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Applying Powder Technology to Improve the Performance of Copper Alloys used in HVAC Pipe Underground

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Abstract: The use of powder technology to enhance the performance of copper alloys in underground HVAC pipes. Powder technology, which includes processes like powder metallurgy and nanomaterial integration, allows for precise customization of copper alloys to meet specific requirements for subterranean HVAC systems. This research aims to develop more durable, long-lasting materials that ensure the reliability and effectiveness of subterranean HVAC pipes, offering insight into the cutting-edge methodology influencing the direction of subsurface HVAC systems. A pipe design with a diameter of 1in and a length of 500 mm was cast from copper powder materials, Cu and CuNiSiCr, to determine the differences in results. Three underground depths and powder thicknesses were used for pressure and powder thickness, with varying results for each depth. The depth of an underground pipe affects vertical force, stresses, and deformations in Cu powder. The deformation value increases with depth, reaching 0.57 mm at 3 meters. The stress increases with depth, reaching 0.54 MPa. The quality of CuNiSiCr powder improves with changes in powder quality, with deformation decreasing to 0.05 mm at 1 meter depth. Increasing copper powder tube thickness improves mechanical stress, with stresses nearly nonexistent at 3 mm thickness.

Keywords: powder technology, copper alloys, performance, HVAC pipe, enhance.

1. Introduction

HVAC systems face increasing demand, particularly in subsurface applications, where pipes face challenges such as changing temperatures, caustic soils, and mechanical stress. Powder technology, which includes processes like powder metallurgy and nanomaterial integration, has emerged as a potential approach to improve the performance of copper alloys in these systems. Copper alloys are known for their thermal conductivity, resistance to corrosion, and intrinsic durability, making them ideal for HVAC applications. However, a significant advance in material technology is needed to meet the changing needs of contemporary subsurface systems. Powder technology aims to rejuvenate common copper alloys and turn them into cutting-edge materials with specific properties, fine-tuning essential properties such as mechanical strength, thermal conductivity, corrosion resistance, and longevity while ensuring compatibility with the demanding conditions of underground HVAC systems. This investigation will explore the methods, procedures, and innovations of powder technology, aiming to advance material science and prepare for more effective, sustainable, and robust HVAC systems.

(Deepanraj et al., 2023) [1] Explored the interaction of copper and zinc in the production of brass, a glossy alloy with unique electrical and mechanical properties. The aim is to understand the powder metallurgy process and improve brass's qualities, focusing on creating and refining specimens under specific conditions, characterizing their mechanical hardness and microstructure, and contrasting these characteristics with the given circumstances. (Varol et al., 2021) [2] Presented a comprehensive analysis of innovative Cu-Ag alloys reinforced with silver coated copper particles. The research reveals that the silver coating affects microstructure, density, hardness, tensile strength, and oxidation resistance. The 100% Cu-Ag alloy has a denser microstructure, higher tensile strength, higher electrical conductivity, and 31% greater oxidation resistance compared to pure Cu samples. (Jadhav et al., 2020) [3] Laser-based additive manufacturing (L-AM) requires high laser power due to high optical reflectivity of reflective metals. A new commercially viable powder surface modification technique on CuCr1 alloy uses chromium diffusion to double optical absorbance, requiring only 20% of the laser energy needed for virgin CuCr1 powder. The modified components have high thermal conductivity and tensile strength. (Karnati et al., 2019) [4] Explored the feasibility of synthesizing copper-nickel alloys using laser metal deposition and mixed powder feedstocks. It found that elemental nickel powder has high gas and shrinkage porosity, making it a poor replacement. Delero-22, a high nickel alloy, was found to be an effective replacement. The alloys were characterized using various tests, including mini-tensile testing, X-ray spectroscopy, Vickers hardness testing, X-ray diffraction, and scanning electron microscopy. The study found that copper concentration improved the material's strength and ductility.

(Tiberto et al., 2019) [5] Explored the challenges of using laser-based additive manufacturing for producing parts with acceptable surface quality and minimal porosity in copper alloys. It examines the impact of alloy composition, powder size, and process parameters on the surface tension, reflectivity, thermal conductivity, melting range, and surface tension. (Wagih and Fathy, 2017) [6] Focused on creating Cu-Al_2O_3 nanocomposite with different Al_2O_3 contents using dry mixing, mechanical alloying, and mechanochemical procedures. The results show that mechanical alloying and dry mixing can create composites with large reinforcement particle sizes and low content, while mechanochemical methods can create high reinforcement weight fractions. The study suggests that enhancing the mechanical and physical qualities of the composites can improve their hardness. (Li et al., 2014) [7] High-strength and high-conductivity copper alloys possess exceptional mechanical and physical properties. They are used in various applications, including lead frame, electrified contact wires, and electrodes. Alumina dispersion enhanced copper alloy is being launched, and in-depth analyses are conducted.

