.74 | 0.90 |
| **12 ± 0.5** | 10.65 | 0.83 | 10.68 | 0.88 |

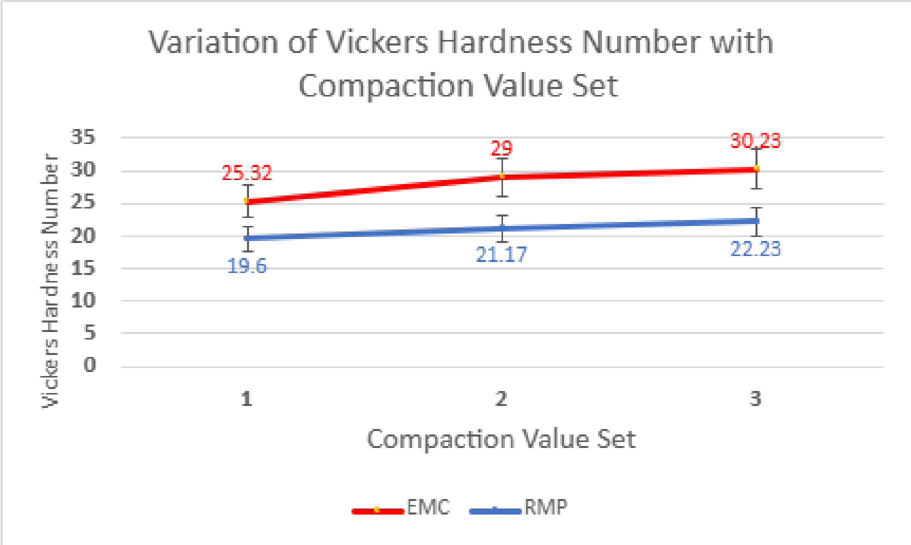
Further, outer diameter data of EMC samples will be used as a set value to compact sample using RMP set up and slip gauges in Controlled way to give final compacted diameter same to its corresponding data obtained by High strain rate process (EMC).

## 4.5 Hardness Testing Results

This section includes a table and graph showing the hardness values achieved for different samples at the center, 1/3rd, and 2/3rd of the radius. Further any trends or variations in hardness across the samples obtained through both the process are discussed and compared.

**Table 6** Vicker Hardness number of RMP and EMC process specimens subject to different compaction Energy or Load and at different radial locations.

| **Vicker Hardness** | **Process** | | | | | |
|---|---|---|---|---|---|---|
| | **High Strain rate Compaction (EMC)** | | | **Radial Mechanical Pressing (RMP)** | | |
| **Position of Indentation** | **Energy (E) kJ** | **Set -1** | **Set-2** | **Load (F) Tons** | **Set-1** | **Set-2** |
| **Center** | **4.70 kJ** | 22.9 | 24.6 | **3 tons** | 15.6 | 15.3 |
| **1/3 rd. of radius** | | 25.4 | 24.2 | | 20.1 | 20.6 |
| **2/3 rd. of radius** | | 27.1 | 27.7 | | 23.8 | 22.7 |
| **Center** | **5.51 kJ** | 27.4 | 28.0 | **5.5 tons** | 16.4 | 16.5 |
| **1/3 rd. of radius** | | 28.7 | 29.6 | | 21.9 | 21.3 |
| **2/3 rd. of radius** | | 30.3 | 30.0 | | 25.2 | 25.7 |
| **Center** | **6.27 kJ** | 29.1 | 28.5 | **12 tons** | 17.7 | 18.1 |
| **1/3 rd. of radius** | | 30.4 | 30.5 | | 22.6 | 23.2 |
| **2/3 rd. of radius** | | 31.6 | 31.3 | | 26.0 | 25.8 |




| **Compaction value set** | **Discharge Energy in EMC** | **Load to Replicate corresponding compaction in RPM** |
|---|---|---|
| 1 | 4.70 KJ | 3 Tons |
| 2 | 5.51 KJ | 5.5 Tons |
| 3 | 6.27 KJ | 12 Tons |

*Figure 41. Variation of Vicker Hardness number with Compaction Set Values for EMC and RMP process.*

(Compaction Value Set is a set which have near about same Contraction in diameter via application of Compaction Energy in EMC and Pressing Load in Case of RMP)

From Graph 1 it can be noted that for the same compaction, Hardness achieved via High strain Rate compaction (EMC) is always slightly greater than what is been achieved by simple Radial mechanical pressing process (RMP). Also, with an increase in compaction achieved by increasing Discharge energy in case of EMC process and pressing Load in case of RMC process, an increase in Hardness trend is observed.

