



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 can be found in automotive, medical, aerospace, electronic industry, and consumer goods industry. Some of the common products which are produced by the use of powder metal technology are gears, bushings, filters, bearings, cutting tools, and magnets. Following the sintering process, a material can be further densified through a variety of processes, generally by subjecting a material to heat, pressure, or a combination of the two, in order to seal remaining pores [2].

The PM process makes tailored materials or components to a level that it is challenging to produce them within the traditional methods due to its simplicity in processing and management [3-4]. It has also been found out through research that cold-forming of ferrous and nonferrous powder preforms have a number of advantages such as, improved surface finish, enhanced precision and strength due to geometric works and hardening. The disadvantages of hot forging though are oxidation, decarburization, over wearing the die-set, inadequate surface finishing 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-Ti₃C₂T_x (MXene) blended powder. The performance of the die-set is evaluated

experimentally by taking into consideration their porosity developed during compaction, the mechanical properties at maximum pressure, and moreover, the character of the compaction. The die-set was developed and tested in simulated environments with the help of Solidworks 2023r1 and Ansys 2023R1. The die-set was successfully tested by producing the green pallet of Ni-Ti₃C₂Tx (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 higher hardness and wear resistance, past studies have proven that die steel material can serve as tool material in some applications including powder metallurgy tooling, draw dies, blanking and shaping tools [38]. Thus, the die and punch were made out of AISI D3 die steel also referred to as high carbon (C) and high chromium (Cr) cold work steel. The dimensions chosen in the die-set were guided by the ASTM standards. The density and maximum compressive stress of AISI D3 steel is 7.7 g/cm³ and 2151 MPa respectively [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-Ti₃C₂Tx(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) = $(\pi/4) \times D_i^2 = 491.07 \text{ mm}^2$

For applied working load, the stress (σ_1) = $F/A = 1629.09 \text{ MPa}$

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

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

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

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.