(Madavali et al., 2014) [8] Examined the coarsening behavior of copper nanopowders during mechanical milling in argon and air atmospheres. After 80 hours, particle size ranged from 7 to 80 m in an air environment, while in an argon environment, it remained 7 to 35 m. Oxygen concentration increased with milling duration, creating oxide layers that affected particle size and microstructure. The differences in microstructure and sizes were explained satisfactorily. (RuŽić et al., 2013) [9] Explored the impact of powder metallurgy techniques and dispersoids creation on the strength and hardening of copper and copper alloy matrix. Materials used include mechanically alloyed Cu-Ti-TiB_2 powders, which were combined using hot isostatic pressing and hot pressing. Thermal aging significantly strengthened the compacts due to the formation of a modular structure and the precipitation of metastable Cu_4Ti(m). The study found that Cu-TiB_2 compacts have high initial and high-temperature hardness due to finely dispersed TiB_2 particles. (Imai et al., 2010) [10] Aimed to create lead-free, machinable brass using powder metallurgy and graphite particles. The weight of brass powder decreased with higher heat treatment temperatures, but zinc evaporation was not observed in spark plasma sintering. The machinability of P/M extruded brass alloys with 1% graphite particles improved significantly compared to traditional brass alloys with lead. (Goryczka and Van Humbeeck, 2008) [11] aimed to determine sintering parameters for producing a Ni(50-X)Ti50CuX alloy using powder technology. Sintering duration and temperature were selected, and microstructure, structure, chemical content, and thermal behavior were examined. Results showed that sintered alloys had non-transformable phases, Ti2(Ni,Cu) and (Ni,Cu)3Ti, with reversible martensitic transitions. These findings enabled the manufacture of NiTiCu shape memory alloy, optimizing sintering conditions.

(Müller and Zauter, 2003) [12] Spray forming is a recent technique for producing metal semi-finished goods, converting a melt into a solid state and creating a compact preform. It offers the advantage of manufacturing materials that cannot be cast or require significant segregation, such as high-tin bronzes and aluminum bronzes. (Da Costa et al., 2003) [13] Explored the impact of dispersion method on the sintering behavior of W-Cu composites. It reveals that the sinterability of W-Cu powders is primarily influenced by the fineness of the tungsten phase and the dispersion of the copper phase. High energy milling can create composite particles with ideal Cu dispersion, enhancing sinterability. (Mowbray, 1986) [14] Discussed the origins and manufacturing techniques of copper powder, highlighting three primary methods and their properties. It explores technical and financial changes to atomized powders, manufacturing, powder characterization, and use of copper alloys. It also analyzes the economic impact of replacing copper powders with cheaper alternatives.

2. Methodology

Copper alloys are a popular material for subterranean HVAC pipelines due to their superior thermal conductivity, resistance to corrosion, and durability. However, as the demand for reliable and long-lasting HVAC systems increases, the performance of copper alloys in these applications needs improvement. Powder technology, which uses processes like powder metallurgy and nano-powder enhancement, can be used to improve the properties of these alloys. By incorporating tiny metal powders or nanoparticles into the structure of standard copper alloys, this technology can maximize mechanical strength, thermal conductivity, corrosion resistance, and lifespan. The main goals of using powder technology on copper alloys for HVAC pipes include enhanced corrosion resistance, improved thermal conductivity, increased tensile strength and fatigue resistance, improved formability and weld ability, and a reduction in environmental impact. This research will explore various methods and procedures used to use powder technology on copper alloys, as well as the advantages and challenges of doing so.

Where a pipe design with a diameter of 1in and a length of 500 mm was cast from two copper powder materials, where Cu and CuNiSiCr were used, and to know the difference in the results that would be obtained [5].

Hexahedron grids were used in this study because they are often effective for complex geometries. Users of ANSYS only need to enter data once to create a mesh for a solid geometry or 3D model. A total of (2766420) cells were gathered for this study; for details, see Figure 1.

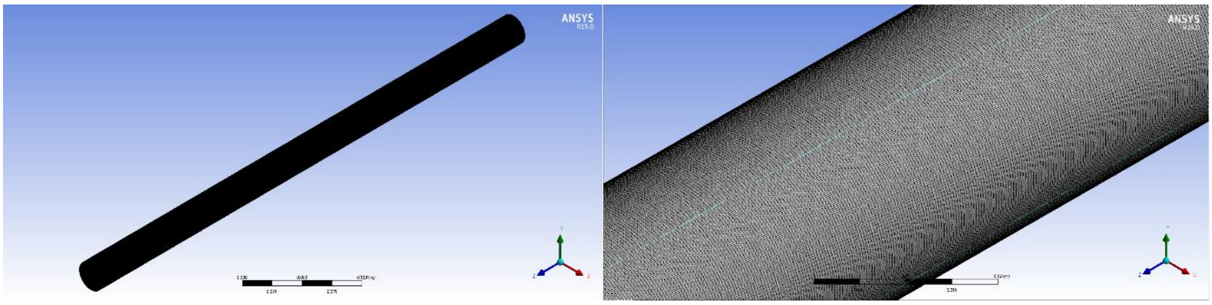


Figure 1. *Mesh generated.*

An accurate model must be created in order to solve the equations because the simulation process relies on complicated algorithms to work through the matrices present in the domain. After then, use the mesh's dependability to find a solution and get the findings to a stable condition. It is important to create more than one mesh and more than one mesh reliability because to the variety of models that have been simulated. The element's value was 2766420 when the maximum deformation, as shown in Table 1, reached 0.19 mm.

Table 1. *Mesh independency.*

Case	Element	Node	Max deformation (mm)
1	1734564	6239423	0.53
2	2064786	8034632	0.25
3	2312556	10463664	0.20
4	2766420	12677759	0.19

Three underground depths were used for the amount of pressure on the pipe: 1 meter underground, once 2, and once 3 meters underground. Three thicknesses of powder were also used: 1 mm, 2 mm, and 3 mm, as in Figure 2.