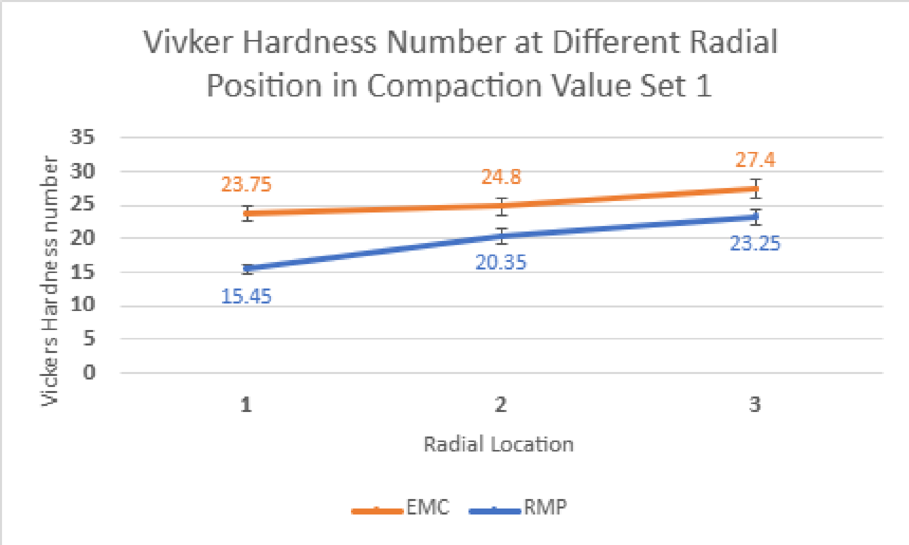



*Figure 42. Variation of Vicker Hardness number with Compaction Set 1 Parameters*

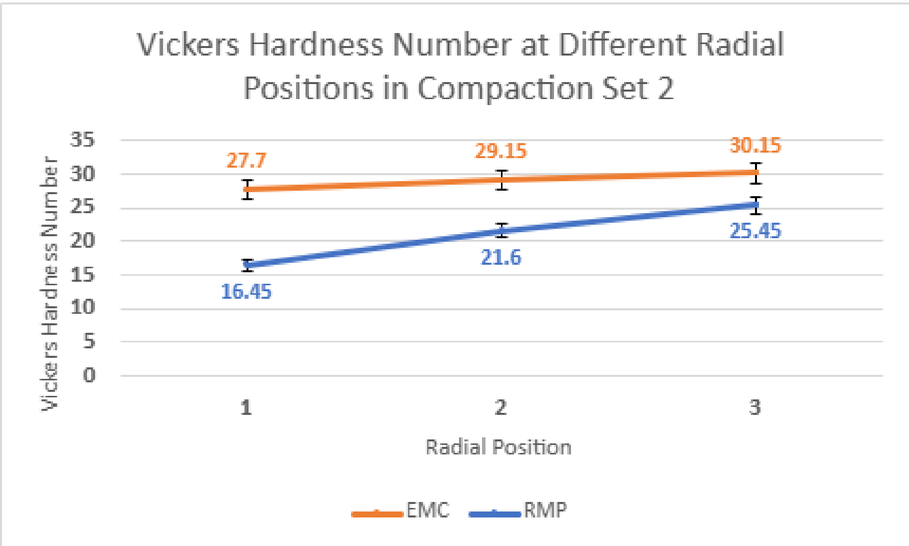



*Figure 43. Variation of Vicker Hardness number with Compaction Set 2 Parameters*

