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RESEARCH ARTICLE

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Additive manufacturing technology in mining engineering research

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Abstract

Nowadays, additive manufacturing, or 3D printing (3DP), though not a new technology in many industrial fields, is still relatively novel in mining engineering. This study explored the application of 3D metal printing, 3D polylactic acid/acrylonitrile butadiene styrene printing, and 3D concrete printing in coal mining. Some examples of physical models established via 3DP technologies were studied in detail, namely, 3DP bolts, 3DP steel ladder beams, 3DP face plates, and 3DP metal arches, which were installed in scaled 3DP concrete prototype models of coal mine excavation. Through the comprehensive laboratory loading tests, the models could simulate the damage scenario highly similar to the real failures. The results show that the 3D printed physical models greatly improved the accuracy and reliability of experiments. On this basis, the conceptual design of a 3DP machine for physical models was proposed, which had the potential of resembling the strata deformation/collapse in natural scenarios. Through assessing the applicability of the additive manufacturing technology in mining engineering, this study aimed to further explore its potential applicability in other engineering contexts such as slope controlling, large underground engineering, and underground space stability.

KEYWORDS

3D printing system, additive manufacturing, coal mine supports, mining engineering, physical model

1 | INTRODUCTION

In the past few years, several advanced research methods, such as intelligent mining, unmanned mining (G. Wang et al., 2022), remote mining, and even machine learning (Duan et al., 2021) have been widely adopted in research on mining engineering. This demonstrates that the knowledge advancement in mining engineering needs new tools and new methods so as to ultimately enhance the resources exploration.

Additive Manufacturing (AM), a.k.a. 3D printing (3DP), is defined as a "process of joining materials to make parts from 3D model data, usually layer upon layer" (Standardization IOF, 2015). It is an alternative to conventional manufacturing processes (Paolini et al., 2019). AM can be adapted to print several materials, for example, some polymers, steel powder, gypsum, and so forth. This technology has been extensively exploited in recent years and its application in rock/civil engineering is still worth further investigating (C. Jiang & Zhao, 2015).

The introduction of 3DP technology in large-scale physical model tests can solve some puzzling geotechnical and geomechanical issues, and also realize complex geological structures (Feng et al., 2019). In geotechnical engineering, many 3DP solutions are highly recommendable, such as 3D printed transparent granular soil (Y. Li et al., 2021), 3D printed small model geogrids (Stathas et al., 2017), tunnel physical model fabrication (L. Song et al., 2018), and rock-like geological materials (Vogler et al., 2017). 3DP can provide quantitative stability evaluation for geotechnical engineering cases (Q. Jiang et al., 2021) as well. There is no doubt about its potential in underground mining engineering.

The potential applications of different printing technologies in fundamental mining research are listed in Figure 1. Based on the proper selection of the printing materials and printing technologies, the prototypes (PTs) of mines can be reproduced. 3D metal printing can be an effective option for manufacturing very small batches of metal parts or for projects with very short timelines, especially for mining metal supports. General supporting components can be 3D printed with different materials, either based on selective laser sintering/selective laser melting or direct ink writing (DIW) (Karakurt & Lin, 2020). DIW has emerged as the most versatile 3DP

