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DESIGN, FABRICATION AND STRUCTURAL ANALYSIS OF PERMANENT MOULD FOR FOUNDRY CRUCIBLE PRODUCTION

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Abstract. Most solid mineral resources, particularly metals used in manufacturing industries, are processed into finished products through casting in foundries, where key equipment such as furnaces, crucibles, and moulds (both temporary and permanent) are essential. However, in a developing country like Nigeria, crucial components, including crucibles are not produced locally, leading foundry industries to rely heavily on imports. In addressing this challenge, this study therefore, focuses on the structural design, analysis, and fabrication of a permanent mould for local crucible production using mild steel, the fabrication was carried out at the Defence Industries Corporation of Nigeria (DICON), Kaduna. Structural analysis performed with SolidWorks 2018 obtained results for both male and female mould components are: maximum-stress values of 67.34 MPa and 53.96 MPa, displacement values of 0.01352 mm and 0.007860 mm, strains obtaining 0.00024 and 0.00020, and factors of safety of 9.2 and 11. Findings show that the results were all within acceptable limits, indicating a structurally sound design. The mould was evaluated by producing crucibles from clay of varying sieve sizes using a hydraulic press with 100bar maximum pressure, and findings showed that smaller sieve sizes required less compaction pressure, confirming the mould's effectiveness and reliability. Additionally, the use of locally available materials for the mould fabrication promotes domestic crucible production and reduces reliance on imports. This work thus offers a sustainable solution to support the Nigerian foundry industry.

Keywords: Mould, Foundry, Fabrication, Structural Analysis, Crucible

1. Introduction

Over the years, the continuous growth and meaningful development of any nation have been largely attributed to its ability to strategically harness and extract solid mineral resources. The extracted resources have long way served as vital raw materials for driving productivity and advancement in various industrial sectors. In Nigeria, according to the recent enumeration by the Federal Ministry of Mines and Steel Development-(FMMSD) about forty useful mineral resources have been discovered in not more than five hundred locations, spreading across the thirty-six states and the Federal Capital-Abuja [1]. These minerals can be grouped into (a)minerals for the industries (such as barite, kaolin, gypsum, feldspar, and limestone); (b) energy minerals (including bitumen, lignite, coal, and uranium); (c) metallic-ore (such as gold, cassiterite, columbite, iron ore, lead-zinc, tin, lithium, and copper); (d) construction minerals (such as granite, gravel, laterite, dolomite, calcite, and sand); and (e) precious stones(including sapphire, tourmaline, emerald, topaz, amethyst, garnet) [2]. Given the urgent demand for certain materials in Nigeria's manufacturing sector and the abundance of natural resources within the country, it is expedient to prioritize the local production of industrial components to meet the need. This approach not only reduces excessive dependence on importation but also aligns production with the specific needs and insights of local industries [3].

Currently, in a bid to diversify Nigeria's economy, the Federal Government is placing increased interest on harnessing solid mineral resources. As part of this initiative, metal smelting for different foundries has emerged as a key industrial practice, driven by the versatility of metals and their extensive applications across various sectors of human activity [4]. Meanwhile, there are various equipment used for melting during metal production in the foundry and the role of crucible among this equipment cannot be overemphasized. Crucibles are ceramic vessels which are open mouthed used for melting various metals and alloys. Rehren [5] described crucibles as portable reaction-vessels designed to withstand high temperatures where chemical and physical transformations occur. They are primarily used in crucible furnaces, which are among the oldest and simplest types of furnaces found in foundries. The furnace are mainly utilized for melting small quantities of non-ferrous metals and are typically employed in small-scale foundries and alloy production [6].

Undoubtedly, crucibles are ancient cross-cultural artifacts or artificial pigments that have been utilized globally for thousands of years in high-temperature processes, serving both physical transformations like melting and a wide array of chemical reactions. What typifies a vessel as a crucible is not necessarily its material composition or stylistic features, but rather its functional use in such high-temperature applications, though some were originally crafted as domestic pottery. According to [8], crucibles can be classified into three categories: (i) stylistic-based attributes, including shape, size, and design features that indicate cultural origin, (ii) by the ceramic fabric from which they are made, and (iii) by their technical function in the processes they support. Conversely, a mould is essentially an assembly of components containing a cavity or impression designed to shape a plasticized material into a desired form through compaction. When a mould is intended for the repeated production of castings, particularly those with simple geometries, it is better used as a permanent mould. Permanent moulds, therefore, are generally categorized into two types: open moulds and closed moulds [9].

