Design and Fabrication of Die-set for Compacting the Powder to Synthesize Green Pallet of Nickel-based Solid Lubricant Nano-composites

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Abstract

In powder metallurgy, the design and fabrication of the die-set are crucial steps because the die characteristics and form directly impact the finished product. The current study aims to design and fabricate a die-set for cold compression to produce a cylindrical specimen or green pallet. The compaction die-set is a deciding aspect of the powder metallurgy process since it is used to shape the loose powder to the desired shape. The die-set is developed according to ASTM requirements and AISI D3 steel has been used as raw material for it. The study demonstrates the design considerations, computations, 2-D drawings, and 3-D models of die-set. To fabricate the die, facing, turning, drilling, grinding, wire-cut EDM and heat Treatment operations were used. The design has been further analyzed using Solidworks 14 and ANSYS 2023R1.

Keywords: Powder metallurgy, Compaction Die-set, Mechanical Properties, Punch.

1. Introduction

In powder metallurgy (PM), the materials in powder form are blended in the desired quantity, compacted to make a green pallet in the desired shape, and further sintered in the atmospheric or controlled environment to get the final components [1]. With the help of this quickly growing technology, a vast range of materials may be developed as alloys and composites. Applications of powder metallurgy extend across various industries, including automotive, medical, aerospace, electronics, and consumer goods. Common products manufactured using powder metallurgy include gears, bushings, filters, bearings, cutting tools, and magnets. After sintering, different processes can be performed to densify a material thoroughly, typically involving applying heat, pressure, or a combination of heat and pressure to close residual pores [2].

Due to its ease of processing and control, the PM process creates bespoke materials or components that would be difficult to manufacture using conventional techniques [3-4]. Research has revealed that cold-forming ferrous and nonferrous powder preforms have several advantages, including better surface finish, more accuracy, and increased strength from geometric work and hardening. However, the drawbacks of hot forging include oxidation, decarburization, excessive die-set wear, insufficient surface polishing, and heat stresses. Further research on PM steels has investigated manufacturing, alloying, mixing, and powder categories for steels [5]. This technique may minimize the requirement for metal removal operations, thereby cutting the production cost [6]. The results show that low-alloy PM steels from elemental powders, such as those containing Cr, Mo, Si, Fe-Si, Cu, and Mn, are suitable for precision automotive engines and gearbox parts [7-8].

The PM process offers an advantage as it allows the component fabrication without material decomposition or dissolution, thus, averting the change in materials property in the solid-liquid phase [9]. Sintered powder materials need much research on plastic deformation because of their unique densification and plastic deformation properties during hot and cold forging. Alloying, heat treatment, and densification may strengthen sintered PM low alloy steels [10-11]. Powder operations give higher flexibility than other manufacturing techniques like casting, extrusion, and forging due to the controlled characteristics of the generated materials [12]. The research considers a novel yield function that computes yield stress using numerical integration and hydrostatic stress. The findings indicate that the yield stress ratio in porous material to completely dense material rises with densification due to plastic deformation. Porous materials' yield and plastic deformation were explained using a non-associated flow rule. Carbon nanotube (CNT) reinforced composites demonstrated better mechanical capabilities, but their macro-scale use was limited by issues like uniform dispersion and carbide reduction [13-15].

According to studies, the intermetallic composites, porous solids, and aggregates produced by the powder processing technique have better material properties. The most straight-forward technique, known as uniaxial compaction, compresses powder under high pressure within a closed die chamber [16-17]. The study found that the addition of CNT has increased its compressive strength, affecting various machine and press tool applications [18-20]. Metal powder compaction is commonly performed at pressures ranging between 150 MPa and 1000 MPa, with the die held vertically with a punch. The powder is squeezed into the correct form, then expelled and sintered at a predetermined temperature [21-22]. Increased permeability and concentric micro-cracking on green compacted surfaces, which are mostly formed during compaction and intensified during sintering due to friction with the die wall and powder particles, are two drawbacks of pressure compaction [23-25]. The procedure involves three steps: mixing compaction to get the desired shape and sintering to diffuse powder particles, allowing for the straight-forward manufacture of finely designed components [26-28]. This method reduces manufacturing costs by eliminating or reducing the need for metal removal processes [29-30].