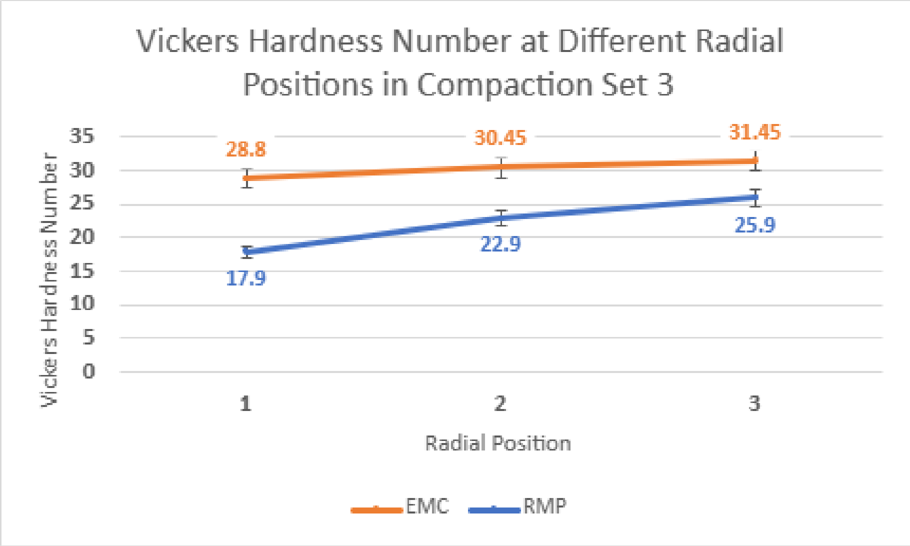



*Figure 44. Variation of Vicker Hardness number with Compaction Set 3 Parameters*

| **Radial Position** | **Location** | **Distance from center** |
|---|---|---|
| 1 | At the Center | 0 mm |
| 2 | At 1/3 rd. of radius | 3.33 mm |
| 3 | At 2/3 rd. of radius | 6.67 mm |

Graph in figure 42,43,44 represents Variation of Vickers Hardness number with radial location at Different Compaction level respectively for their corresponding process perimeters (Discharge Energy in EMC and Load in case of RMP). It can be noted from comparative observation of graph in figure 42,43,44 that Hardness increases slightly as one goes away from center in radial direction in both the process but the variation of Hardness with location is far greater in case of RMP as compared to EMC I.e., at high strain rate. Further this variation with location tends to diminish in case of High Strain process as the compaction fraction increase but that doesn't appear to be the case with RMP.

## 4.6 Microstructure Images

In this section microstructure capture for RMP and EMC is presented, and their Comparisons are made in the end of this section.

