Design and Development of Punch-Die Assembly for Compaction of Metal Powders by using ANSYS software and CNC machine- A Review

Preksha Verma [*1], Shweta Mishra[*2], Sunil Sahai[*3]
[*1]M. Tech Scholar, Department of Mechanical Engineering,
[*2,3]Assistant Professor, Department of Mechanical Engineering,
[*1,2,3] Dr. Ram Manohar Lohia Avadh University, Ayodhya, India

ABSTRACT

Powder Metallurgy is a fabrication tool that has been in practice since ancient times till now. The Iron Pillar in Delhi is the best example of powder metallurgy which was built in 1600 years ago. This process includes various processes among which compaction of metal powder performs a vital role. The powder density at the beginning of process and the synergy of powders and its particles and die/punch play a significant role in the final quality of the compact. Studying the impact of various shapes, punching schedules, and material interactions is an essential for achieving better results. Extensive experiments are required to establish the optimized parameters to get the desired results for a particular powder mixture. By reviewing various research papers. This research seeks to develop a pressure compaction die that compacts metal powder with minimum porosity and microcracks. By applying maximum pressure through a ANSYS Software, simulation, and Universal Testing machine the performance of the die has also been tested by analyzing the compaction behaviour of metal powder, the porosity produced during compaction, and its mechanical properties.

Keywords: Powder metallurgy, compaction die, ANSYS Software, simulation.

INTRODUCTION

Most alloys and composites are developed using Powder Metallurgy (PM). It is the process in which Powdered materials are mixed, compressed into the required shape, and then heated to bind the particles together. Due to the ease of processing and control, it can also be used to fabricate specially designed materials and parts that are hard to produce with other processes such as melting or forming. This process reduces the cost by diminishing the need for metal removal. Moreover, this process avoids material changes in the melting phase, which leads to component degradation or dissolution. Due to the controlled attributes of the products produced by powder processes, powder processes are more flexible than other production methods such as casting, extrusion, and forging. According to several studies, the PM process effectively manufactures porous solids, aggregates, and intermetallic composites with improved material characteristics. Several methods can process the powder, but uni-axial compaction is the primitive approach. The powder is compacted in uni-axial compaction by applying pressures to the metal powder in a tightly sealed chamber. It is common for the metal powder to be compressed at pressures ranging from 150 MPa to 1000 MPa. This is generally accomplished by holding the die vertically with the punch. Following the powder pressing process, the powder is ejected from the die chamber, and a controlled environment is used to sinter the material at a specific temperature.

A significant limitation of pressure compaction is its tendency to produce green compacts with high porosity and circumferential microcracks resulting from friction between the die wall and the composite particles. Microcracks originate during the compaction step in PM-processed components and are widened during sintering. This research seeks to develop a pressure compaction die that compacts metal powder with minimum porosity and microcracks. By applying maximum pressure through a universal testing machine, the performance of the die has also been tested by analyzing the compaction behaviour of metal powder, the porosity produced during compaction, and its mechanical properties.

The Compacting Cycle

Three stages comprise the compacting process:
1. Filling the die,
2. Densification and granulation
3. Separating the die from the compact.

Introduction to computer numerical control

CNC, or computer numerical control, refers to any mechanical device, such as a drill, mill, or lathe, where a computer controls the motion of one or more axes through coding. In contrast to conventional machines, the machining Control Unit (MCU) CNC creates a motion signal that is transmitted to a servo motor connected to each axis of the machine through a controller board. In this way, the servo motor rotates a ball screw attached to the desk, slide, or column, causing it to move. A transmitter connected to the ballscrew continuously monitors and compares the fundamental role of the axis to the commanded role. Because the ballscrew has almost no backlash, there is no delay between the direction of the slip change commanded by the servo and the slip change when it reverses the path. A summary of CNC machined parts to be turned, drilled, milled, and shaped is presented here. There are many industries that use CNC machines for different applications such as grinding, plasma cutting, laser cutting, foam cutting, water jet cutting, tube bending, turret presses, punching machines, and electric discharge machining (EDM) for measuring machines and industrial robots. Furthermore, CNC machines are more flexible in how parts are held, avoiding the need for costly jigs that are required for traditional machines. The exchange of components can be performed quickly, and dimensions can be changed easily. This allows smaller batches and shorter production runs to be accommodated easily.