The PM technique provides higher flexibility and regulated end qualities than conventional production processes, thus proving useful in creating ceramic-metallic composites and porous alloys with increased properties [31-32]. Cold compaction is the most effective technique for powder compression since it includes exerting a larger vertical downward force in a die cavity [33]. After the compression into the appropriate shape, the compacted sample was withdrawn from the die cavity, and sintering was performed at a pre-defined temperature under a desired atmosphere to bind the powder particles to provide an appropriate strength between the particles [34-38]. However, current research focuses on designing and fabricating the pressure compaction die-set for compacting the Ni-Ti_3C_2Tx (MXene) blended powder. The porosity created during compaction, mechanical properties at maximum pressure, and compaction behavior are used to assess the performance of the die-set experimentally. Solidworks14 and Ansys 2023R1 were used to develop and test the die-set in simulated settings. The die-set was successfully tested by producing the green pallet of Ni-Ti_3C_2Tx (MXene) powder under an applied load of 800 KN using a Universal Testing Machine (UTM).

2. Materials and Method

2.1 Die and Punch Material

Due to its increased hardness and wear resistance, previous research demonstrated that die steel is a suitable material for tooling applications such as powder metallurgy tooling, draw dies, and blanking and shaping tools [38]. So, the die and punch were fabricated from AISI D3 die steel, also known as high carbon (C) and high chromium (Cr) cold work steel. The die-set dimensions were selected according to the American Society for Testing and Materials (ASTM) standards. AISI D3 steel has a density of 7.7 g/cm³ and a maximum compressive stress of 2151 MPa [39]. AISI D3 die steel, was procured from a local supplier and was characterized using EDX. Table 1 shows the compositional characteristics of AISI D3 steel. Depending on the heat treatment parameters, AISI D3 steel may have hardness values ranging from 30 to 69 HRC, tensile strengths of 990 to 2900 MPa, and yield strengths of 705 to 2400 MPa [40].

Table 1 Chemical composition of AISI D3 Steel (wt.%).

Element	Cr	C	W	V	Mn	Si	Ni	Cu	P	S
Content (%)	12	2.1	1	1	0.6	0.6	0.3	0.25	0.03	0.03

2.2 Die-set Design and Safety Calculations

The compaction die-set was developed for manufacturing green pallets of Ni-Ti_3C_2Tx(MXene) composite having a diameter of 25 mm. The following is the design of the compaction die-set:

Ultimate yield strength of the AISI D3 steel (σ_y) = 2100 MPa

Inner diameter of die block (D_i) = 25mm

Outer diameter of die block (D_o) = 80mm

Applied working Load (F) = 800 KN

Cross Section area of inner chamber (A) = $(\pi/4) \times Di^2 = 491.07\ mm^2$

For applied working load, the stress (σ_1) = F/A = 1629.09 MPa

Hence, $\sigma_1 < \sigma_y$ (upper punch in a Safe working condition)

Stress generated in the die block as load is applied on the upper punch is given by