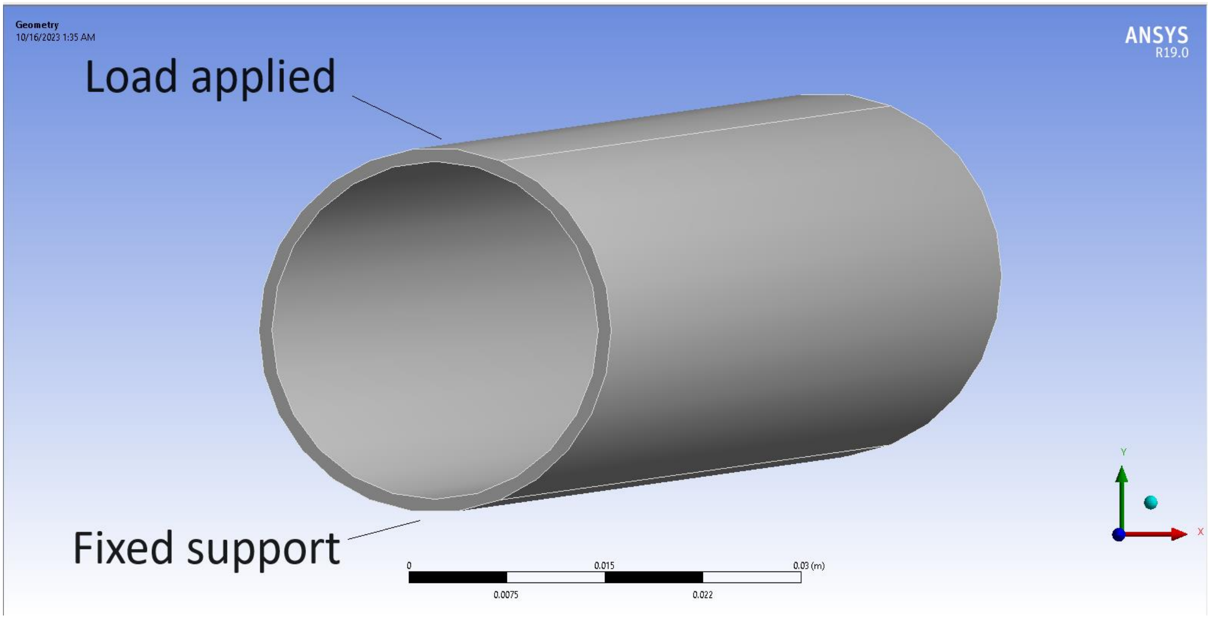


Figure 2. *Boundary condition.*

In ANSYS, static structural analysis solves for the equilibrium of a structure under applied loads. The primary equation for static structural analysis is based on the principles of linear elasticity and equilibrium, and it can be expressed as follows:

$$\nabla \cdot \sigma + \mathrm{F} = 0 \tag{1}$$

Where:

σ represents the stress tensor. $\nabla \cdot \sigma$ is the divergence of the stress tensor, which accounts for the change in stress within the structure. F represents the applied external forces and boundary conditions. The goal of this equation is to ensure that the structure is in a state of static equilibrium, meaning that the sum of forces and moments acting on the structure is zero. In this equation, σ and F are further broken down into components along each spatial direction (e.g., x, y, z), resulting in a set of equations for each direction. For a three-dimensional problem, this leads to three equilibrium equations for forces and three for moments in each element or node of the finite element model. These equations are then solved using the finite element method, which divides the structure into discrete elements and iteratively calculates the displacements, strains, and stresses within each element.

Hooke's Law (Stress-Strain Relationship):

$$\sigma = E\varepsilon \tag{2}$$

σ is the stress tensor.

E is the Young's Modulus, which characterizes the material's stiffness.

ε is the strain tensor.

Strain-Displacement Relationship:

$$\varepsilon = \nabla u \tag{3}$$

ε is the strain tensor.

∇ represents the gradient operator.

u is the displacement vector.

Global Displacement-Force Equations:

The global displacement vector (u) and the global nodal force vector (F) can be represented as:

$$\mathrm{F} = [K]\mathrm{u} \tag{4}$$

F is the global nodal force vector.

u is the global displacement vector.

$[K]$ is the global stiffness matrix assembled from the individual element stiffness matrices.

The Von Mises stress is often used to assess yielding and failure in materials under multiaxial stress. It is based on the concept of equivalent stress and can be expressed as:

$$\sigma_{\mathrm{VM}} = \sqrt{\frac{3}{2}\sigma^2 + 3\tau^2} \tag{5}$$

σ_{VM} is the Von Mises equivalent stress.

σ represents the normal stress components.

τ represents the shear stress components.