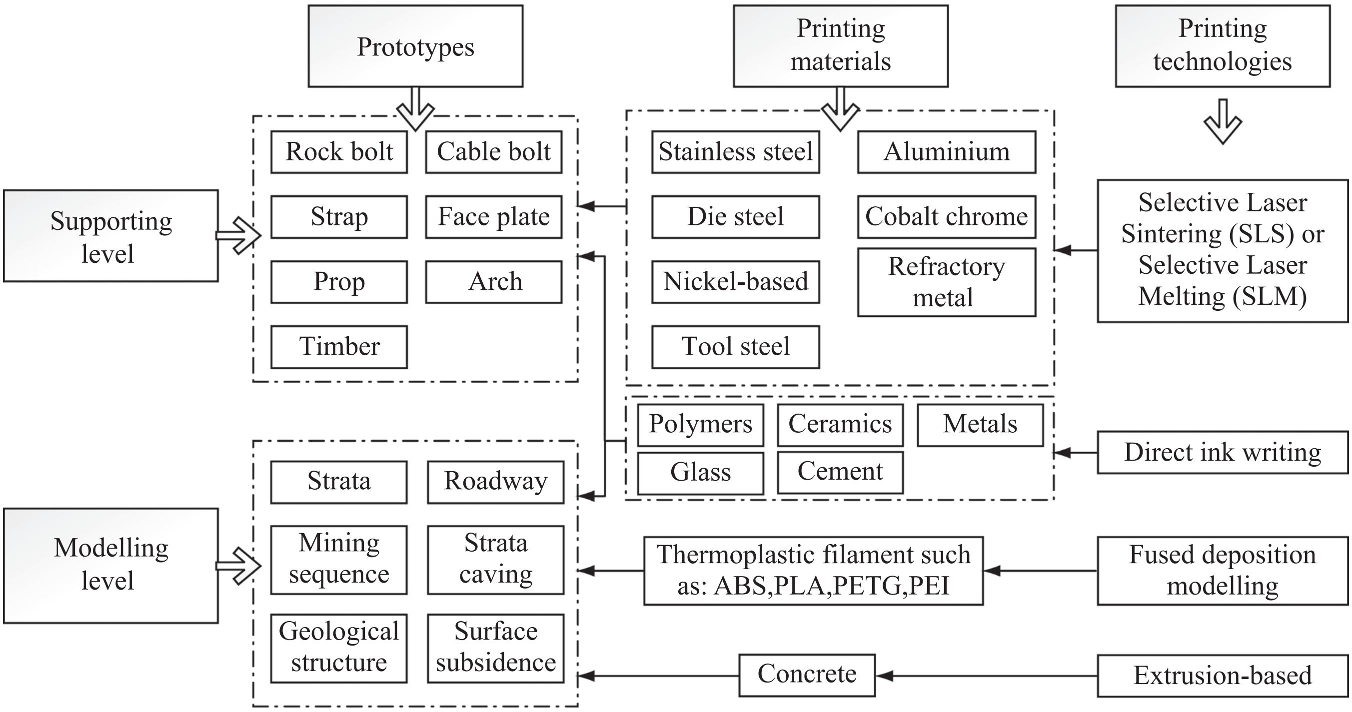

FIGURE 1 A flow chart of 3DP in laboratory mining research. ABS, acrylonitrile butadiene styrene; PEI, polyetherimide; PETG, polyethylene terephthalate glycol; PLA, polylactic acid.

technique for the broadest range of materials. DIW can support the printing of practically any material, as long as the precursor ink can be engineered to demonstrate appropriate rheological behavior (Saadi et al., 2022). Fused Deposition Modeling (FDM) technology can produce layer thickness of 0.10–0.25 mm and a maximum wall thickness of 0.8–1.0 mm, thus having a wide application in printing models that can assist mining research. Extrusion-based technology is adopted for 3D concrete printing. It is of great potential to construct physical mining engineering models resembling geological structures.

In this study, AM technologies were explored to better understand fundamental mining issues. The application of different 3DP technologies and different printing materials, potentially suitable for mining-related research, was analyzed with consideration of some examples in real mining engineering scenarios. Finally, a conceptual design of a 3DP machine for mine physical models was proposed. In a word, though this technology is still in its preliminary stage in mining engineering, its potentials are worth exploring and thus academic attention from researchers both at home and abroad.

2 | 3DP TECHNOLOGIES IN MINING ENGINEERING

2.1 | Application of 3D metal printing

Considering that most supporting structures in coal mining are made of carbon steel, among all alternative printing materials and printing technologies, metal powder printing is the most potential one that can fabricate components with mechanical properties close to the engineering ones. By exploiting the precise controlling ability of 3DP, the supporting structures can be easily reduced in size and then reproduced.

Metal supporting components in coal mines include props, bolts, arches, meshes, cable bolts, and so forth. Figure 2 presents some examples of 3D printed supporting components, including original size bolt, scaled bolt, face plate, arches, and so forth. Their advantages are presented below in detail.

Rock bolts are a typical supporting component frequently installed in underground excavations or used on the ground surface for slope controlling purposes. Studies on scaled bolting mainly use substitutes to simulate rock bolts, such as smooth bars, wooden sticks, irons, screws, and so forth. These simplifications ignore the mechanical bonding at the interfaces and the support-rock relationship. Therefore, the results obtained are sometimes questionable. In this sense, improvements are of great necessity to better simulate the real conditions.

The bolts can be produced precisely by 3DP. Figure 2a displays three 3D printed rock bolts respectively manufactured by aluminum powder, die steel powder, and stainless-steel powder (SS). The black one on the top is the PT Q235 rebar bolt with a diameter of 18 mm. As can be seen clearly, the printed bolts have a high similarity of geometry with the PT one. The manufacturing process involves a detailed digital model necessary for a 3D printer and 3D scanning (Feng & Xue, 2020). To be specific, the 3D scanning generates a stereo-lithography file, which afterward is input into the printing machine for manufacturing. Then, the printed objects are further improved via heating and polishing.