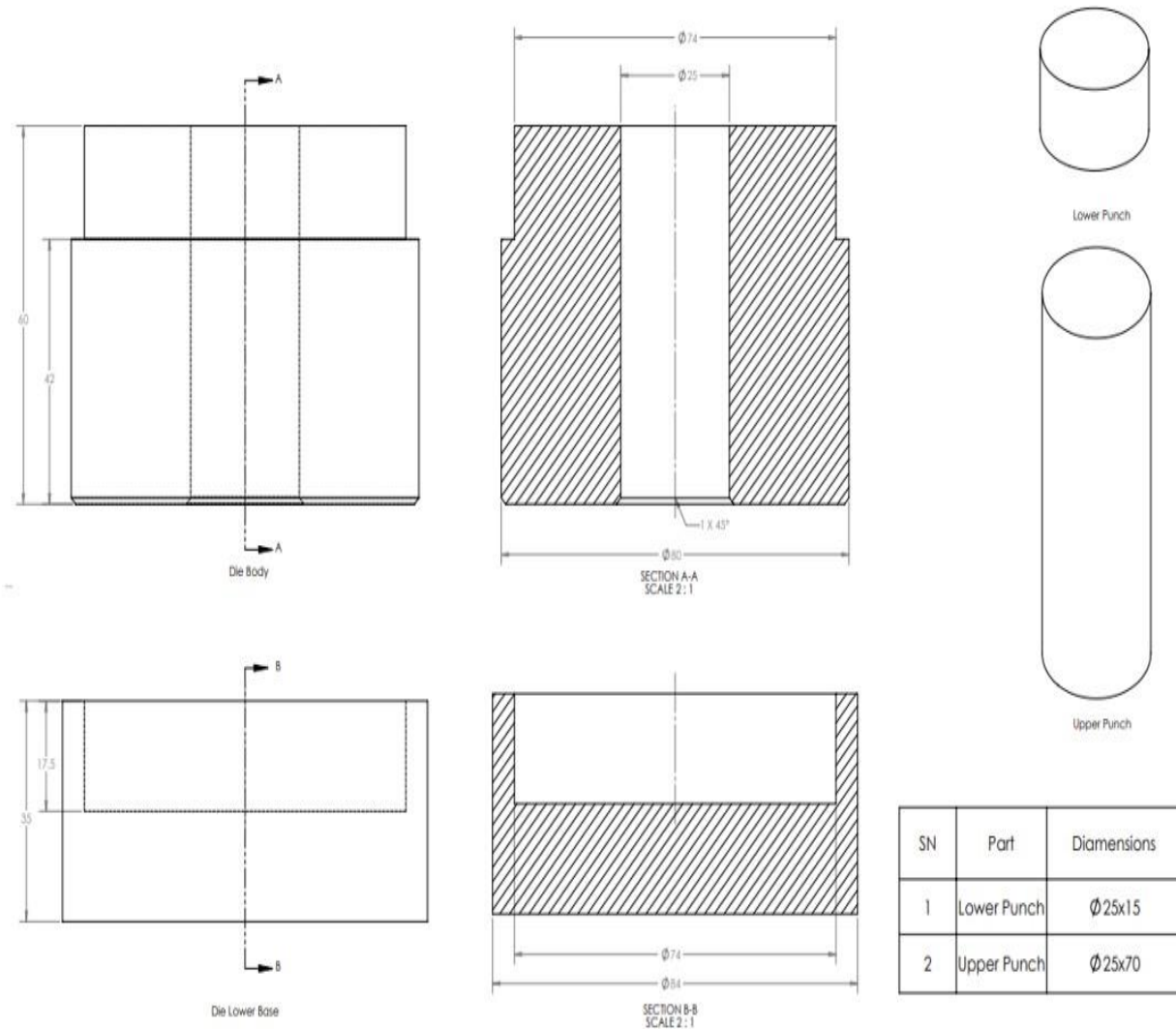


Fig. 1 2D drawing of individual components of die-set.

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.

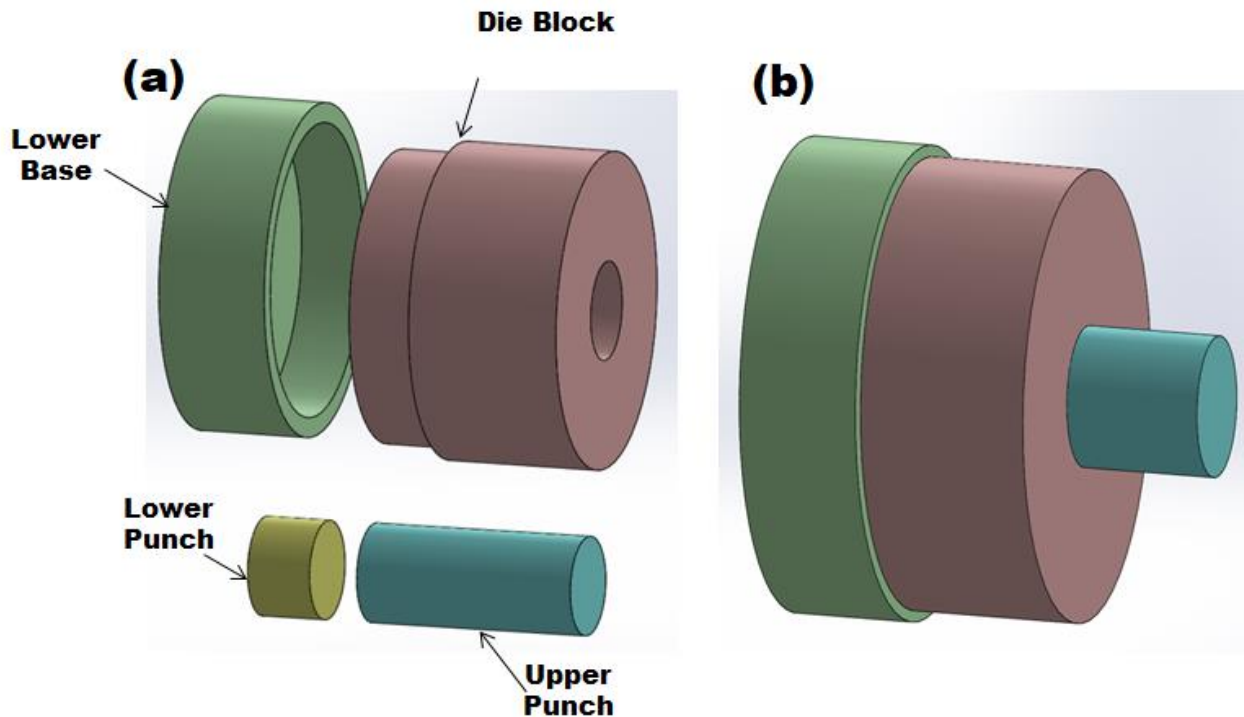


Fig. 2 (a) 3D design exploded view of the die and punch (b) Assembly view of Die-set

3. Fabrication of Die-set

AISI D3 steel rod of $\phi 90 \times 130$ mm was selected for making the die block, and $\phi 30$ mm \times 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.