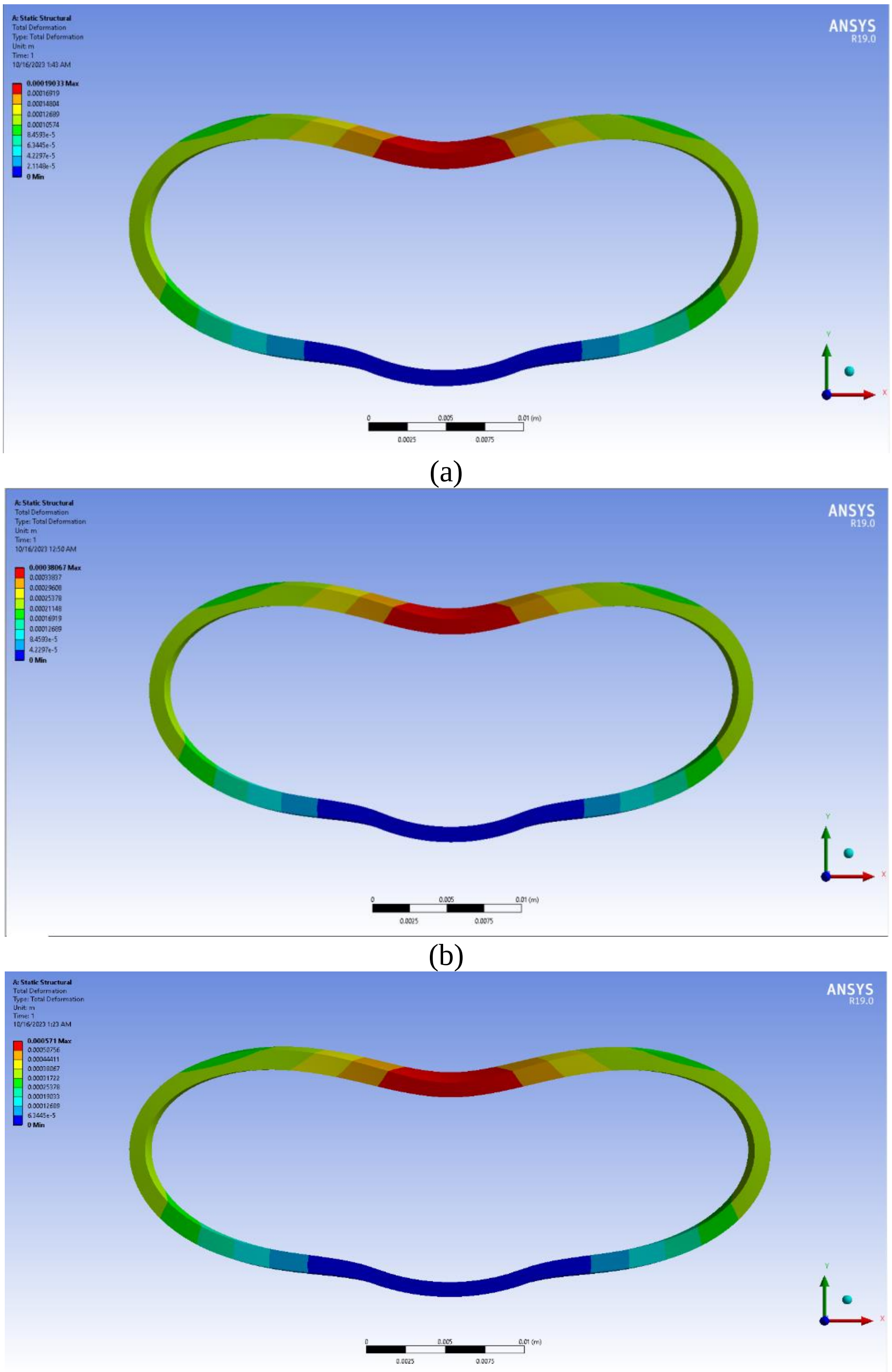
3. Results and discussion

In this section, all the results obtained through the simulation program will be reviewed with the change in pouring type of copper powder and the difference in dimensions, as well as the depth of the tube.

3.1 The effect of pipe depth on stresses

The subterranean installation depth of HVAC pipes significantly impacts the strains they endure. The external pressure exerted by the earth above pipes at shallow depths is modest, causing radial stress. Higher axial and radial strains are placed on the pipe due to the growth of external pressure. Thermal strains are more likely to occur at shallow depths due to temperature changes, while deeper pipes are exposed to constant temperatures. Soil qualities also affect the load distribution on the pipe at shallow depths. Deeper pipelines often face more uniform and compacted soil conditions, leading to even loading. Groundwater effects can also affect the pipe's stresses at shallow depths.

Figure 3 shows the effect of the depth of the underground pipe on the force applied vertically to it and the amount of stresses and resulting deformations. It is noted that the greater the depth of the underground pipe, the greater the deformation value on the quality of the powder, Cu, as it reached 0.57 mm at a depth of 3 meters.



(a)