### 4.6.1 Radial Mechanical Pressing (RMP)

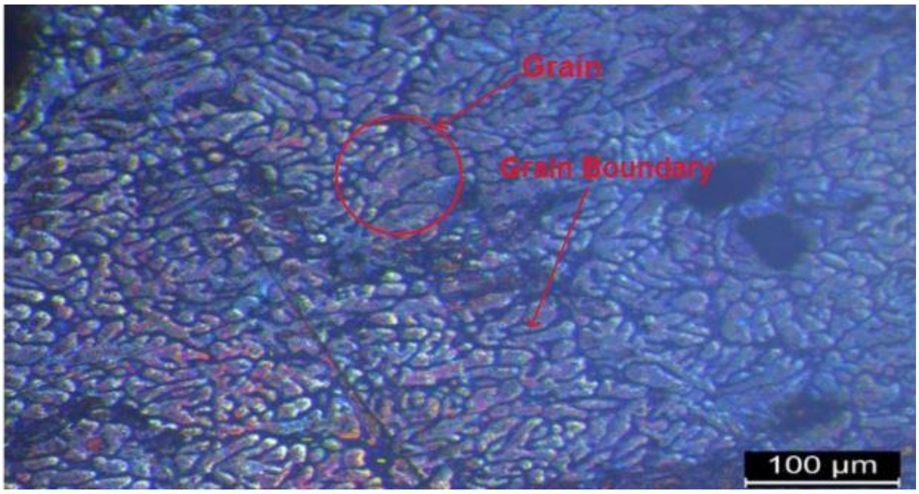



*Figure 441. Microstructure Obtain Through RMP (Set-2, 12 TONS).*

### 4.6.2 High Strain Rate Process (EMC)

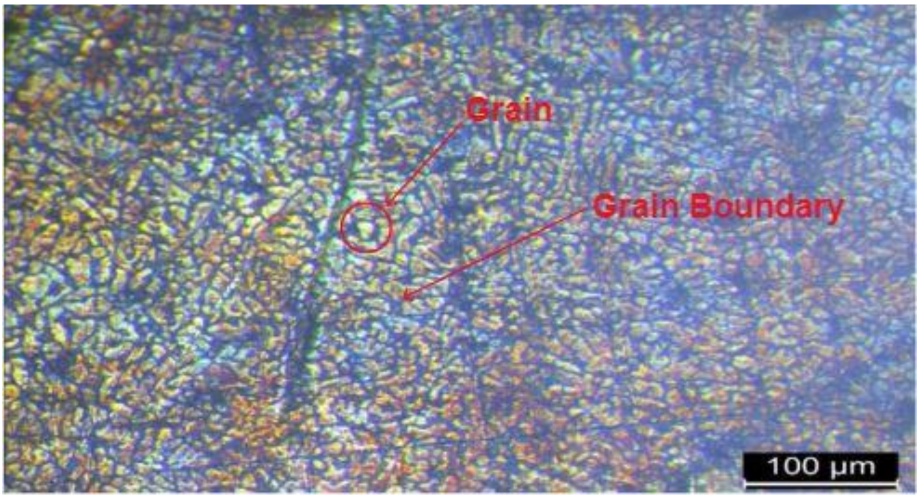



*Figure 42 Microstructure obtained through EMC (Set-1, 6.27 kJ).*

Microstructure Captured suggest that Grains obtained in EMC are less coarse as compared to what obtained in RMP. Further Grains for RMP are more directional as compared to grains obtained in EMC which are Fairly randomised.

## 4.7 Summary

This chapter presented the experimental results obtained from both the high strain rate powder compaction using electromagnetic compaction and the conventional mechanical pressing processes. The results encompass images, data, and findings that will be further analyzed and discussed in Chapter 5, where the implications of the findings will be explored.

# Chapter 5:

# Discussion And Implication of Findings

In this chapter, we analyse and discuss the key findings obtained from the experimental results presented in Chapter 4. The implications of these findings are explored in the context of high strain rate powder compaction using electromagnetic compaction and conventional mechanical pressing. The discussion aims to shed light on the observed trends, differences, and significance of the obtained results.

## 5.1 Diameter Variation with Energy

Upon measuring the diameters of the compacted samples, a notable trend emerges. As the energy supplied in the electromagnetic compaction process increases, the diameter of the compacted samples decreases. This relationship is observed across varying energy levels, indicating a consistent behaviour of the compaction process. This outcome suggests that higher energy levels result in greater densification and compaction within the samples.

## 5.2 Microstructural Comparison

A detailed analysis of the SEM images of compacted samples reveals intriguing differences in microstructural features. A direct comparison between samples from high strain rate compaction and mechanical pressing highlights distinct boundaries of powder grains. In the high strain rate compaction samples, the boundaries between powder grains appear more diffused, indicating a more interparticle bonding and strength. This contrasts with the mechanical pressing samples, where the grain boundaries are less diffused and exhibit a more directional arrangement.

## 5.3 Influence of Energy and Load on Microstructure

Further examination of SEM images from high strain rate compaction at different energy levels provides additional insights. As the energy supplied during compaction increases, the junctions appearing between powder grains decrease, signifying a more diffuse boundary between grains in higher-energy samples. This observation underscores the impact of compaction energy on the microstructure, with higher energy levels promoting finer and more diffuse grain boundaries.

## 5.4 Hardness Variation

Hardness testing across different sections of the samples reveals interesting trends. A slight increase in hardness is observed from the centre to the inner periphery of the tube in both the high strain rate and mechanical pressing samples. However, the average hardness of the high strain rate samples is marginally greater, with comparatively lower variations along its length compared to the mechanical pressing samples. Furthermore, in the case of high strain rate compaction, hardness shows a slight increase with higher compaction energy, while in mechanical pressing, hardness increases with applied load.

## 5.5 Microstructure Characteristics

Microstructure examination through optical microscopy uncovers important grain characteristics. High strain rate compaction results in finer and less coarse grains, implying a greater degree of densification and homogeneity. Additionally, the grains in high strain rate samples exhibit a more randomized distribution, contrasting with the more directional grain arrangement in the mechanical pressing samples.

## 5.6 Implications and Future Directions

The observed trends and differences provide valuable insights into the effects of high strain rate compaction and mechanical pressing on the microstructure and mechanical properties of the compacted samples. The findings suggest that high strain rate compaction results in more uniform microstructures, finer grains, and slightly increased hardness. These observations have implications for material performance in engineering applications.

The differences between the two compaction methods may arise from the distinct loading rates and energy inputs. However, a comprehensive analysis of these findings requires further investigation and detailed characterization. Future research could delve deeper into the mechanisms responsible for the observed microstructural changes and their direct impact on material properties.