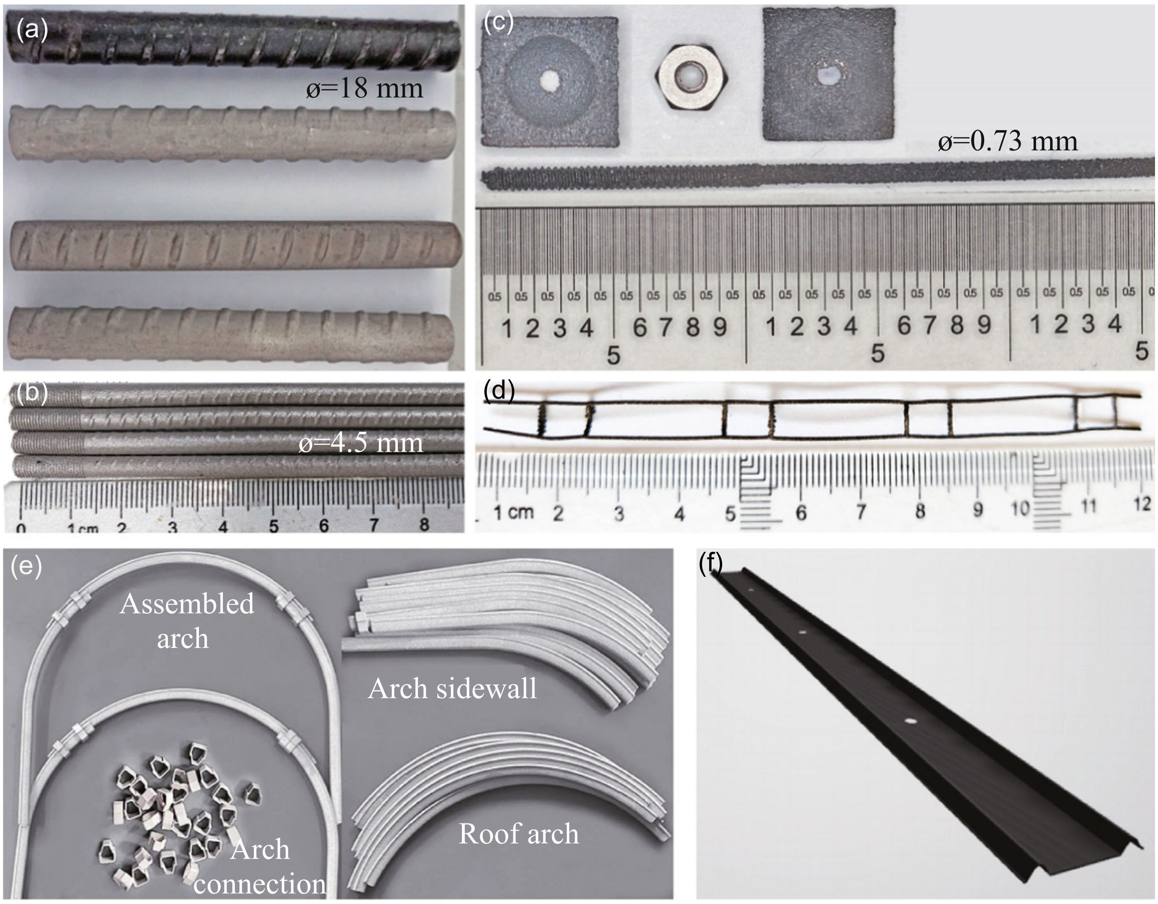

FIGURE 2 Typical 3D printing components for underground supports. (a) Prototype bolt and 3D printed bolts with original dimension, (b) scaled 3D printed bolt, (c) scaled 3D printed face plates and bolt, (d) scaled 3D printed ladder beam, (e) scaled 3D printed arches, (f) digital visualization of a strap.

Based on preliminary mechanical tests on different types of 3D printed bolts (Feng & Xue, 2020), it has been demonstrated that the SS printed bolt displays high strength, with tensile stress close to 760 MPa and shear stress close to 480 MPa. These values fit the requirements of the common bolts. Moreover, the density of the SS printed bolt is 7.93 g/cm^3, which is very close to the Q235 bolt (7.74 g/cm^3).

It is worth noting that the PT bolt has higher elongation, which is suitable for displacement controlling of rock mass (Kang et al., 2020). Through heat treatment, the elongation property of the SS printed bolt can be improved by the recrystallization process (Kong et al., 2019), leading to a similar performance to the PT bolt. In view of the above results, stainless steel powder can be selected as suitable printing material for bolt manufacturing, considering the economic cost and performance.

Figure 2b shows scaled 3D printed bolts with a diameter of 4.5 mm, which is about four times scaled from the PT one of 18 mm. Clearly, the geometric details are still well reproduced, and the screw section can be adjusted to match the standard nuts.

Figure 2c presents a rock bolt with a scaled ratio of 30, specifically, from an original diameter of 22 mm to a scaled diameter of 0.73 mm. Figure 2c also exhibits the accessories such as face plates and commercial nut. The bolt and face plate are all manufactured out of stainless-steel powder by 3DP. The precisely fabricated screw section is suitable for the standard M1 nut adapted to apply pretension force in real applications. The digital model of the face plate is constructed by CAD and that of the bolt is scaled based on the model obtained by 3D scanning. All scaling procedure is controlled by software; therefore, precision can be guaranteed.

A steel ladder beam is a component pinned by rock bolts in the engineering field, which bridges the gaps among neighboring bolts. It serves as a protective beam to restrain the deformation of rock mass (He et al., 2019). It is common practice to ignore the steel ladder beam in traditional modeling tests. In Figure 2d, a steel ladder beam reduced by 30 times from its PT is presented. Manufactured out of stainless-steel powder by 3DP, this steel ladder beam can be used for real laboratory modeling tests.