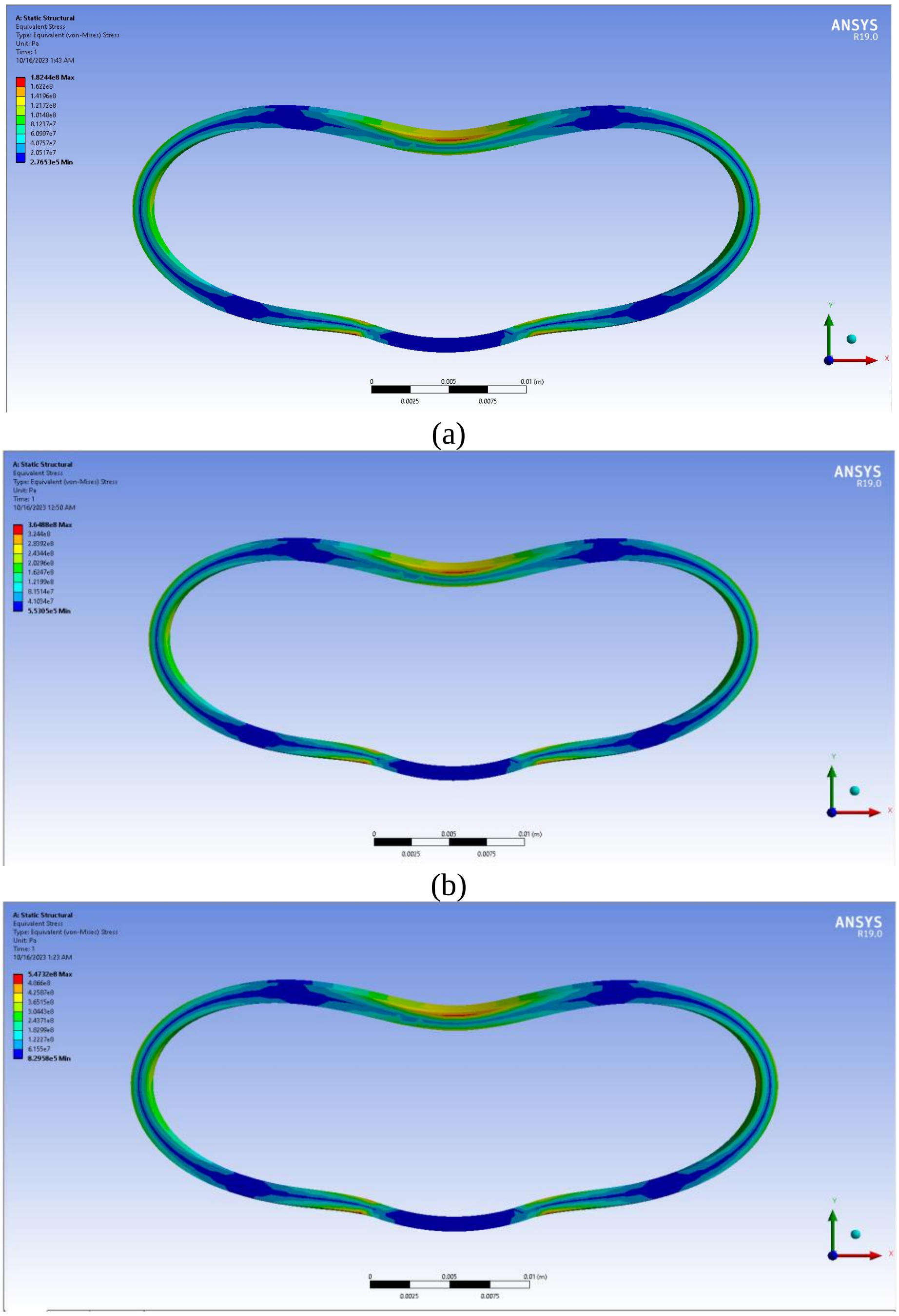
(b)

(c)

Figure 3. *Deformation contour of Cu powder at different depth of ground. (a) 1m, (b) 2m, (c) 3m.*

Powder technology can improve the performance of copper alloys used in HVAC pipes installed at varying depths. It can create composite materials by incorporating reinforcing nanoparticles into the copper alloy matrix, enhancing the material's strength and resistance to stresses. Corrosion-resistant powder materials provide a protective layer to shield the copper alloy from aggressive soil conditions, ensuring pipe longevity. Thermal conductivity is improved by incorporating thermally conductive powders, ensuring efficient heat transfer in the HVAC system. Finally, strengthening powders can enhance the mechanical properties of copper alloys, making them more resilient to stresses imposed by varying depths and soil conditions.

Figure 4 represents the amount of stresses generated as a result of the increase in depth, as the amount of stresses increases as the depth increases, reaching 0.54 MPa at a depth of 3 meters in the type of powder pouring Cu.



(a)

(b)

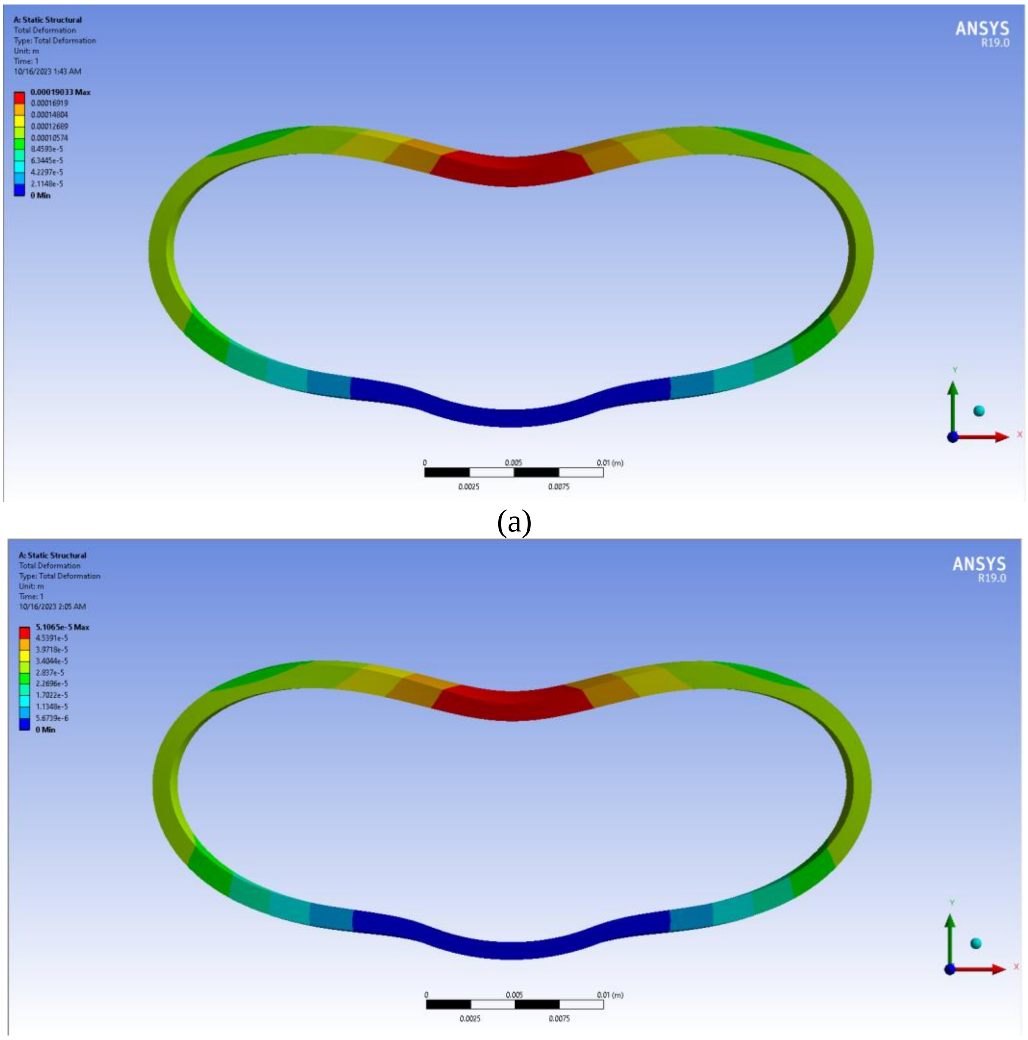
(c)