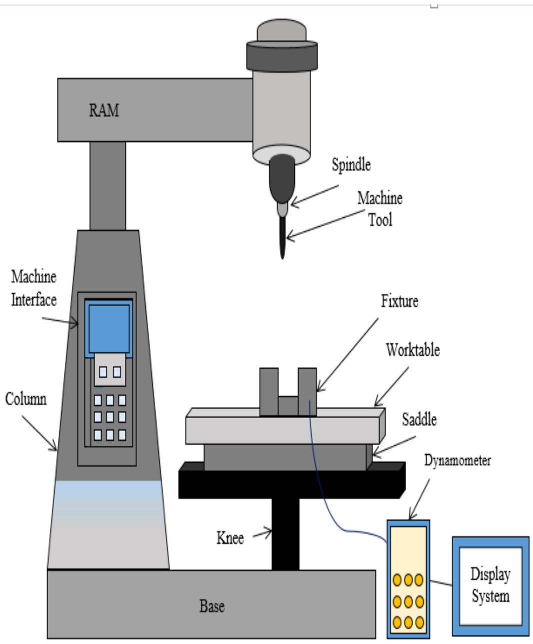

Fig. Schematic 3D- Diagram of CNC milling machine

Motion can therefore be resolved in six axes, namely three linear axes, X, Y, and Z, and three corresponding rotational axes, A, B, and C. These machines are very sophisticated and can have multiple cutting tools in a tool magazine.

Different Cutting Tools and problems associated with the machining of HSS alloy

Radially available tools must have the essential characteristics to facilitate the machining of input parameters with the output parameters. So, selecting a proper tool is crucial while machining HSS alloy to improve machining time by cutting down the cycle time. Different tools available for machining stainless steel and its alloys are PVD coated carbide tools, CVD coated carbide tools, tungsten carbide insert, cubic boron nitride (CBN) Cermet tools. The adequately selected cutting tool can reduce the machining cost by 30%. Tool materials are used to face high cutting temperatures while machining to overcome this problem, and tool materials should have hot hardness. Tool material like cermet is used to have superior wear properties and corrosive properties. Tool material should also possess chemical inertness to avoid bonding with the material. Tool material like tungsten carbide is used to have a more significant property like high hardness at an elevated temperature. Many researchers have claimed that it is beyond the hardness of corundum. This tool material must have good thermal conductivity, high compressive and tensile strength, and high toughness. They have so selected tool material, i.e., tungsten carbide used to encompass overall properties, which used to be required for a tool material to turn the workpiece material to achieve the desired results. HSS alloys used to be machined through coated and uncoated carbide tools generally. The researchers for HSS alloys do not recognize ceramic tools. These materials show poor thermal conductivity and excessive wear rate while machining. At a higher temperature scenario, workpiece material gets diffused with the tool material, i.e., tungsten carbide. As a result, a chemical reaction occurs, resulting in the layered formation of carbides. Using a traditional cooling method, machining HSS alloys at speeds between 50 and 100 m/min with coated carbide tools has been reported. Due to the positive effects of ultra-hardened tool materials, their use among dry turning of aerospace alloys remains unknown as they're more expensive than carbides and ceramic tools. So different tools have been selected for the machining process like tungsten carbide, cubic boron nitride (CBN), cemented carbide insert, etc. HSS alloys machining does consume lots of energy. A more significant amount of cutting fluids during machining used to be required while machining; as a result, they have a more significant environmental impact. There must be technological advancement in coolant media to overcome this, ultimately facilitating industry relations with nature. After conducting lots and lots of research, a method has been advanced in which we can apply the coolant so that wastes of coolant can be minimized, and as a result, the machining cost can be minimized. Minimum quantity lubrication and minimum quantity cooling lubrication-based cooling approaches as an advantage over usual flood cooling are now being investigated by metal cutting researchers.

Cutting fluid also allows for greater temperature control throughout the cutting process, which leads to more extraordinary tool life and superior machining performance. The atmosphere provided at the cutting zone, variation of input and output parameters, machine tool characteristics on which machining is going to conduct, selected cutting tool that has the characteristic properties, and workpiece nature are all parameters that influence the effect of the machining performance. Cutting fluid, mechanism of fluid application, thermo-fluidic properties of the cutting fluid, quantity applied, and flow rate /pressure of the cutting fluid in the cutting environment all play a role in machining performance. So, researchers need to look from a different aspect because to maximize the machining rate, we can't work like that all the time. We should develop a process that can ease machining significance with nature by adopting dry machining.

The motivation of the current research

Based on the literature, researchers have put a lot of work into understanding the problem associated with the machining of die and punch. A significant amount of work has been done in the machining process behavior, such as parametric influence, analysis of tool failure, cutting forces encountered while machining, and many others.