By assembling the rock bolts, face plates, nuts, and steel ladder beam together, the original engineering model can be reproduced on a laboratory scale. For instance, for a roadway with a width of 4500 mm and a height of 3000 mm, which can be a typical dimension in the engineering field, a reduced dimension of 150 and 100 mm, respectively, can be adapted for the loading test in the laboratory. Scaling the supporting components by the same ratio (30), the reduced dimension of the assemblage is suitable for most rock loading machines.

Not only being used for components with simple geometry but 3DP can also be employed to fabricate complex ones. Figure 2e presents 3DP arches manufactured with stainless steel powder. The thinnest part, after dimension reduction, can even drop below 1 mm, which is unwise and not economical for traditional manufacturing methods. By 3DP, each part of the arch can be produced with high precision. One important feature of the arch lies in its yielding ability because the arch can bear a certain amount of deformation due to rock's squeeze. This index is important to control rock mass deformation. Through 3DP, both the dimensions and the mechanical properties can be optimized by assembling the parts together. Doubtlessly, it is a significant advancement for mining research.

The strap is another key supporting component that can be used to increase the overall stability of the rock mass. It is useful when applied in brecciate area. Such component is frequently ignored in previous laboratory research. Figure 2f shows the digital model of a strap for 3DP manufacturing. This model can be adjusted to meet different geometric similarities to real components and optimized considering the proper position of the hole for bolts, thus leading to improved stability of the loose rock mass.

2.2 | Application of 3D polylactic acid/acrylonitrile butadiene styrene (PLA/ABS) printing

PLA/ABS can be printed by FDM technology. The proper utilization of this material can greatly facilitate relevant research for its low cost. Based on the previous research, Figure 3 shows some examples of its application which are useful for rock/mining engineering research.

Figure 3a displays small-scale rock bolts manufactured by 3DP. The red ones are made of PLA and the metallic ones are fabricated out of stainless steel powder. The PLA bolts can be applied for tests which require reduced dimension and strength; while the metallic ones can be used for tests with scaled dimension and high strength.

In Figure 3b, a rectangular contour roadway mold is printed by PLA, and the boreholes are precisely designed by CAD software. By inserting this mold into a physical model, the construction process can be greatly facilitated, ensuring an accurate bolts installation inside the physical model.

Figure 3c shows the on-process printing of a batch of bolts with PLA material. These bolts are suitable to simulate rock bolts in physical modeling test with the scaled strength criterion. The strength could be adjusted by altering the material filling rate in the software before printing, to be specific, the higher the filling rate is, the higher the strength would be, and vice versa.

Figure 3d shows 3D printed molds with PLA material, which can assist the preparation of cement joint of cylindrical rock specimen (Feng et al., 2020). The joint angle is adjustable with high precision, and the preset borehole can accommodate 3D printed rods. The rods can be later removed for scaled 3DP rock bolts