Moreover, nearly all iron production-based industries depend on foundry-cast products, as metal casting is essential for their production. Industries, including automobile, aerospace, heavy-duty water and dam system, and communication are particularly reliant on the foundry sector [10]. Despite the longstanding presence and practice of foundry technology in both rural and urban areas in developing countries such as Nigeria, the sector has not evolved sufficiently to significantly support the nation's technological advancement. Locally cast products often fail to meet specification and need, let alone being internationally accepted. The implication has contributed to Nigeria's continued dependence on imported goods and services [11].Several other factors have continued to hinder the growth of the foundry industry in Nigeria, despite the abundance of natural resources. These include unstable electricity supply, lack of essential tools and equipment, inadequate characterization of locally available raw materials, shortage of skilled manpower, high levels of illiteracy, and the costly importation of basic implements necessary for the efficient operation of existing furnaces. The adverse impacts of these challenges are evident in the form of low productivity, increased production costs, and job losses resulting from the closure of some industries [12].

Consequently, the production and accessibility of crucible as one of the foundry equipment still remain a great challenge to the industry, especially small and medium scale operators in Nigeria. In the alternative, the foundry practitioners have been using make shift "used-refrigerator compressor or cut-out gas cylinder" container for crucible but the refractoriness of these containers cannot be compared with that of crucible. Therefore, there is a need for the production of this essential equipment in Nigeria since the country is blessed with the required raw materials such as graphite, kaolin and petroleum coke in desired quantity and quality.

2. Materials and Method

2.1. Material

A mould should be able to withstand high pressure and must be resistance to shear, hence, the material used for the mould is mild steel because of the strength requirement. Also, mild steels have good machinability and can be sourced locally. The mould design and structural analysis was done using commercially available CAD (Computer Aided Design) Software - Solidwork. The sequence of work adopted for this research is shown in Fig. 1.

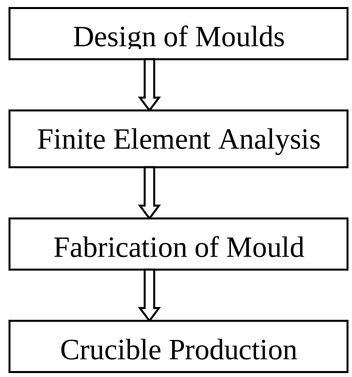

Fig. 1: Work sequence

2.2. Materials for Permanent Mould Production

According to Bhardwaj et al. [13], materials used for permanent mould castings must possess certain essential properties to ensure efficiency and durability. The study considered factors, including: (i) resilient tensile strength and machine-ability; (ii) high yield strength, stable dimensional, excellent high-temperature strength, and resistance to thermal shock; (iii) superior formability and long-term durability; and (iv) ease of machining into the desired shape.

2.3. Design and Modelling of Mould

The design and fabrication of the mould was based on the following concepts and considerations:

i. The design of the mould includes part drawings, assembly drawing and exploded drawing which was carried out using SolidWork Application Software.
ii. SolidWork application was used for 2-D and 3-D physical-solid modeling of the mould, design and stress analysis.
iii. Mould comprising female and male: the female was designed to be an assembly of two parts (that is two pieces) within which an impression of the refractory mixture is placed and then compacted. The 3D modelling showing the two halves of the female mould and modelling of male mould are, as shown in Figs. 2(a) and 2(b) respectively.