$\sigma_2 = \sigma_1[\ \{R_o^2 + R_i^2\}/\{R_o^2 - R_i^2\}]$

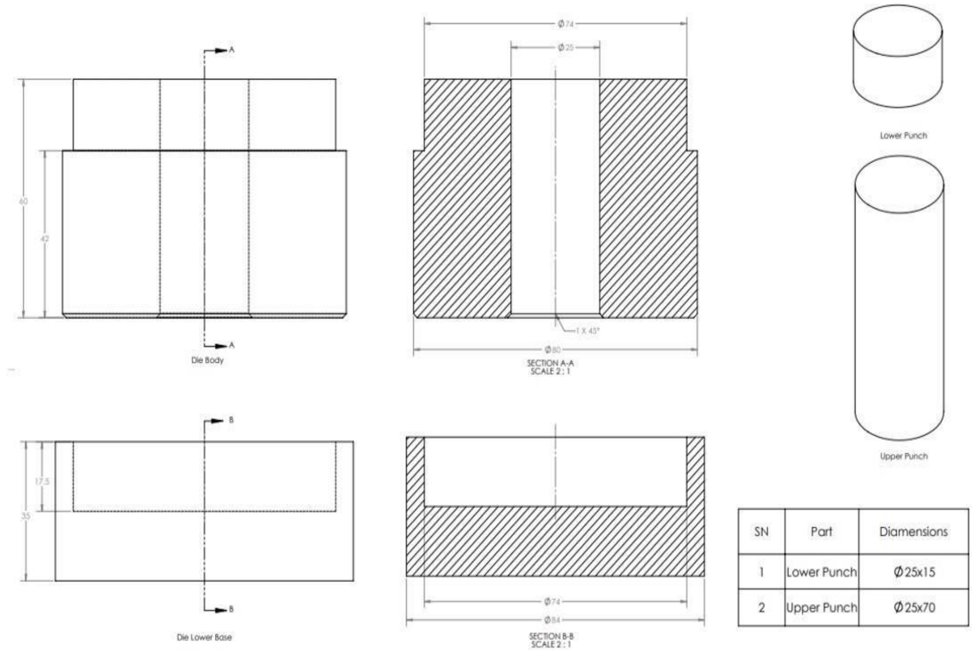
$\sigma_2 = 1629.09[\ \{40^2 + 12.5^2\}/\{40^2 - 12.5^2\}] = 1981.71$ MPa

Hence, $\sigma_2 < \sigma_y$ (Safe working condition for the die chamber)

Therefore, Both die and punch can easily sustain the applied load of 800 KN and are safe to use up to 800 KN.

2.3 2D Drawing Compaction Die and Punch Set

Figure 1 depicts the 2D designs of the individual components of the die-set. The design is based on ASTM B925-08 guidelines. The designs were designed separately in Solidworks14, entirely with the appropriate dimensions and geometry, as shown in Fig. 1.



SN	Part	Diamensions
1	Lower Punch	Ø25x15
2	Upper Punch	Ø25x70

Fig. 1 2D drawing of individual components of die-set.

2.4 3D Design of Die-set

SOLIDWORKS 14 software was used to create the 3D model of the die-set, which includes the modes of the die block, lower punch, and upper punch. 3D models of the individual parts and die-set assembly were prepared, as illustrated in Fig. 2. The relief in the punch minimizes the contact with the die cavity wall, resulting in less wear and friction. The lower and upper punches have been provided with a clearance of 0.5 mm.

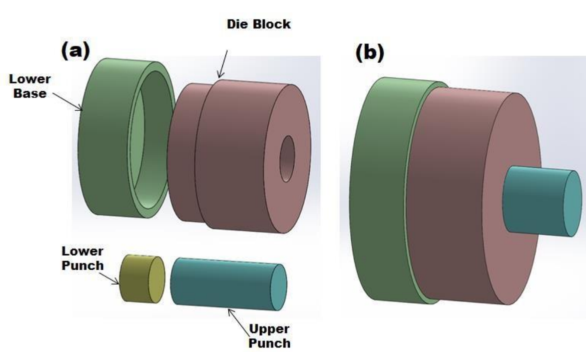


Fig. 2 (a) 3D design exploded view of the die and punch (b) Assembly view of Die-set.

3. Fabrication of Die-set

AISI D3 steel rod of ϕ90 x 130 mm was selected for making the die block, and ϕ30 mm x 100 mm was selected for making the punch. Both materials were procured from Mittal Metal Alloys Private Ltd., Chaudhary Road, Ghaziabad, India. The high-speed steel and carbide tools were employed for machining operation. A power hack saw was used to cut the materials into the appropriate size for the die block, upper punch, and lower punch. Figure 3 shows the standard lathe machine operations (facing, turning, drilling, and boring) performed to pre-machine the die block, upper punch, and lower punch. After pre-machining, the die block and punch set have undergone the three stages of heat treatment in a muffle furnace: stress relieving, hardening, and tempering. After heat treatment, the surface was finished using the cylindrical and flat grinder[41-42] and the final die-set, as illustrated in Fig. 4, has been fabricated and ready to use to make green pallets.