Literature

Dry-pressing, also known as powder compaction here and in the next sections, is an essential stage in the fabrication of hard metal components. It entails loading powder agglomerates (i.e., powder grains) into the pressing die, powder transfer, granule deformation and densification during compaction, and lastly ejection of the powder compact from the pressing die. Compacts (i.e., green bodies) made by dry-pressing procedures invariably contain density gradients, which have been shown to effect dimensional changes during sintering as well as mechanical qualities (defects) of the sintered body. The mechanical behavior of the powder compaction process may be separated into three stages in principle. The filling and packing of the powder into a container are the first and most basic procedure. The powder die is then cold or hot pressed in the second step of the process. Powder is surrounded by open pores in this stage, and contact sites between powders are tiny, allowing each contact to be addressed independently. Finally, in the third step, increased pressure is applied until the material reaches a high density, at which point it behaves like a porous solid. It should also be mentioned that a sintering phase is required to fully analyze the powder compaction process. The deformations [1], random [2] as well as frictional [3] behavior of powders, optimization [4], modeling [5] and computational aspects [6] of the process have been the focus of researchers.

Andersson et al.[7] carried out a numerical analysis of punch shapes using finite element method to look into the stress distribution during compaction of powder at higher densities. The uniaxial compression test can be used to investigate the effect of punch shape. A skewed punch geometry is the best option for the compaction of the powder material as per study results. This results however are difficult to implement from practical point of view.

Kwon et al. [8] investigated the densification behavior during cold die compaction of stainless-steel powder. The finite element results were compared with experimental data. The friction coefficient was $\mu = 0.1$, as determined from the relationship between the ejection pressure and compaction pressure, between the die and a powder compact. There was strong agreement between the experimental and finite element analysis results for density distribution during die compaction.

Non-homogeneous density of the compact can ascend from several factors, particularly variations in the packing density of the powder particles after die filling and powder transfer. The influence of the filling and transfer conditions on the density distribution of the compact are the areas of interest for researchers from a long time. Coube et al.[9] Modelled the powder die compaction using the finite element method and a material model. The Drucker–Prager cap model was modified to explain the formation of cracks during the process. The stages included powder transfer, compaction, unloading, and ejection of the parts from the die. The parameters considered were the cohesive strength and the cohesion slope. These parameters characterize the current strength of the powder compact in the Drucker–Prager model, as state dependent variables. These variables were used to formulate evolution equations. These equations determined the relation as that the strength increases by densification and decreases by forced shear deformation. Few of the parameters used in the evolution equations were calculated from measured green strength values. An iron-based powder was used for the experiments. The results of this study shows that it is possible to calculate the density distribution accurately. The cracking behavior can be modelled correctly along with the simulation of the compaction of complex 3D parts. Another study by the authors [10] has shown that regardless of the initial density distribution, the depression after transfer causes an irreversible lower densification. The solution to this problem is 'pre-compacting' the powder prior to the transfer to a certain density. The depressions are prevented in this case as the powder transfers as a compacted body. However, this pre-transfer density should be controlled carefully to avoid the risk of creating cracks during transfer. After the transfer phase, the kinematics of the motions of the tool can influence the density distribution. The variation of density in the part is minimized using variation of pressing schedule, although full consistency is not attained. The finite element analysis results from this study shows that it is vital to investigate all factors of the manufacturing process and the effect of the combination of these factors in the density distribution of green compact. The nonhomogeneous density distribution in transfer and filling has small effect compare to the depression effect during setting phase.

The interface friction is another very significant factor in powder compaction. As this friction may result in non-uniform packing density within the powder compact and may influence the performance of the final component. The high wall friction can cause high stress gradients which leads to fluctuations in the density. After the sintering the compact shows these variations and the shape of final compact may significantly vary from the green compact. Therefore, the control and precision of wall friction is central for overall integrity of the compact. Briscoe et al.[11] studied the effect of wall friction on powder compaction. The results of this studies have shown that the maximum density is achieved in the topmost and center region and minimum density region is the circumference at the outer region in bottom. The low- and high-density zones are found at the top and bottom of the compact respectively. The finite element modeling can give highly accurate results but is heavily dependent on the precise modeling of bulk powder behavior and wall friction interactions. The generated density data can be used to produce near net shape compacts. Solimanjad [12] developed a new method for determination of coefficient of friction in compaction. To continuously measure the coefficient of friction directly in a complex process like compaction is a difficult process. The coefficient of friction fluctuates due to variation in the process parameters including pressure distributions, powder surface deformation etc. The measurements were carried out through strain gauges mounted on the upper punch. The upper punch surface in the device resembles to the die wall in a conventional press. The sliding velocity, compaction velocity, normal load and temperature are measured and can be controlled. The study shows that the powder compaction can be controlled by an elastic and plastic deformation of the particles as well as the powder re-arrangement. At densities below 4g cm^{-3} the particle rearrangement is the governing process. At these values of the density there is no plastic deformation of the particles. At densities more than 4·5 g cm^{-3} the coefficient of friction is almost constant due to the completion of the plastic deformation of the powder surface in contact with the die wall. Wu et al. [13] investigated the influence of powder properties and particle-to-die size ratio on the powder transfer process. The study results shows that the powder characteristics (such as morphology and average particle size) and the inter-particle friction coefficient affects the degree of depression which is a typical feature on the top of the die cavity. The depression is directly proportional to the irregularity of the powder morphology, the inter-particle friction, and the average particle size. Further the shear zone formed in transfer has a lower relative density. The major features of powder transfer stage have also been captured accurately using discrete element simulations.