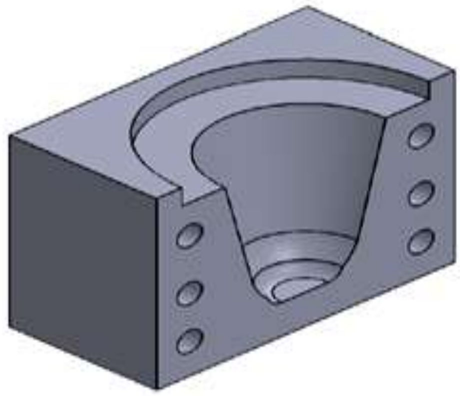

Fig. 2(a): 3D Model of a Half of the Two Piece Mould

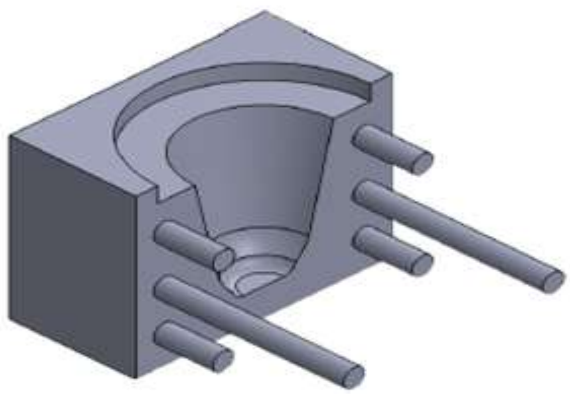

Fig. 2(b): 3D Model of the Second Half of the Two Piece Mould

2.4. Crucible Mould Design

The conceptual crucible developed in this study is a conical-shaped type as can be observed from Figs. 2(a) and 2(b), which was characterized by a top opening with a larger outer diameter that gradually tapers down to a smaller base or bottom diameter. Its side walls are designed to be straight, forming the classic conical geometry [14]. The key design parameters necessary for constructing the conical crucible mould, as illustrated in Fig 3, include: (i) the outer-diameter (D); (ii) the inner-diameter (d); (iii) the height or depth (H); and (iv) the volume (V) of the crucible.

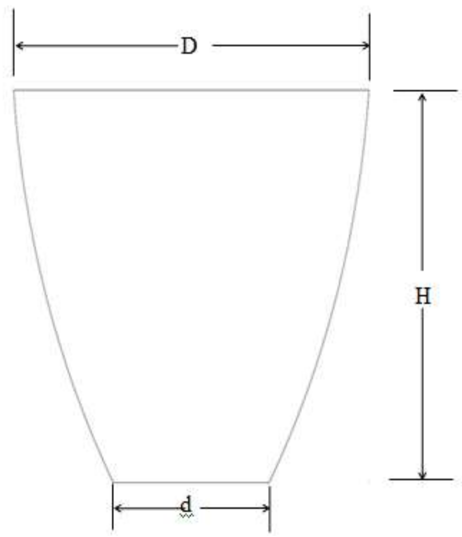

Fig. 3: Crucible Mould Design

The design parameter for the crucible can be summarized in Table 1.

Table 1**:** Design Parameters for Crucible

S/N	Dimension	Symbol	Value
1	Inner diameter	D	$0.1m^3$
2	Radius	R	$0.05m^3$
3	Height of crucible	H	$0.07m^3$
4	Volume of crucible	V	$0.00018328m^3$

Determining the appropriate mould size needed to achieve the desired crucible specifications, crucible thickness to mould size is expressed in Equation (1) as follows:

$D_d = D_m - T_c$ (1)

where D_d denotes male-mould diameter, D_m represents female-mould diameter ($0.1m^3$), T_c denotesthe crucible thickness ($0.012m^3$)

Therefore,

D_d = 0.1 – 0.012 = $0.088m^3$

The material properties for both male and female moulds are presented in Table 2 and detailed of orthographic projection of one half of the mould is shown in Fig.4.

Table 2: Material Properties of Moulds

Properties	
Name:	Alloy Steel
Default failure criterion:	Max von Mises Stress
Yield strength:	620.4MPa
Tensile strength:	723.8MPa
Elastic modulus:	210GPa
Poisson's ratio:	0.28
Mass density:	7700 kg/m^3
Shear modulus:	79GPa
Thermal expansion coefficient:	0.000013/Kelvin