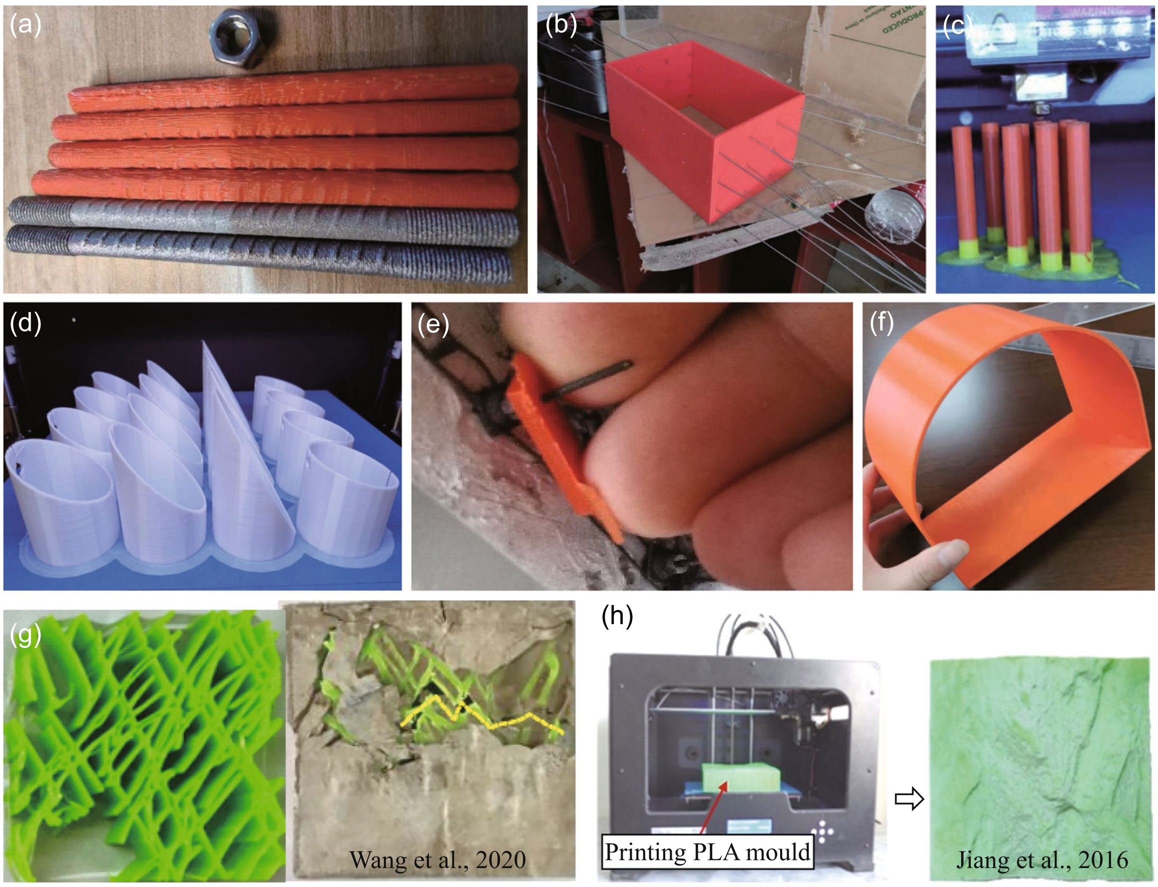

FIGURE 3 Examples of application of PLA-based 3D printing in rock/mining engineering research. (a) small scale rock bolts, (b) rectangular contour roadway mold, (c) on-process printing of a batch of bolts, (d) molds for cement joints, (e) small torque for pretension of 3D printed bolt, (f) 3D printed roadway, (g) complex fracture network, (h) replication of rock joint plane.

insertion and bolting. In this way, the bolting effects on joint rock mass can be investigated.

Figure 3e presents a 3D printed small torque which can be used for applying pretension force to 3D printed bolt. The diameter of the 3D printed bolt is 1.1 mm, 20 times scaled from its PT, and the nut is M1 standard. By means of 3DP technology, the design and manufacture of M1 standard torque can be easy, time-saving, and economic.

Figure 3f shows a 3D printed roadway, 30 times scaled from the actual engineering dimension, which is useful for physical model casting in the laboratory. The accuracy of roadway with semicircle roof connected by straight walls has always been a challenge for conventional physical model construction. By 3D PLA printing, it can be accomplished in an easy and economical way.

Not only for the above-mentioned applications, but PLA-based 3DP can also be competitive when a complex fracture network in rock mass needs to be established based on natural rock (Wang et al., 2020), As is shown in Figure 3g, the network can be printed by PLA material, which is then incorporated into a concrete model to simulate the complex scenario.

Besides, it can also replicate rock joint plane based on 3D scanning and concrete casting, as shown in Figure 3h. By means of 3D scanning, a digital profile of the joint plane is created for printing, then the rock mass with the natural joint plane would be replicated by concrete casting (Jiang et al., 2016).

2.3 | Application of 3D concrete printing

Due to the very similar mechanical and failure behaviors between concrete and natural rock mass, cementitious materials have been adopted to simulate rock mass for analyzing the rock mechanics (Moradian et al., 2010). In addition, cement is also a key material to prepare the physical model of real engineering PTs. However, the physical model is frequently denounced for some shortcomings such as pseudo collapse pattern, physical parameters interference, and manual error.

3DP based on cementitious material provides a new option for construction. It has been extensively demonstrated that the 3D cement printing can produce objects with different strengths and serving life (Paolini et al., 2019). Furthermore, the layered accumulation pattern of the 3DP can make this technology more favorable, since it can simulate and reveal the laminated formation of strata to some extent (Frith et al., 2018).

The key techniques to realize the 3DP physical model lie in the physical and mechanical parameters of the concrete, especially the flowability, extrudability, and buildability (Zhang et al., 2019). Hence, the pumping characteristics of printable concrete directly determine whether the technology is suitable or not, or whether the reduction in worktime and formwork can be achieved (Mohan et al., 2021). In addition, the natural formation of strata determines the bonding strength between neighboring rock layers. Hence, the bonding strength of the printed layers is another challenge that needs to be faced.

Based on the research conducted by the author previously, 3DP concrete physical models can reproduce real engineering failure modes (see Section 3). However, the 3DP concrete model can have regular weak planes inside, which are completely different from the randomly distributed pores inside a cast model. The weak planes increase the complexity of the model failures, thus weakening the reliability of the prediction rendered by theoretical models. Figure 4a exhibits the failure patterns of a coal mine physical model fabricated by 3D concrete printing. In Figure 4a, the inner pattern of a failed model shows regularly aligned slot pores. Each slot separates two adjacent printing layers. The slot is formed when the filament extruding from the rounded nozzle pushes the neighboring filaments. The original filament is round because of the nozzle shape, which is then deformed into a rounded rectangular shape due to the nozzle squeezing under the preset layer height.

Since the buildability should be maintained during the whole printing process, the slot cannot be sealed by itself. It thus leaves the potential inner flaws for cracking connection and extension that disturb the failure pattern. Figure 4b shows a cubic 3DP specimens under uniaxial compression test. The pores cannot be seen from the outside and only some cracks emerge on the surface. Figure 4c gives the side-view pattern of the slot pores.