At the low density ranges the material characterization of powder mixtures is still an open question. It is very difficult to overcome the experimental difficulties related with the measurements of mechanical properties. Furthermore, the densification of the powders at those low densities are challenging to measure. The other option is to numerically investigate the powder transfer in powder compaction which again requires accurate measurements of the powder densification at low densities. Lammens et al. [14] conducted a study and showed diameter has no effect on the lower punch pressure whereas the in upper punch pressure the density is inversely proportional to the diameter. Yousuff et al. [15] showed that the coefficient of internal friction was unaffected by particle shape factor or specific surface area. Particle size had the greatest impact on the spectrum of powder properties studied, with the smaller particle samples having the highest friction. The coefficient of internal friction calculated from shear cell and die pressing studies were in good qualitative agreement. Despite indications of powder cohesion in die pressing studies, the linearity of the axial stress-radial stress relationships suggested that the powder reaction could be described by a constant value of the coefficient of internal friction. Dynamic compaction produces significantly lower radial stresses. Under these stress conditions, this is compatible with more internal friction. Hong et al. [16] investigated the die stress profiles during compaction. The powders used in this study were commercial grade pure titanium (Ti) and commercial lubricated iron (Fe). An instrumented die was used for experimentation. The multiple strain gauge pins were used along the height to measure the stress profile of a double-action pressing die. The experimentation shows that even after removal of axial compression load, there is residual stress stored in the radial direction. The shape of residual stress and axial stress profile is unique for both powders and is symmetric along the height of the compact. The titanium powder has high radial stress at the center with the top and bottom of the compact showing steep pressure gradient whereas Iron has more uniform distribution of radial stress along the height.

Secondi [17] developed a pressure–density law starting with assumptions on porosity and work hardening. The powder behavior was accurately described for five powders using this law. However, for low density cases (3-12 MPa) the results were not in agreement with experimentation. The plasticity threshold is defined as a function of hydrostatic pressure and deviatory stress. The physical behaviors of the powder is described by investigating the effect of shear on compaction. The tri-axial experiments with WC-Co powders were used to determine the fitting parameters. The results have shown that the isotactic compaction and plain die pressing can be used to determine the parameters which can help in faster characterizations of hard powders. Sharma et al. [18] using a 1000 MPa load on UTM, shown that the compaction die can be used to generate NiTi composite. Minimum stresses are spread on the die and upper punch, whereas maximum stresses are placed on the powder and lower punch, according to the finite element study. The NiTi powder was effectively crushed into a green compact with a sample density of 4.89 g/cm^3 and a porosity of 27.56 percent, according to the experimental results. Due to the creation of necking between the composite grains and the evaporation of moisture and lubricant, sintering boosts sample density even further. When compared to theoretical values for compressive yield strength, ultimate compressive strength, and hardness, the mechanical characteristics of sintered sample are optimal. The maximum failure load was measured by sandwiching the sample between two flat plates. A Rockwell hardness tester with a diamond indenter was used to conduct the hardness test. The findings demonstrate that the sample compacted under 1000 MPa load has compressive yield strength, ultimate compressive strength, and Rockwell hardness of 37.737 MPa, 115 MPa, and 67 HRC, respectively. Due to induced porosity during the compaction process, the compressive yield strength and ultimate compressive strength of NiTi composite are on the lower side. The hardness of the created NiTi composite, on the other hand, is close to the theoretical Rockwell hardness of NiTi alloy (58-65 HRC). After compression and sintering, the density of the generated sample was measured. After compaction and sintering, the density of a NiTi composite sample was compared to the theoretical density of NiTi composite. The results demonstrate that the density obtained after sample compaction (4.89 g/cm3) is lower than the theoretical density of NiTi powder (6.75 g/cm3). Due to the creation of necking between the NiTi particles and the evaporation of moisture and lubricant, the density of the sintered sample (5.02 g/cm3) was somewhat enhanced. Equation 1 was used to calculate the porosity of a sintered NiTi composite sample. During the compaction process, 27.56 percent porosity was discovered.