Figure 4. *Stress contour of Cu powder at different depth of ground. (a) 1m, (b) 2m, (c) 3m.*

3.2 The effect of powder type

The choice of powder type in powder metallurgy and materials science significantly impacts the properties and performance of materials, including copper alloys used in underground HVAC pipes. Strength and robustness are enhanced by reinforcing powders, such as carbide or nitrides, which improve the material's resistance to pressures. Thermally conductive powders, like aluminum or copper nanoparticles, enhance heat transfer, ensuring effective heat transmission even in subterranean installations. Corrosion-resistant powders protect copper alloys from soil corrosive effects. Formability and ductility are affected by the powder type and processing conditions, affecting the material's ductility and formability. Electrical conductivity is crucial in certain HVAC applications, and powders can affect it.

In changing the quality of the powder material, we notice a clear improvement in the quality of CuNiSiCr powder, and this is shown in Figure 5, which shows the amount of deformation reduced to 0.05 mm, which is the best condition reached at a depth of 1 meter.



(a)

(b)

Figure 5. *Deformation contour of at different of powder type. (a) Cu, (b) CuNiSiCr.*

Lightweight powders can be employed when lower weight is desired. The size and distribution of powder particles also affect the material's properties. Environmental considerations, such as meeting environmental or regulatory standards, can influence the choice of powder type. Cost and availability also influence material selection. In the context of underground HVAC pipes, selecting the powder type that aligns with the specific performance requirements is essential. Proper material engineering and testing are often necessary to determine the most suitable powder type for the desired properties and performance. Figure 6 shows the stresses generated because of changing the quality of the powder, where the value of the stresses reached 0.1824 MPa.