## 5.7 Conclusion

In this chapter, we analysed and discussed the experimental findings, highlighting trends and differences in microstructure and hardness between high strain rate powder compaction and conventional mechanical pressing. The discussion sets the stage for the conclusions drawn from these findings and their relevance to the field of powder metallurgy. The next chapter will present the conclusions drawn from the analysis and the implications of this research.

# Chapter 6:

# Conclusion And Future Directions

This chapter presents the conclusions drawn from the comprehensive investigation of high strain rate powder compaction using electromagnetic compaction and conventional mechanical pressing. The implications of the findings and the significance of the research are summarized, providing insights into the potential applications and future directions for this field of study.

## 6.1 Summary of Findings

The experimental results presented in Chapter 4, along with the detailed analysis and discussion in Chapter 5, reveal distinct differences between high strain rate powder compaction and conventional mechanical pressing. The observations of diameter variation, microstructural characteristics, hardness variations, and grain distribution underscore the unique effects of each compaction process on the resulting material properties. The findings collectively suggest that high strain rate compaction results in finer grains, more uniform microstructures, and slightly increased hardness compared to mechanical pressing.

## 6.2 Implications and Significance

The outcomes of this research hold significant implications for various engineering applications. The enhanced microstructural homogeneity and improved hardness of high strain rate compacted samples may lead to materials with superior mechanical properties. These findings offer potential benefits for industries that rely on powder metallurgy processes to create components with specific performance characteristics.

## 6.3 Limitations and Future Research

While this study sheds light on the effects of high strain rate powder compaction, there are limitations that could be addressed in future research. The investigation focused on a specific set of parameters, energy levels, and materials. Expanding the scope to different materials, compaction conditions, and energy ranges could provide a more comprehensive understanding of the underlying mechanisms.

## 6.4 Recommendations for Further Study

The results of this research open avenues for further exploration. In-depth studies could delve into the relationship between compaction energy and microstructural evolution. Investigating the role of other parameters, such as powder characteristics and compaction rates, could provide a broader perspective on the influence of high strain rate compaction.

## 6.5 Practical Applications

The findings of this study could directly impact industries that rely on powder metallurgy processes. Components produced through high strain rate powder compaction may exhibit improved mechanical properties, offering advantages in terms of strength, durability, and performance. The insights gained from this research contribute to the optimization of compaction processes for specific applications.

## 6.6 Conclusion

In conclusion, this research provides valuable insights into the effects of high strain rate powder compaction and conventional mechanical pressing on the microstructure and mechanical properties of compacted materials. The findings underscore the potential benefits of high strain rate compaction in achieving enhanced microstructural homogeneity and improved hardness. As this study contributes to the understanding of powder compaction techniques, it also opens avenues for further investigation and optimization in the field of powder metallurgy.

# REFERENCES

[1] Thirupathi, Nadimetla, Ramesh Kumar, and Sachin D. Kore. "Effect of Electromagnetic Force on the Strength of Electromagnetic Impulse Powder Compaction." *Journal of Materials Engineering and Performance* (2022): 1-14.

[2] C.L Martin, D Bouvard, S Shima,Study of particle rearrangement during powder compaction by the Discrete Element Method,Journal of the Mechanics and Physics of Solids,Volume 51, Issue 4,2003, Pages 667-693.

[3] Gourdin, William H. "Dynamic consolidation of metal powders." *Progress in Materials Science* 30.1 (1986): 39-80.

[4] Prummer, R. "Explosive compaction of powders, principle and prospects." *Materialwissenschaft und Werkstofftechnik* 20.12 (1989): 410-415.

[5] E. Smugeresky and W. H. Gourdin: in 'Metallurgical applications of shock-wave and high-strain-rate phenomena', (ed. L. E. Murr et al.), 1st edn, 107–128; 1986, New York, Marcel Dekker.

[6] Gourdin, W. H. "Energy deposition and microstructural modification in dynamically consolidated metal powders." *Journal of applied physics* 55.1 (1984): 172-181.

[7] Cui, Junjia, et al. "Effect of discharge energy of magnetic pulse compaction on the powder compaction characteristics and spring back behavior of copper compacts." *Metals and Materials International* 27.9 (2021): 3385-3397.

[8] Moon, In-Hyung, and Kyung-Hyup Kim. "Relationship between compacting pressure, green density, and green strength of copper powder compacts." *Powder Metallurgy* 27.2 (1984): 80-84.