$$\text{Porosity} = \{1- (\text{sample density}/\text{theoretical density})\} *100 \text{ ----(1)}$$

Compaction pressure has a direct impact on the compaction behaviour of NiTi powder. The compaction behaviour of NiTi composite powder shows higher punch displacement in the beginning of compaction due to the larger space available between the particles of composite powder, but due to green strength and less space developed between composite particles at higher loads, the displacement becomes constant at the end of compaction. The NiTi composite powder was successfully crushed to maximum density without significant die deformation, according to the results.

Barbosa et al. [19] done a failure analysis of tool steel-based compaction punch used in powder metallurgy. The failure is usually result of decreased fracture strength which is the consequence of surface defects causing stress concentration. The compaction punch underwent failure and was investigated using optical microscopes and scan electron microscopes. The results shown that the stress concentrations due to machining grooves resulted in the premature fracture of the punch.

Summary of Literature

The initial powder density and the interaction between particles and interactions between powders and die/punch play an essential role in the final quality of the compact. Studying the impact of various shapes, punching schedules, and material interactions is essential to achieving better results. Extensive experimentation is required to establish the optimized process parameters to get the best results for a particular powder mixture.

Research Gaps

The following research gaps were identified based on the literature survey:

- There is no uniform design for different materials
- The new materials fabricated through powder metallurgy need extensive testing before use in different applications

Research Objectives

The following research objectives are selected based on the research gaps:

1. The CAD design of Die and Punch for fabrication of tensile testing specimen using powder metallurgy.
2. The finite element analysis of the Punch and Die

3. Fabrication of the Die and Punch using CNC machines
4. Compaction of metal powders for green pallet

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Results and discussion

Powder metallurgy criteria is used for the sample preparation. Different metal powders were used for the compaction process. Die and punch assembly is designed and manufactured for the compaction of the metal powders. Autodesk fusion 360 software is used to design and model the punch and die. After designing and modelling, CNC codes are generated from the manufacturing module considering the optimal machine process parameters. The following results can be drawn from the thesis:

1. Aluminium is used for die material with dimensions of 180.05 mm * 64 mm * 10.02 mm. Total tensile specimen slot dimensions are 124 mm * 20 mm * 8 mm. Neck length of slot is 30 mm. Similarly punch dimensions were selected as per the ASTM standards. Converging angle at the neck is taken as 36^0.
2. Ansys workbench 2021 software is used to analyze the punch or the tensile specimen for the maximum stress generation and deflection after applying the required load.
3. Static structure of the sample is analysed for von-mises stress generation. Maximum stress is generating at minimum cross section area, i.e. gauge neck. The values of the maximum and minimum stress generation are 4.7815 GPa and 0.9370 GPa respectively at neck area and end edge.
4. Strain value reflects the percent change in the length on the application of the load. Tensile specimen shows the maximum and minimum strain values of 0.024809 and 0.0045571 at gage neck and bar end position for the static structure of tensile specimen.
5. Deflection in the specimen is calculated on the application of the load. The maximum deflection of 2.9612 mm observed at the end edge of the sample.

Based on the requirement, different type of materials can be selected for the punch and die assembly. Different type of tensile specimens can also be produced using different punch-die combinations for metal powder compactions. Along with the fusion 360 and ansys, other modelling and simulation softwares like Abacus can also be used for the punch and die modelling and manufacturing. For the compression process, one should use factor of safety as per the material.

Conclusions and Future Scope

Based on the experiments, it may be concluded that the die and punch assembly can be used for the metal powder compression process. Design, modelling and simulation of any die and punch assembly can be successfully implemented using softwares. Combination of the fusion 360 and ansys software is best suited for analysis of any component. The assembly that has been manufactured, can be widely used for compression of any kind of metal powders. ASTM standard E8 is used for the dimensions of the specimens. There is nut-bolt assembly for the engagement of the die. Close tolerances have been taken for the die and punch dimensions. The manufactured die can hold high compression load upto 20 tons.
Aluminium is used for die material and
mild steel is used for punch material.

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