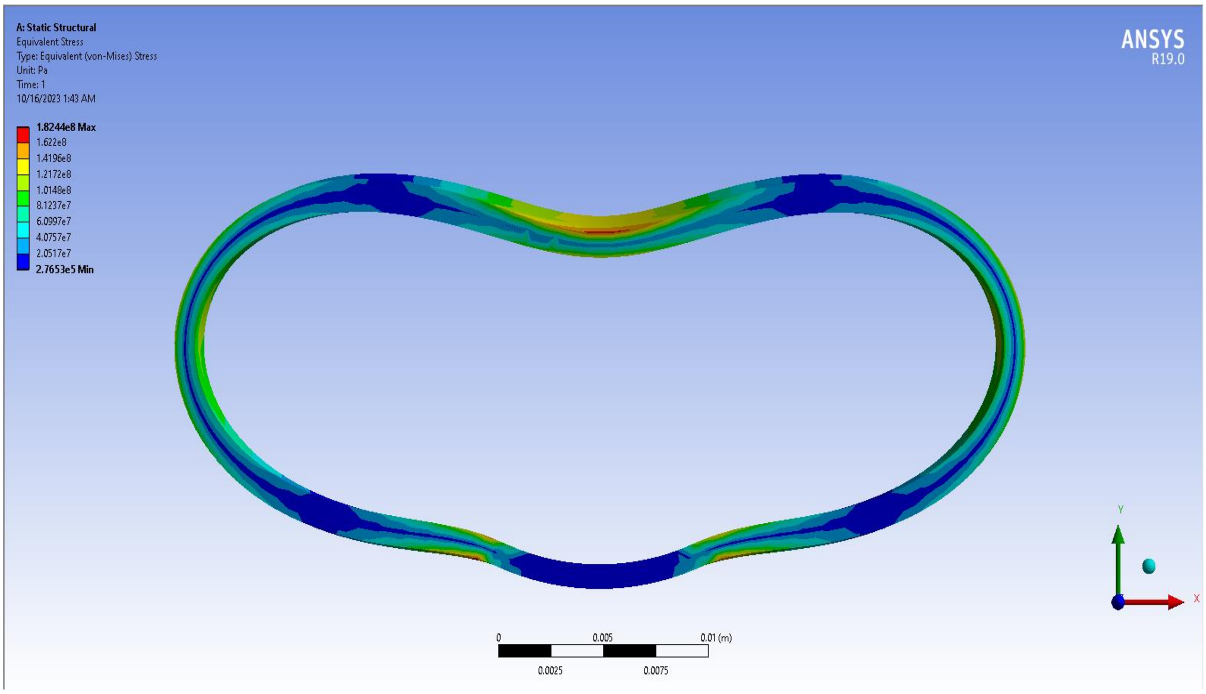
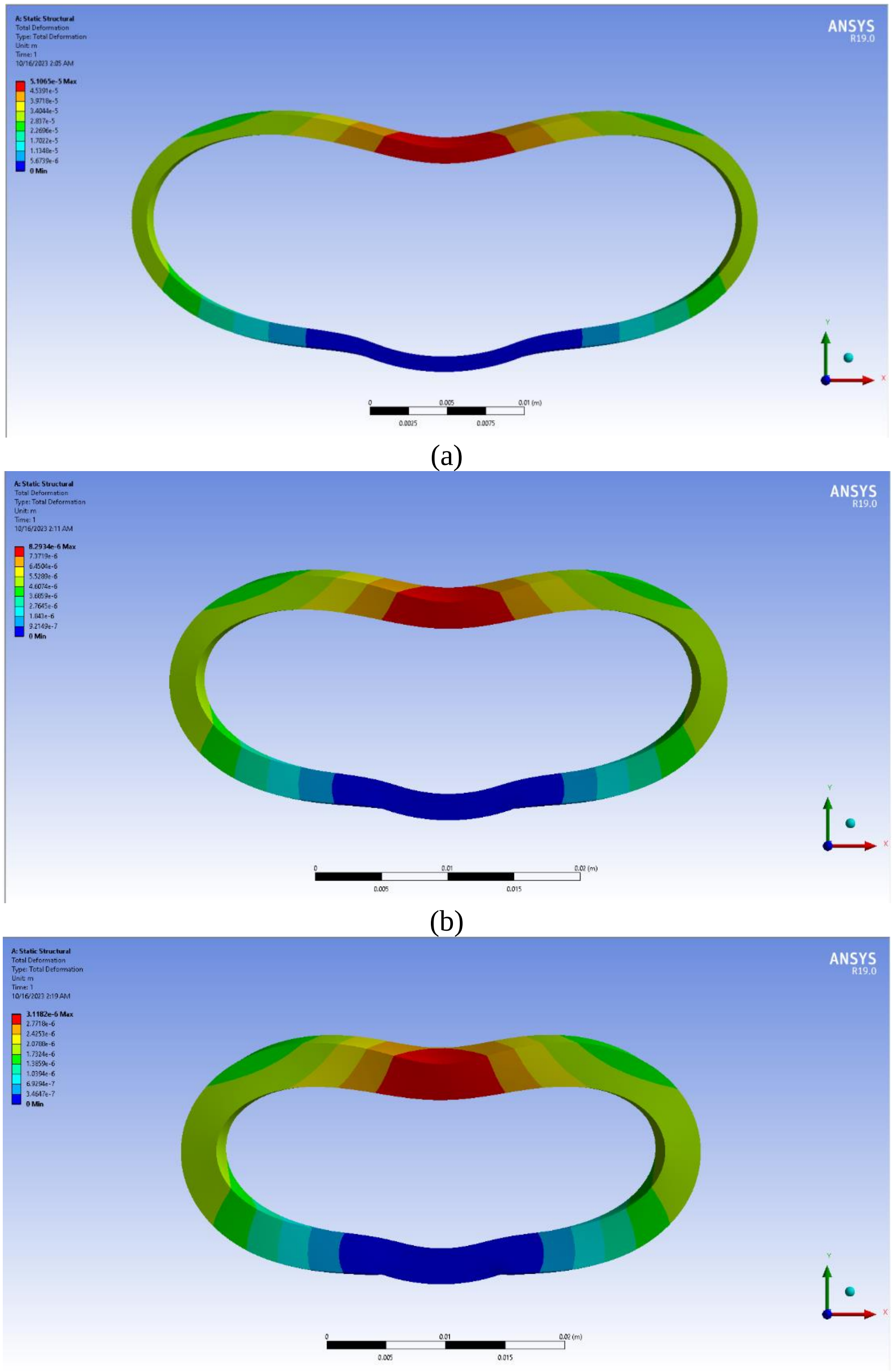


Figure 6. *Stress contour of at different of powder type.*

3.3 The effect of pipe thickness

The performance and behavior of subsurface HVAC systems are significantly influenced by the pipe thickness used. Thicker pipes have more stiffness and structural strength, making them more resilient to external pressures and mechanical stresses. They also have greater suspension resistance, making them more resistant to buckling. They also provide better corrosion protection with thick protective coatings, increasing the service life of the pipe. Thicker pipes also have different thermal properties, such as lower heat uptake or loss, and can affect fluid transportation. They also provide greater insulation capacity, which is crucial in applications sensitive to temperature.

Increasing the thickness of the copper powder tube has the ability to improve the mechanical stress in relation to the stresses, as it can be seen from Figure 7, which shows the difference in the thickness of the copper powder, that the amount of stresses was reduced to 0.003 mm, meaning they are almost non-existent at a thickness of 3 mm, which is the best condition that has been achieved.