In spite of the above-mentioned shortcomings, 3D concrete printing is still featured with great convenience for the construction of coal mine physical model. Instead of being removed, the pores can be adjusted by spraying

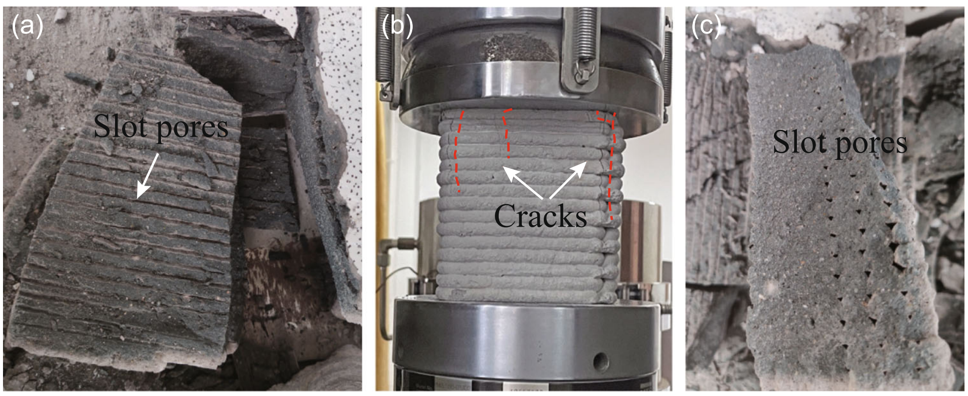

FIGURE 4 Failure patterns of 3DP concrete. (a) Slot pores inside a failed coal mine model, (b) cracks on the specimen's surface, and (c) slot pores observed from one end.

an interlayer weakening agent, such as mica, to change the bond strength between layers. In this way, horizontal layer separation can be easily achieved, which resembles the strata separation due to mining. Furthermore, the slot pores can be minimized by changing the nozzle shape, such as using a rounded rectangular nozzle to replace the pure rounded one.

3 | EXAMPLES OF 3DP APPLICATIONS IN MINING RESEARCH

3.1 | Exploitation of 3DP in physical models

In this section, physical models of coal mine PTs are discussed. They are completely or partially constructed by 3DP technologies (Figure 5). The model shown in Figure 5a replicates an entry in a coal mine in Xuzhou city, China. The model body is prepared with a concrete cast. The rectangular entry is supported by 3DP bolts and 3DP steel ladder beams, and the whole model strictly reproduces the engineering scenario by the scale ratio of 30. The bolts inside the entry are pretensioned and pressed tightly on the 3DP face plates. The pretension is completed by PLA-based 3DP torque.

Figure 5b exhibits the compression failure mode of the model shown in Figure 5a. As can be seen, the rib spalling is prominent, and the roof subsidence is observable. The distortion of steel ladder beams is also visible. Figure 5c presents a steel ladder beam with two neighboring bolts. The resin residue is still adhered on the bolts, which demonstrates an effective bond of resin and bolt (Chen et al., 2022). The entry deformation and the support distortion are very similar to the actual case in the engineering sites.

Figure 5d shows a roadway shaped by a semicircle roof connected by straight walls. It is a scaled PT of a coal mine in Huainan city, China (Feng et al., 2022). Different from the model in Figure 5a, the model body is prepared by 3D concrete printing. The layered formation that simulates the laminated rock mass can be seen on both ribs of the roadway. The arch supports are manufactured out of stainless-steel powder by 3DP, which are the same as the ones presented in Figure 2e. The whole model is 30 time scaled from the engineering dimensions.

Figure 5e shows the compression failure mode of the model shown in Figure 5d, and Figure 5f exhibits the failed fragments of the 3DP arches. The deformation of the excavation and the cracking trajectories of the model are consistent with the existing theories (Wu et al., 2020); floor heave, ribs spalling, and roof subsidence can be observed clearly. As for the arches, the distortion is also very similar to the engineering ones, indicating the supporting effectiveness during the loading process.

Compared with existing studies, only 3DP can reproduce accurately all the details of physical models. By the traditional techniques, the models fabricated by different persons or at a different time can lead to different test results. For example, Figure 6 shows two models using red sandstone (Luo et al., 2019) and granite (Gong et al., 2019). Predrilled holes with a similar shape to the engineering ones resemble the engineering sites, but the supporting components are removed in both models. The two examples highlight the unrealistic scenarios adopted in the previous studies in that the components are ignored. However, with 3DP, both the main structure and supporting components can be precisely manufactured so as to establish reliable models.