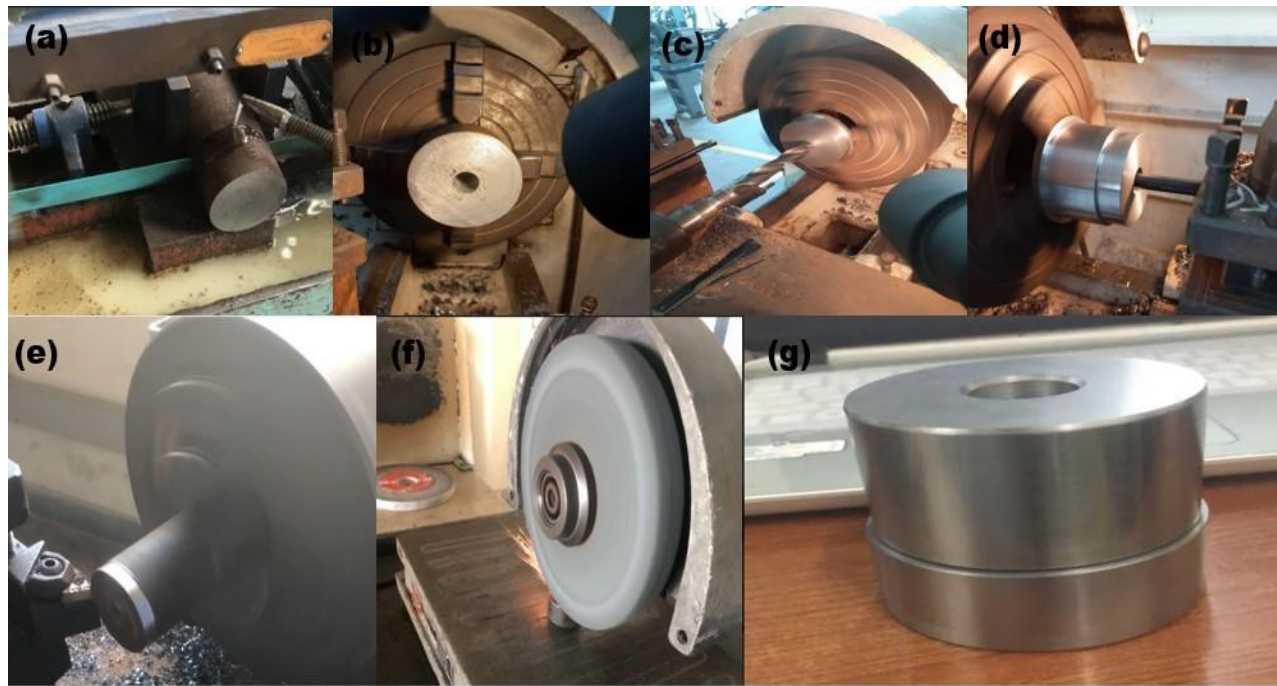


Fig. 3 Representation of (a) Power hack saw (b) Facing (c) Drilling (d) Boring (e) Turning (f) Grinding operations employed to machine the raw material (g) Die block after the machining process.



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-Ti₃C₂T_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-Ti₃C₂T_x. After providing graphite powder lubrication on the interior of the die block, 25 gm of Ni-Ti₃C₂T_x 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-Ti₃C₂T_x was synthesized, which was further sintered and used for mechanical and tribological analysis.