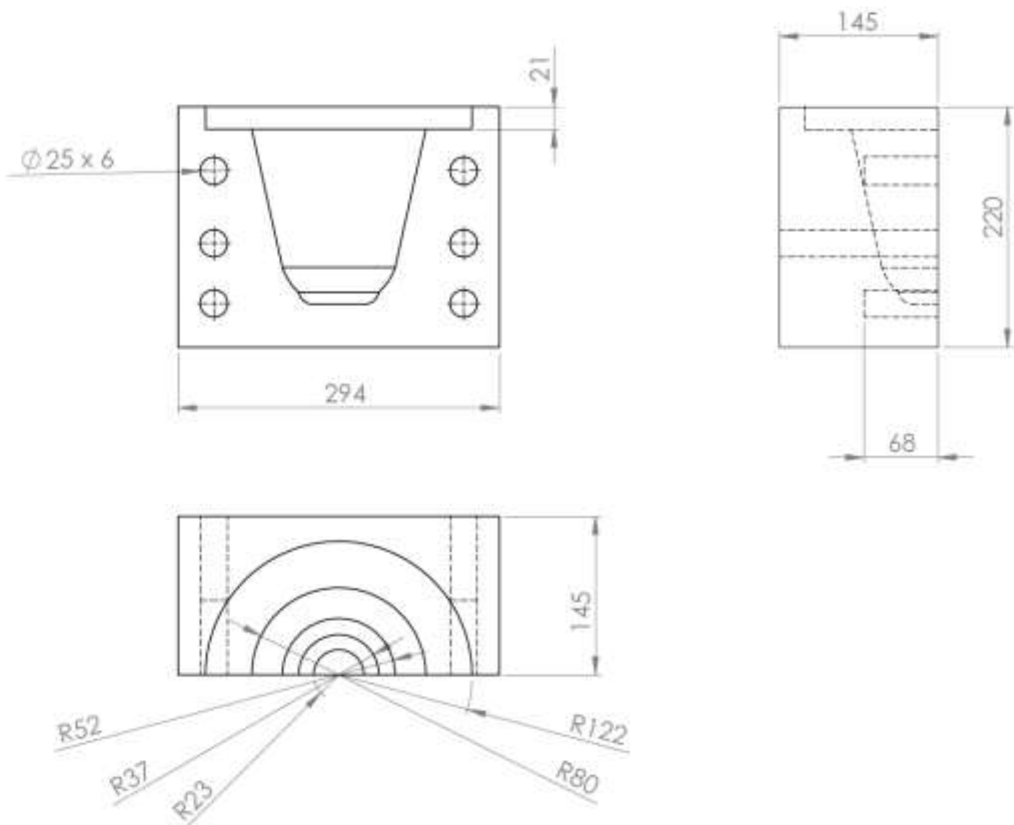

Fig. 4: Orthographic projection of one half of the female mould

2.5 Die (Male Mould)

The main area of focus while designing a die for compaction is the entrance diameter and the depth of travel. For this work, the die (Male Mould) and Female mould are both made of steel, the properties of which have been stated in Table 2; the 3-D Model and orthogonal view of the mould are shown in Figs. 5 and 6 respectively.