[9] German, Randall M. "Powder metallurgy science." *Metal Powder Industries Federation, 105 College Rd. E, Princeton, N. J. 08540, U. S. A, 1984. 279* (1984).

[10] C. Y. Chiem: in ‘Shock wave and high strain rate phenomena in materials’, (ed. M. A. Meyers et al.), 1st edn, 69–86; 1992, New York, Marcel Dekker.

[11] B. O. Reinders and H. D. Kunze: in ‘Shock wave and high strain rate phenomena in materials’, (ed. M. A. Meyers et al.), 1st edn, 127–136; 1992, New York, Marcel Dekker.

[12] J. Lankford, H. Couque, A. Bose and C. E. Anderson: in ‘Shock wave and high strain rate phenomena in materials’, (ed. M. A. Meyers et al.), 1st edn, 137–146; 1992, New York, Marcel Dekker.

[13] Sethi, G., N. S. Myers, and Randall M. German. "An overview of dynamic compaction in powder metallurgy." *International Materials Reviews* 53.4 (2008): 219-234.

[14] R. S. Coates and K. T. Ramesh: in ‘Shock wave and high strain rate phenomena in materials’, (ed. M. A. Meyers et al.), 1st edn, 203–212; 1992, New York, Marcel Dekker.

[15] T. Kathrina and R. D. Rawlings: Br. Ceram. Trans., 1996, 95, 233– 237.

[16] A. L. Dawson, L. Piche and A. Hamel: Powder Metall., 1996, 39, 275.

[17] A. L. Dawson and J. F. Bussiere: Proc. 1997 Int. Conf. on ‘Powder metallurgy and particulate materials’, Chicago, IL, USA, June– July 1997, Metal Powder Industries Federation, 16?67–16?81.

[18] Benson, David J. "The calculation of the shock velocity—particle velocity relationship for a copper powder by direct numerical simulation." *Wave Motion* 21.1 (1995): 85-99.

[19] Skoglund P. High density PM components by high velocity compaction. Powder Metall 2002; 44(3): 14–17.

[20] Bai H. A meso-simulation study on the effect of interfacial friction on iron powder compaction. Hefei Univ Technol 2009; 20–26.

[21] S. Elwakil and R. Davies: Proc. 13th Int. Conf. on 'Machine tool design research', 435–440; 1973, Oxford, Pergamon Press.

[22] Meyers, Marc A., Lawrence Eugene Murr, and Karl P. Staudhammer. *Shock-wave and high-strain-rate phenomena in materials*. CRC, 1992.

[23] Iyer, N. C., W. R. Lovic, and A. T. Male. "Dynamic compaction of P/M Aluminium alloy as related to powder form, microstructures and properties." *Industrial heating* 53.5 (1986): 18-21.

[24] Stein, Eugene M., John R. Van Orsdel, and Peter V. Schneider. "High velocity compaction of iron powder." *Iron Powder Metallurgy*. Springer, Boston, MA, 1968. 154-160.

[25] Shaat, Mohamed, Adel Fathy, and Ahmed Wagih. "Correlation between grain boundary evolution and mechanical properties of ultrafine-grained metals." *Mechanics of Materials* 143 (2020): 103321.

[26] D. Raybould: Proc. 15th Int. Conf. on 'Machine tool design and research', Birmingham, UK, September 1974, 627–636; 1975, London, MacMillan.

[27] R. M. Rusnak: Int. J. Powder Metall. Powder Technol., 1976, 12, 91–99.

[28] K. Takashima, H. Tonda, I. Shimizu, N. Tomonoh and M. Miyamoto: J. Jpn Inst. Met., 1990, 54, 581–588.

[29] ElWakil, Sherif D., and R. Davies. "Lubrication effects in the compaction of sponge-iron powder at low and high speeds." *Powder Metallurgy* 16.31 (1973): 72-87.

[30] Häggblad, Hans-Åke, et al. "Simulation of high velocity compaction of powder in a rubber mould with characterization of silicone rubber and titanium powder using a modified split Hopkinson set-up." *Powder technology* 154.1 (2005): 33-42.

[31] Eriksson, Magnus, et al. "New semi-isostatic high velocity compaction method to prepare titanium dental copings." *Powder metallurgy* 47.4 (2004): 335-342.

[32] Zhou, Jian, et al. "Comparisons Between 2D anD 3D mpFem simulations in moDeling uniaxial HigH VeloCity CompaCtion BeHaViors oF ti-6al-4V powder." *Archives of Metallurgy and Materials* 67 (2022).