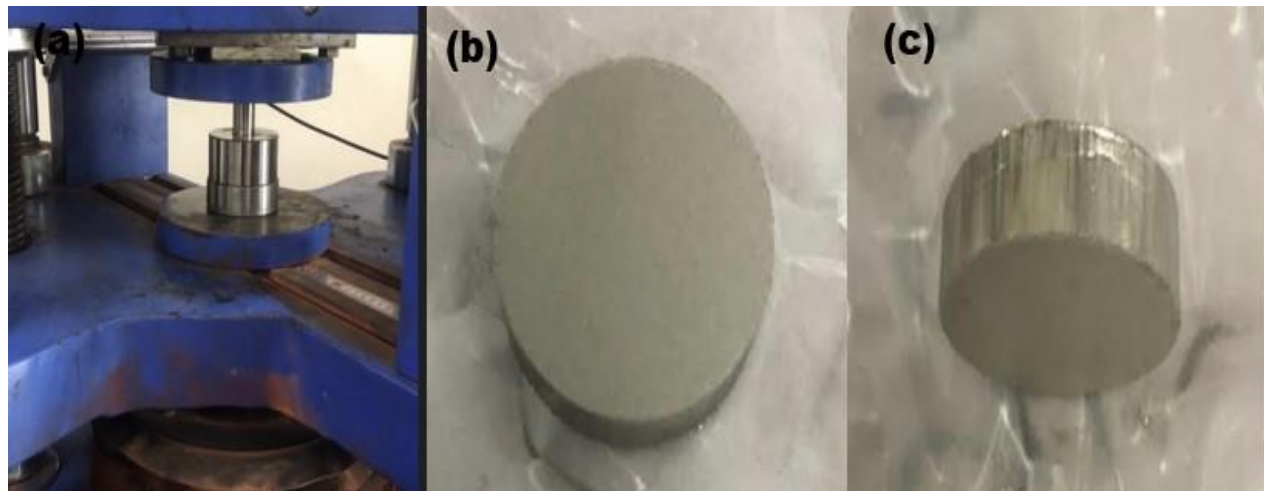


Fig. 5 (a) Compression of the Ni-Ti₃C₂T_x powder using die-set in UTM (b) Top view and (c) Side view of compacted Ni-Ti₃C₂T_x powder sample.

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.

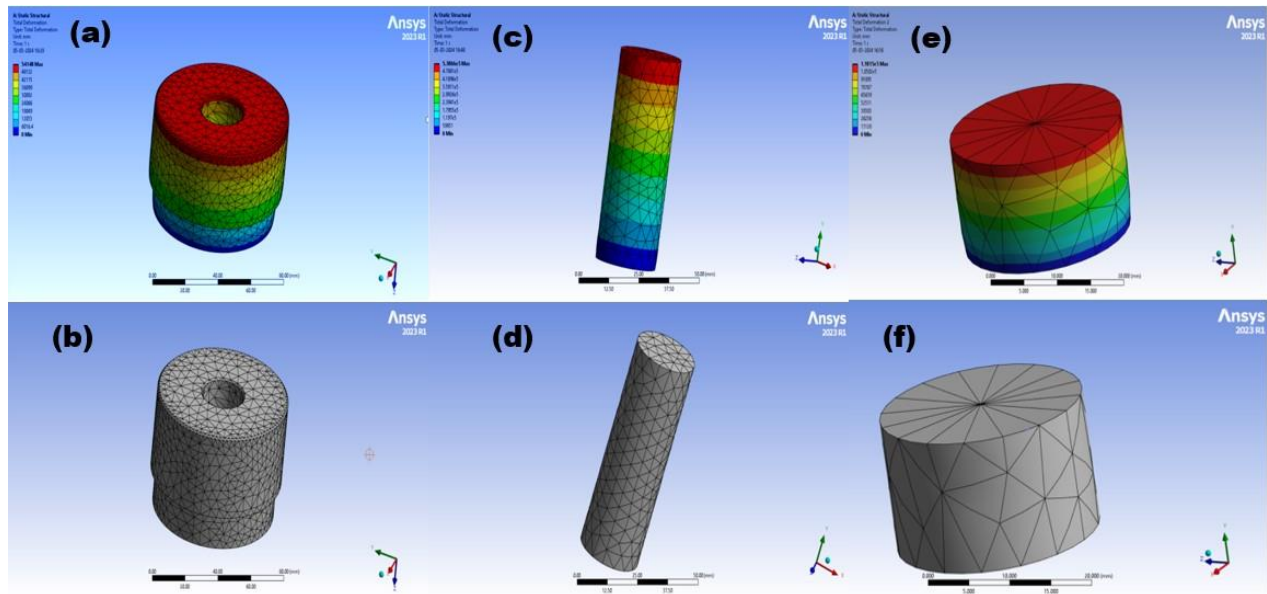


Fig. 6 (a) Total deformation of die block (b) 3D meshed model of die block (c) Total deformation of the upper punch (d) 3D meshed model of the upper punch (e) Total deformation of the lower punch (f) 3D meshed model of the lower punch.

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 die-set compaction was developed and built successfully to produce a Ticas concrete made of $Ti_3 C_2 T_x$ that has a 800 KN load. The lining of the graphite coating on both inside of the die block and outside of the punch periphery will be able to reduce the friction between the punch and the die block and assist in easy removal of the component after the process of compacting. The solidwork and ANSYS 2023R1 analysis indicated that the die and top punch had the most insignificant stresses and the bottom punch had the most significant. A successful processing of $Ti_3 C_2 T_x$ composite can be obtained by the die-set in a 800 KN compaction load.

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