3.2 | Scaled bolts reinforcement on joint-separated rock mass

In the past studies, the small-scale bolting test on joint-separated rock mass was always a big challenge, since

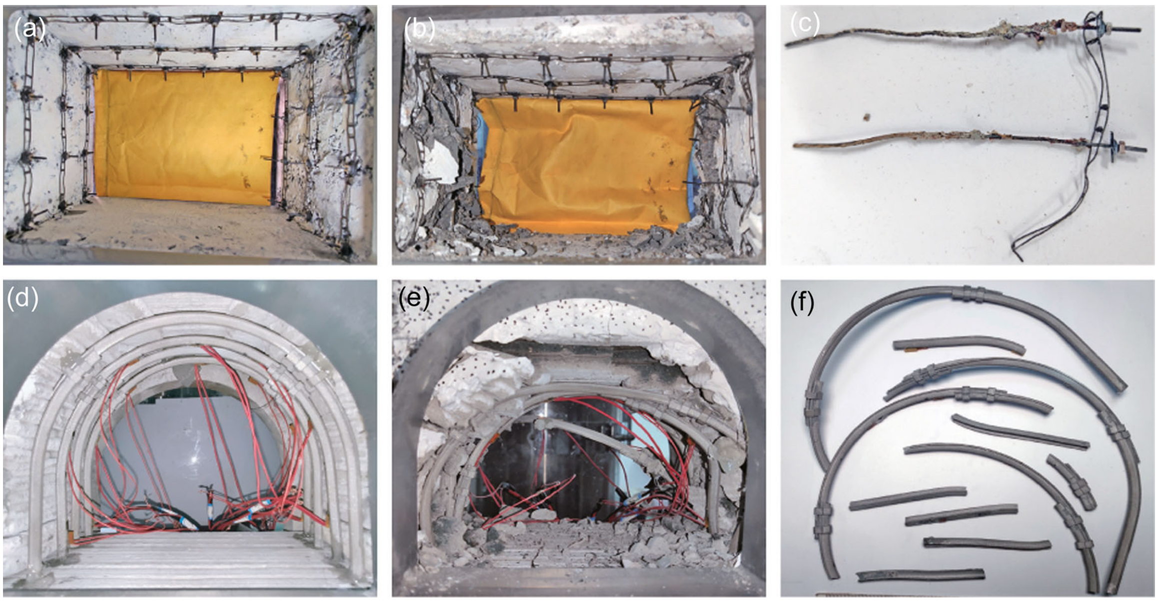

FIGURE 5 3DP applications in physical model for mining research. (a) Rectangular roadway supported by 3DP components, (b) failed pattern of (a), (c) 3DP bolt supporting system of (b), (d) 3DP roadway shaped as a semicircle roof connected by straight walls and 3DP arch supports, (e) failed pattern of (d), (f) 3DP arch supports of (e).

researchers used different materials with different mechanical properties and geometries to simulate the bolts (Chen et al., 2022; Lin et al., 2020; Wu et al., 2019). 3DP provides a manufacturing technique to overcome those drawbacks.

The failure patterns of rock bolts are detailed in Figure 7. Figure 7a–c displays the failure patterns discovered by the existing studies, and Figure 7d gives the failure patterns of 3D printed bolts for the purpose of comparison and contrast. In Figure 7d, shearing bending, detachment of resin annulus, decoupling at interfaces have been observed. It demonstrates that 3DP is a suitable technique for small-scale laboratory test to reproduce the interaction between artificial support components and the natural body.

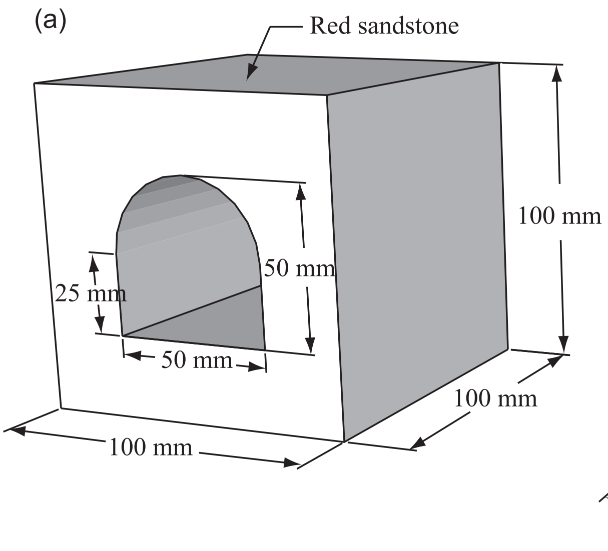

FIGURE 6 Redrawn sketches of previous studies on physical modeling tests. (a) The cubic red sandstone specimen with a D-shaped hole to mimic underground excavation (Luo et al., 2019), (b) the granite specimen with a through-rectangular hole to mimic underground excavation (Gong et al., 2019).