[33] Wei, Zhang, et al. "EFFECT OF PARTICLE SIZE DISTRIBUTION ON FORCE CHAIN EVOLUTION MECHANISM IN IRON POWDER COMPACTION BY DISCRETE ELEMENT METHOD." *力学学报* 54.9 (2022): 1-12.

[34] Benson, David J. "The calculation of the shock velocity—particle velocity relationship for a copper powder by direct numerical simulation." *Wave Motion* 21.1 (1995): 85-99.

[35] Zhenhua C. Rheological problems of powder compression (II)-rheological model of powder compression. Rare Met Mater Eng 1992; 21(2): 1–11.

[36] Souriou, David, et al. "Influence of the formulation of an alumina powder on compaction." *Powder Technology* 190.1-2 (2009): 152-159.

[37] Jauffres D, Lame O, Vigier G, et al. Microstructural origin of physical and mechanical properties of ultra high molecular weight polyethylene processed by high velocity compaction. Polymer 2007; 48(21): 6374–6383.

[38] Kawakita, Kimio, and Karl-Helmut Lüdde. "Some considerations on powder compression equations." *Powder technology* 4.2 (1971): 61-68.

[39] Kostornov, Anatolii G. "Mikhail Yulievich Bal'shin: Development of the scientific bases of fiber metallurgy." *Powder Metallurgy and Metal Ceramics* 42.11 (2003): 563-567.

[40] Heckel, R. W. "Density-pressure relationship in powder compaction." *Trans. Met. Soc., AIME* 221 (1961): 671-675.

[41] Huang P. Principles of powder metallurgy. Beijing: Metallurgical Industry Press, 1982, pp.182–184.

[42] Johnson, Gordon R. "A constitutive model and data for materials subjected to large strains, high strain rates, and high temperatures." *Proc. 7th Inf. Sympo. Ballistics* (1983): 541-547.

[43] Guo S, Chi Y, Meng F, et al. Compaction equation of powder metallurgy high velocity compaction. Powder Metall Mater Sci Eng 2006; 11(1): 24–27.

[44] Richard, F. "HVC punches PM to new mass production limits." *Metal Powder Report* 57.9 (2002): 26-30.

[45] Wang LL. Stress wave foundation. Beijing: National Defense Industry Press, 1985, pp.1–2.

[46] Ju Y, Yang Y, Mao Y, et al. Experimental study on stress wave propagation mechanism in porous media. Chin Sci 2009; 39(5): 904–917 .

[47] Zhenhua C. Rheology of powder compression (I)-rheology of powder. Rare Met Mater Eng 1992; 21(1): 3–7.

[48] Zhenhua C. Rheological problems of powder compression (II)-rheological model of powder compression. Rare Met Mater Eng 1992; 21(2): 1–11.

[49] Roman, O. V., A. P. Mirilenko, and I. M. Pikus. "Effect of high-speed loading conditions on the pressing mechanism." *Soviet Powder Metallurgy and Metal Ceramics* 28.11 (1989): 840-844.

[50]. A. B. Sawaoka (ed.): ‘Shock waves in materials science’, 1st edn, 227; 1993, New York, Springer-Verlag.

[51] Stein, Eugene M., John R. Van Orsdel, and Peter V. Schneider. "High velocity compaction of iron powder." *Iron Powder Metallurgy*. Springer, Boston, MA, 1968. 154-160.

[52] S. Elwakil and R. Davies: Proc. 13th Int. Conf. on ‘Machine tool design research’, 435–440; 1973, Oxford, Pergamon Press.

[53] Ni, Peng, et al. "Laser shock dynamic compaction of aluminium powder." *Journal of Manufacturing Processes* 77 (2022): 694-707.

[54] Thirupathi, Nadimetla, Ramesh Kumar, and Sachin D. Kore. "Experimental and numerical investigations on electromagnetic powder compaction of Aluminium 6061 alloy powder." *Powder Technology* (2022): 117579.

[55] Bai, Yu, et al. "A review on high velocity compaction mechanism of powder metallurgy." *Science Progress* 104.2 (2021): 00368504211016945.

[56] Prasad, K. Sajun, et al. "A rapid throughput system for shock and impact characterization: design and examples in compaction, spallation, and impact welding." *Journal of Manufacturing and Materials Processing* 4.4 (2020): 116.