(a)

(b)

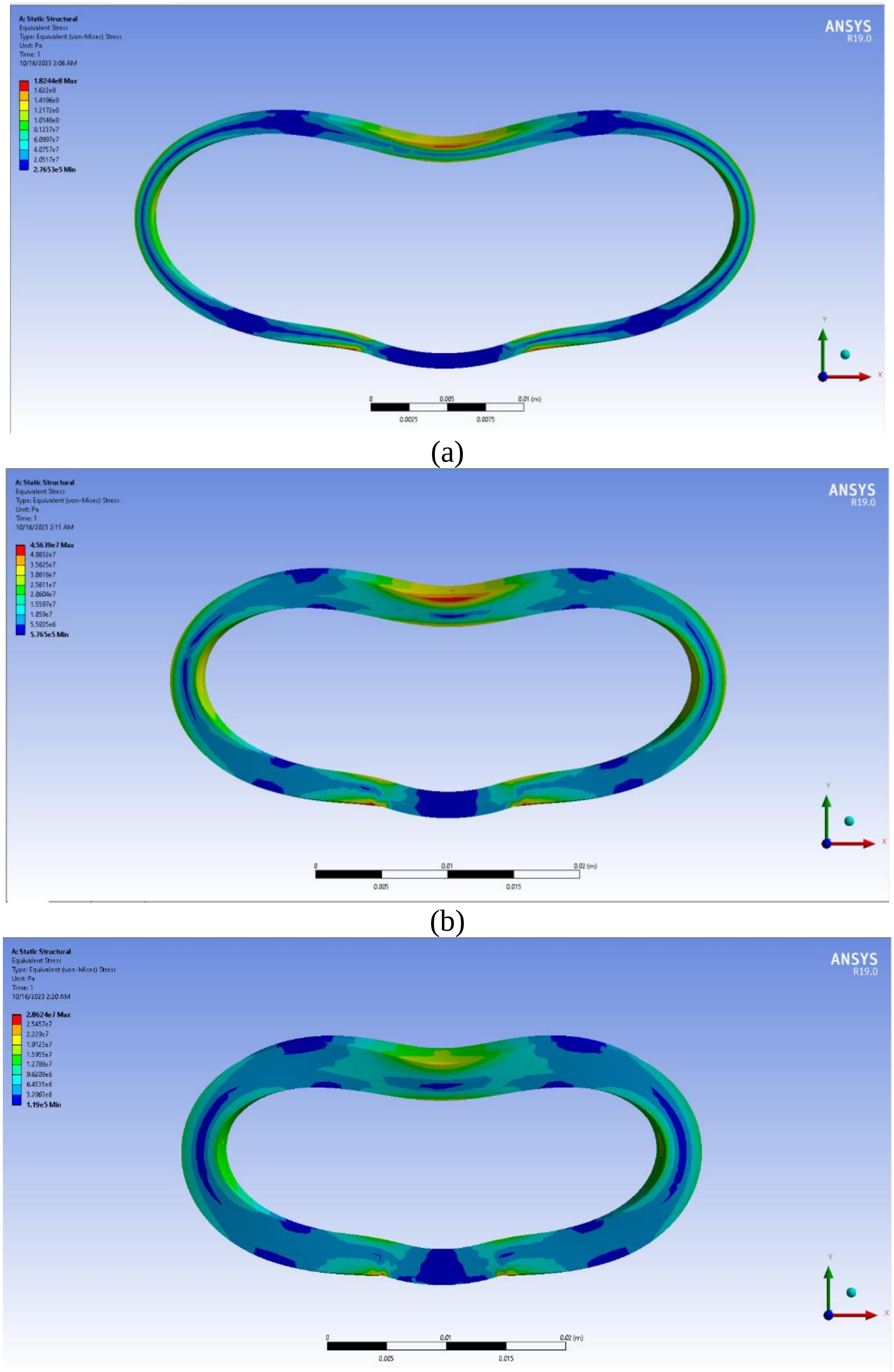
(c)

Figure 7. *Deformation contour of CuNiSiCr powder at different pipe thickness. (a) 1mm, (b) 2mm, (c) 3mm.*

Handling and weight of thicker pipes can be more difficult due to the need for equipment and manpower. Costs may be affected by the need for more material, but the potential savings from increased performance and lifespan may outweigh this expense. Space restrictions may also affect the choice of pipe thickness. Industry codes and standards may regulate the thickness of pipes, and environmental considerations may also impact the choice. The selection of the appropriate pipe thickness should consider the specific requirements of the HVAC system, such as installation depth, soil type, temperature conditions, and desired performance characteristics.

Proper engineering and analysis, often involving structural and thermal simulations, can help determine the ideal thickness for a given application.

Also, as for the stresses, they decreased significantly, and this is shown in Figure 8, where the value of the stresses reached 0.028 MPa at a thickness of 3 mm, which is the best condition that was achieved.



(a)

(b)

(c)

Figure 8. *Stress contour of CuNiSiCr powder at different pipe thickness. (a) 1mm, (b) 2mm, (c) 3mm.*

4. Conclusion

To compare the variations in performance, a pipe design with a diameter of 1 in and a length of 500 mm was cast from copper powder materials, Cu and CuNiSiCr. Pressure and powder thickness were measured at three different subsurface depths, with variable findings for each level.

1. The impact of the underground pipe's depth on the force exerted vertically, the quantity of stresses, and the degree of deformations that follow. It should be mentioned that the deformation value on the quality of the powder, Cu, increased with the depth of the underground pipe, reaching 0.57 mm at a depth of 3 meters. the rise in stresses caused by increasing depth, with the amount of strains reaching 0.54 MPa at a depth of 3 meters in the kind of powder pouring Cu.
2. The quality of CuNiSiCr powder has improved noticeably as the powder quality has changed; the quantity of deformation has decreased to 0.05 mm, which is the optimum condition at a depth of 1 meter. the tensions produced as a result of altering the powder's quality, where the value of the stresses reached 0.1824 MPa.
3. The mechanical stress in relation to the stresses can be improved by increasing the thickness of the copper powder tube. At a thickness of 3 mm, which is the best condition that has been attained, the amount of stresses was reduced to 0.003 mm, meaning they are almost nonexistent. The stresses greatly fell as well, with the ideal condition being attained at a thickness of 3 mm when the value of the stresses approached 0.028 MPa.

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