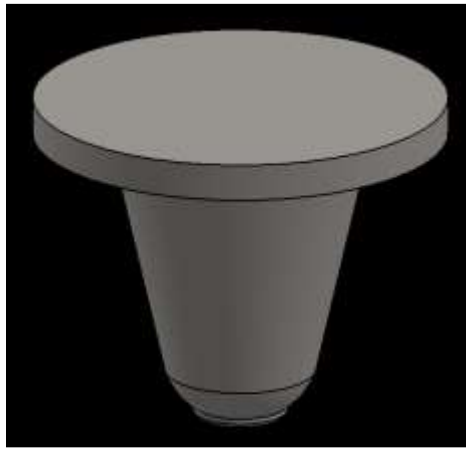

Fig 5: 3D of the Male Mould

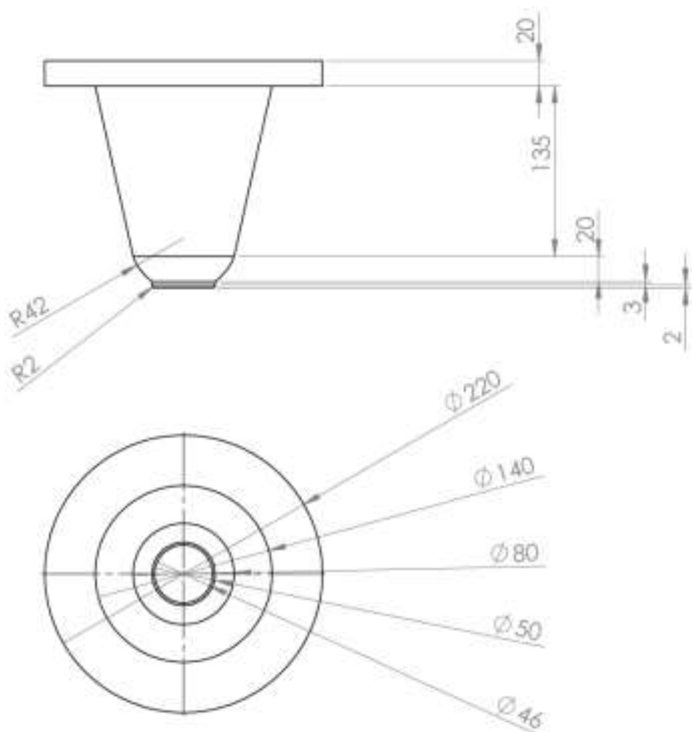

Fig 6: Orthographic Projection of the Die

2.6 Simulation and Fabrication of the Mould

In the simulation process, a notable Newton's Law as expressed in Equation (2), which governs the dynamic behavior of the system; the strain-displacement relationship in Equation (3), which links deformation to displacement; and the constitutive equation for elastic materials as Hooke's Law in Equation (4) were used. The equations define the stress-strain relationship within the material being analyzed [15].

$$\nabla.\sigma + F = \sigma \ddot{u} \quad (2)$$

$$\varepsilon = 12[\nabla u + (\nabla u)\ T] \quad (3)$$

$$\sigma = C{:}\varepsilon \quad (4)$$

where, ∇, σ, F, ρ, $\ddot{u}$, ε, u, T and C represent the nabla-operator, Cauchy-stress tensor, the applied force, body/mass-density, second-derivative of the displacement with time, strain-tensor, displacement vector, a transpose, and stiffness-tensor, respectively.

Moreover, the mould underwent simulation using SolidWorks 2018, where a load of 50,000 N was applied to mimic the pressing force. Mild steel was chosen as the base material for the mould. Prior to simulation, the male and female components were discretized, and a solid mesh configuration was applied, yielding 58,749 elements for the female and 43,987 elements for the male component, as shown in Fig. 7. The simulation process aimed to assess key parameters such as Von Mises stress, displacement, strain, and safety factor for both parts [15]. Upon completion of the simulation, the mould was successfully fabricated, as illustrated in Fig. 8.

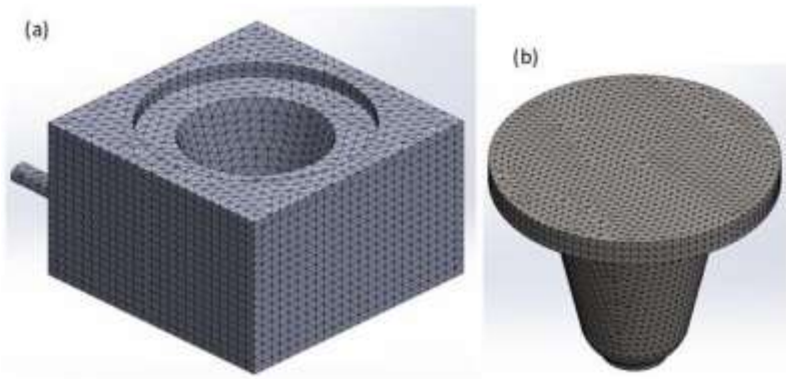

Fig 7: Mesh design of the mould in (a) female mould, in (b) male mould

Fig 8(a): Female Mould

Fig 8(b): Male Mould

3. Results and Discussion

3.1 Simulation Results

4 The maximum stress recorded on the inner surface and flange area of the mould was 53.96 MPa, as depicted in Fig. 9. Corresponding maximum displacement and strain values were 0.007860 mm and 0.0002012, respectively, as shown in Fig. 10, with a calculated factor of safety of 11. Given the yield strength of mild steel is 620.4 MPa, the finding revealed that the mould is structurally safe under operational conditions. The maximum stress as observed is significantly below the material's yield limit, the factor of safety exceeds 1, and both displacement and strain are minimal, which confirm the reliability and integrity of the design.