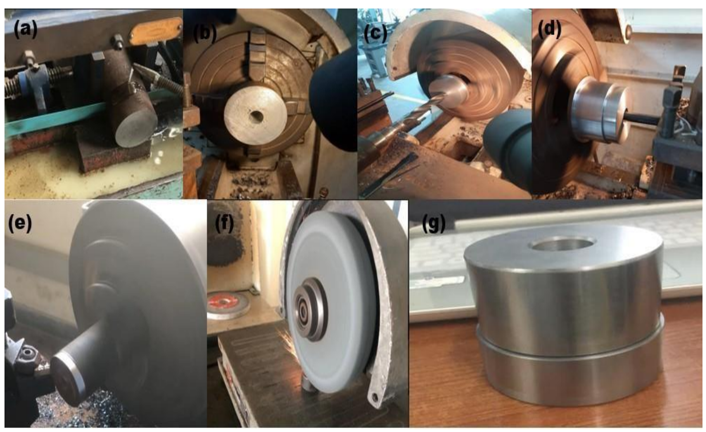


Fig. 3 Representation of (a) Power hack saw (b) Facing (c) Drilling (d) Boring (e) Turning (f) Grinding operations employed to machine the raw material (g) Die block after the machining process.

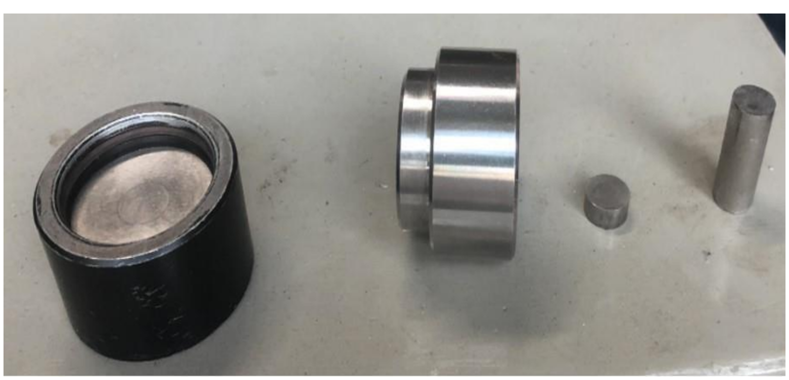


Fig. 4 Digital images of fabricated die and punch components.

4. Testing of Compaction Die-set.

The suitability of the fabricated die-set for its application was experimentally evaluated by compacting Ni-$Ti_3C_2T_x$ blended powder using a universal testing machine (Maximum capacity-1500 KN) at Material Testing Laboratory, Sharda University, Greater Noida, Uttar Pradesh, India. Figure 5 illustrates how the die and punch were used for compression to make a green pallet of Ni-$Ti_3C_2T_x$. After providing graphite powder lubrication on the interior of the die block, 25 gm of Ni-Ti_3C_2Tx powder was placed into the die block, which was closed from the downside through the lower punch. After filling the powder, the die block was also closed from the upper side using the lower punch. The graphite powder was also provided to the periphery of the lower and upper punch to facilitate its easy removal after compacting. Then, the powder was pressed gradually to a working load of 800 KN, as shown in Fig. 5(a), and after reaching to 800 KN, the compaction was held for 10 min to achieve uniformity. After that load was removed, and compacted powder was taken out from the die-set. Thus, the green pallet of Ni-$Ti_3C_2T_x$ was synthesized, which was further sintered and used for mechanical and tribological analysis.