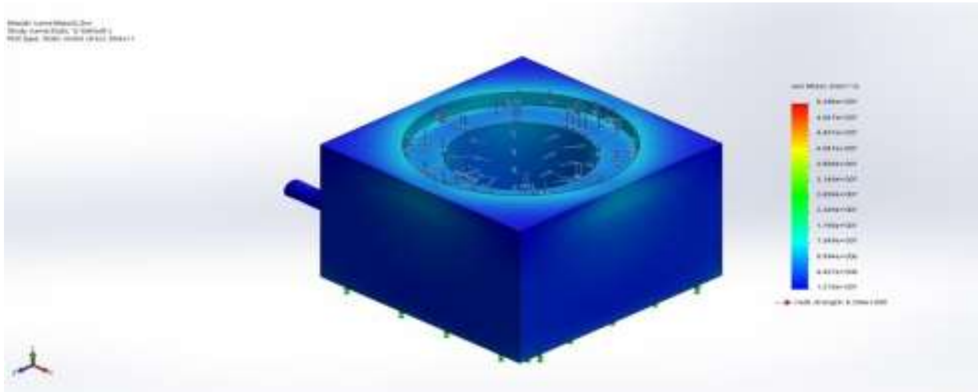

Fig 9: Stress Distribution on Female Mould

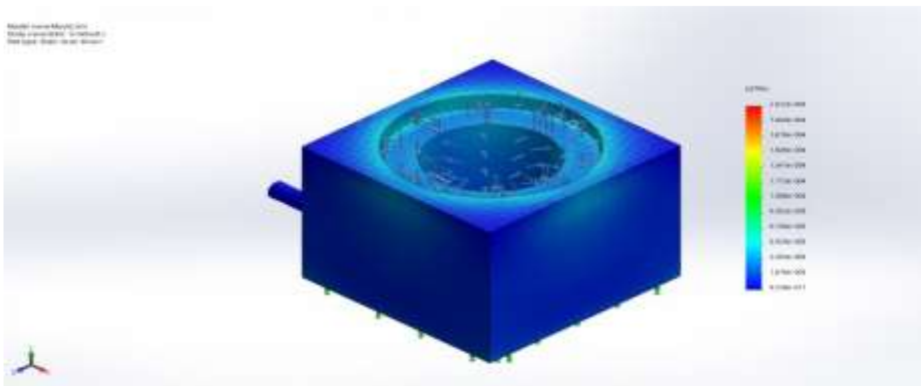

Fig 10: Maximum Strain Distribution on Female Mould

Furthermore, the stress distribution in the male mould, which was fabricated using alloy steel obtained a yield strength of 620.4 MPa. The mould recorded a maximum-stress of 67.34 MPa, while its corresponding maximum displacement and strain were 0.01352 mm and 0.0002428, respectively, as shown in Fig. 12. The factor of safety was calculated to be 9.2. These results and the finding thereof, confirm that the mould is structurally sound for operational use. It was observed that the maximum stress remains well below the material's yield strength, the factor of safety is significantly above 1, and both displacement and strain are negligible.

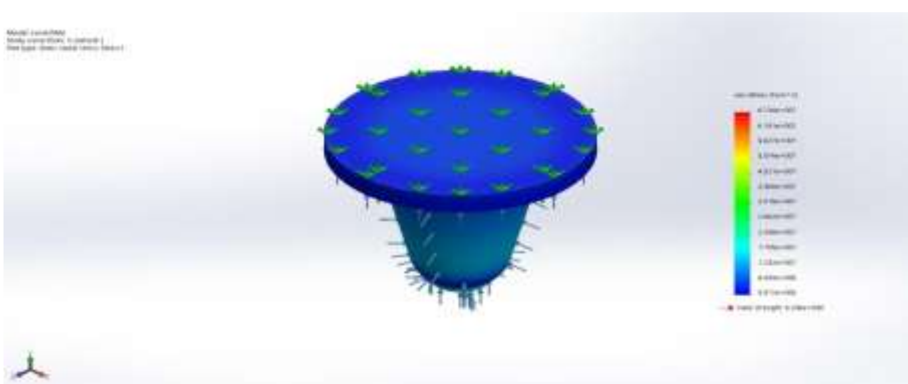

Fig 11: Stress Distribution on Male Mould

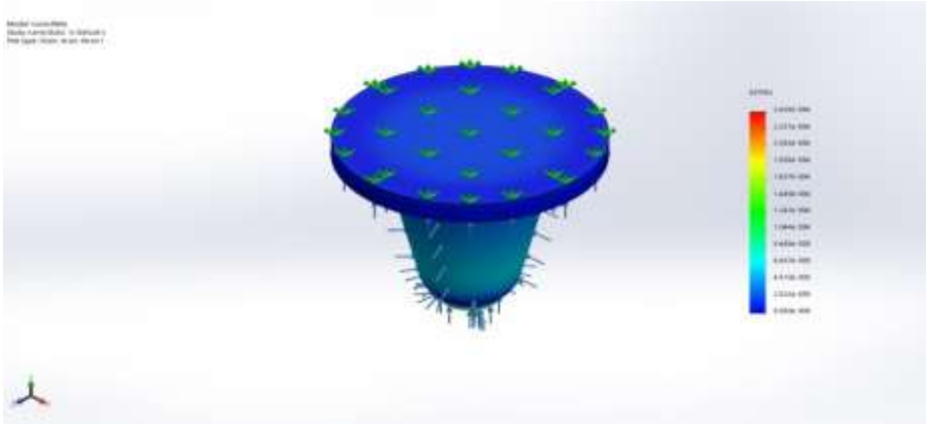

Fig 12: Maximum Strain Distribution

4.1 Performance Evaluation of the Developed Mould

The clay used for the evaluation of the mould was sourced from Kajuru Local Government of Kaduna State. It was sieved at Civil Engineering Laboratory of Federal University of Technology Akure using four different sizes of sieve comprising 4.75mm, 2.36 mm, 1.7 mm, and 0.6 mm, respectively. It was observed that as the grain size of the clay particles decreases, the pressure for compaction also decreases. For sieve sizes of 4.75 and 2.36 mm, the pressure remains at 100 bar while for the sieve sizes of 1.7 and 0.6 mm, the pressure drops to 90 bar.

Using visual inspection, it was revealed that the smoothness of the surface finish of the produced crucibles improved as the sieve size decreased, as depicted in Figs. 13 and 14. The mould having been subjected to a 5-ton load using a hydraulic press to compact the clay, the results demonstrated satisfactory performance. It successfully formed crucibles from clay of varying sieve sizes at a maximum applied pressure of 100 bar. Observing the resulting crucibles, shown in Figs 13 and 14, influence of using different sieve sizes and compaction pressures are well notable.

Fig 13: Crucible Produced at Pressure of 90 bar and Sieve Size 0.6 and 1.70 mm respectively

Fig 14: Crucible Produced at Pressure of 100 bar and Sieve Size 4.76 and 2.36 mm respectively

4. Conclusion

The role of crucible as one of the main foundry equipment used for melting metals cannot be overemphasized. Consequently, accessing this equipment in Nigeria has been a serious challenge to small and medium scale foundry operators. This is as a result of unavailability of locally produced crucibles and incapability of some of the foundry operators to import it due to high cost. The developed mould in this work performed optimally well by withstanding the applied force of 100 bar and can therefore be used for mass production of crucible. It is, therefore, recommended that the mould in this paper be produced on a commercial scale to ensure accessibility for foundry operators, thereby increasing the availability of crucibles for casting applications. The initiative would further support the production of crucibles tailored to the needs of small- and medium-scale industries in developing countries like Nigeria. Additionally, the mould fabrication has been demonstrated in a user-friendly approach, which requires minimal maintenance when produced and can compete favourably with imported designs.

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