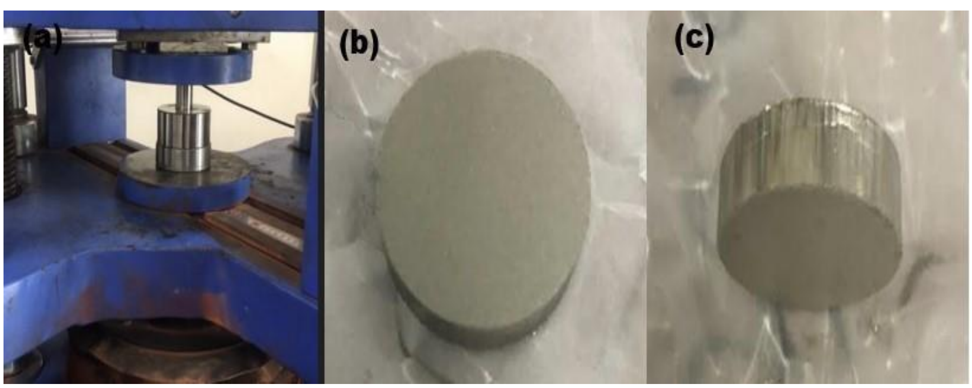


Fig. 5 (a) Compression of the Ni-$Ti_3C_2T_x$ powder using die-set in UTM (b) Top view and (c) Side view of compacted Ni-$Ti_3C_2T_x$ powder sample.

5. Finite Element Analysis of Die-set

The stress distribution in the fabricated die block was analyzed using ANSYS 2023R1. The static structural analysis type and the solid-concrete 63 element were chosen for this purpose. A .igs file consisting of the design of the die-set was imported to ANSYS 2023R1 from Solidworks 14, and material features were added (Young's Modulus of 2.1×10^5 MPa and Poisson's Ratio of 0.3). The model was further meshed using a SOLID 65 tetrahedron at size level 4 [43]. A load of 800 KN was imposed on the die, and the die displacement was analyzed in all directions from the exterior of the die. Figure 6 demonstrates the corresponding meshed and total deformation under the simulated conditions. The ultimate yield strength of the AISI D3 tool steel is ~2100 MPa. The most incredible stress intensity was found to be 1600 MPa, which is less than the permissible stress of AISI D3 tool steel. At the same time, the most excellent deflection achieved is also lower. So, the fabricated die-set is acceptable and safe to use under the given circumstances.

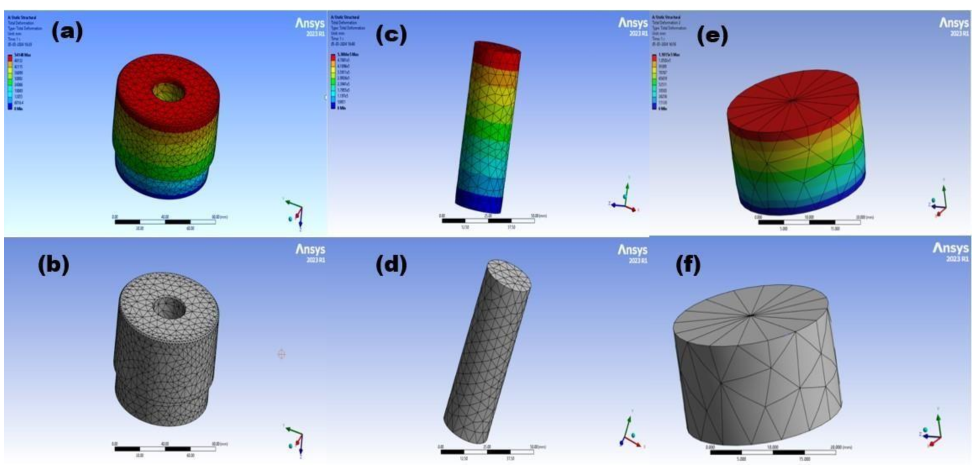


Fig. 6 (a) Total deformation of die block (b) 3D meshed model of die block (c) Total deformation of the upper punch (d) 3D meshed model of the upper punch (e) Total deformation of the lower punch (f) 3D meshed model of the lower punch.

6. Conclusions

The current study focused on designing and fabricating a die-set to make green pallets for powder metallurgy products. The die-set was fabricated using high-grade steel (AISI D3) as it exhibits more significant mechanical and thermal properties. The compaction die-set was successfully developed and manufactured to create a Ti_3C_2Tx composite with an 800 KN load on UTM. The graphite coating inside the die block and outside the punch periphery can decrease the friction between the punch and die block and help easy removal of the component after compacting. Solidwork14 and ANSYS 2023R1 analysis demonstrated that the die and top punch had the lowest stresses, while the bottom punch had the highest. Ti_3C_2Tx composite can be successfully synthesized by using the die-set under a compaction load of 800 KN.

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