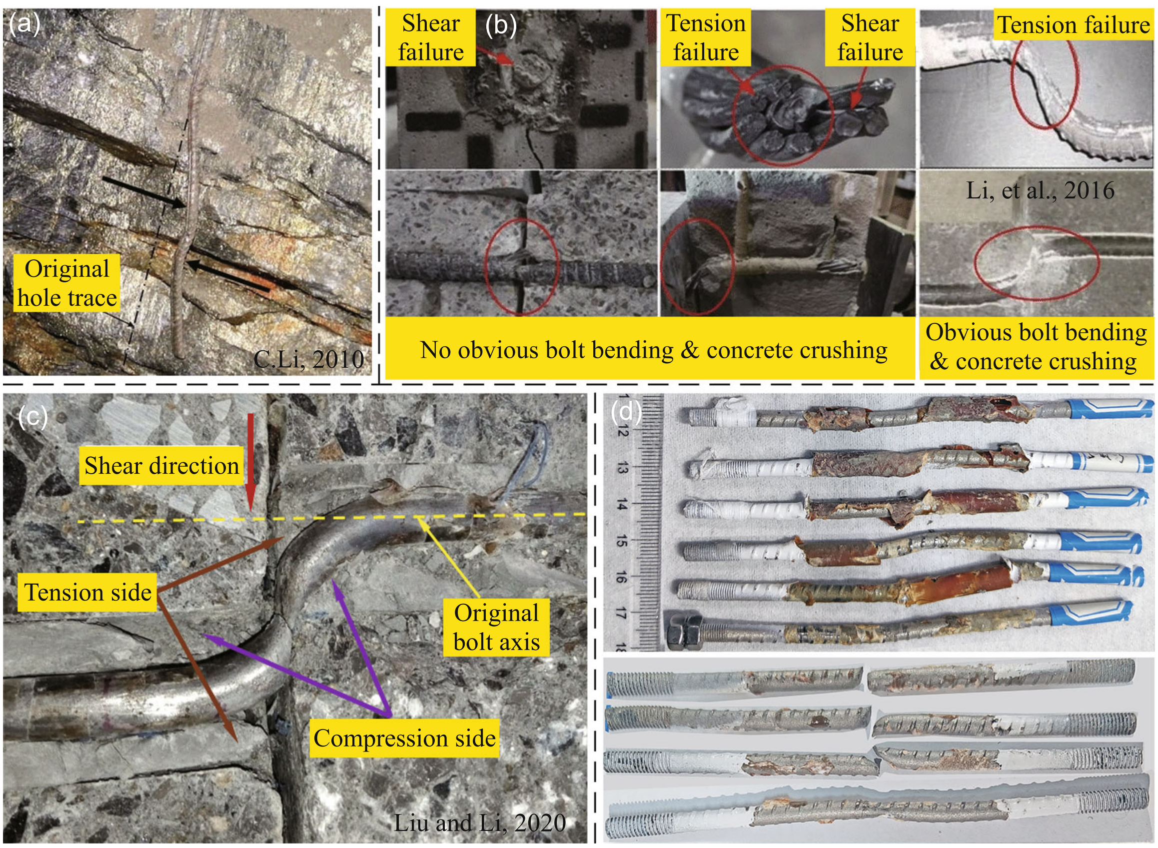

FIGURE 7 Failure modes comparison of bolts among existing studies and 3DP bolts. (a) A failed bolt due to shearing of a cut-and-fill mine stope (Li, 2019), (b) failure modes of different types of bolts in reinforcing 40 MPa concrete joints (Li et al., 2016), (c) a failed bolt due to shearing (Liu & Li, 2020), (d) failure of 3DP bolts due to shearing by different angles (Feng et al., 2020, 2021).

Overall, in Figure 7, a high similarity can be noticed between engineering and laboratory scenarios. The bending and necking nearby the shearing point indicate an opposite parallel tearing phenomenon. From this point of view, the 3DP bolts can be a technically feasible solution for the scaled physical model test of underground space stability-controlling research. However, the ductility of 3DP bolts may not be favorable compared with counterparts in Figure 7b,c, but this flaw can be improved by changing the constituent of the steel powder or by the heating procedure.

3.3 | Conceptual design of 3DP machine for physical models

In view of the above applications, a conceptual design of 3DP machine for mining engineering physical models is proposed. It is a large double-nozzle 3DP system, which can reproduce the strata by the main nozzle extruding concrete and the auxiliary nozzle extruding interlayer bonding agent.

The working mechanism of the main and auxiliary nozzles is drawn in Figure 8. Three axes motor control is achieved by the PLC software through the external computer numerical control system. At the same time, the switch of the solenoid valve of the nozzle is controlled by PLC software.

The systematic sketch of the double-nozzle 3DP system is shown in Figure 9. Before the concrete printing process, it is highly necessary to fully explore the properties of the concrete. The proper cementitious material system, coagulant, thickener, reinforcing fiber, water reducing agent, and water-binder ratio should be strictly calibrated to achieve the needed fluidity, shrinkage, mechanical properties, and other parameters of the concrete. These parameters must be controlled to achieve similar features of the modeled strata.

As for the nozzle, parameters such as nozzle angle, shape, size, moving speed, slurry extrusion speed, and printing interval time must be investigated to meet the requirements of strata accumulation during the printing process.

4 | DISCUSSION AND CONCLUSIONS

This paper presents an overview of possible applications of 3DP technologies to study mining-related issues, especially the improvements in laboratory modeling tests. The proper material for 3D printed supporting components including bolts, straps, steel ladder beams, and arches have been illustrated. By 3DP technologies, many supporting components can be scaled to meet the experimental requirements and ensure the mechanical characteristics maximally close to the real PTs.

The 3D concrete printing is used to create the layered formation simulating laminated strata. As is shown by the tests, the 3D concrete printing can be coupled to the 3D metal printing to construct an engineering scenario that precisely follows a specific scaled ratio in the

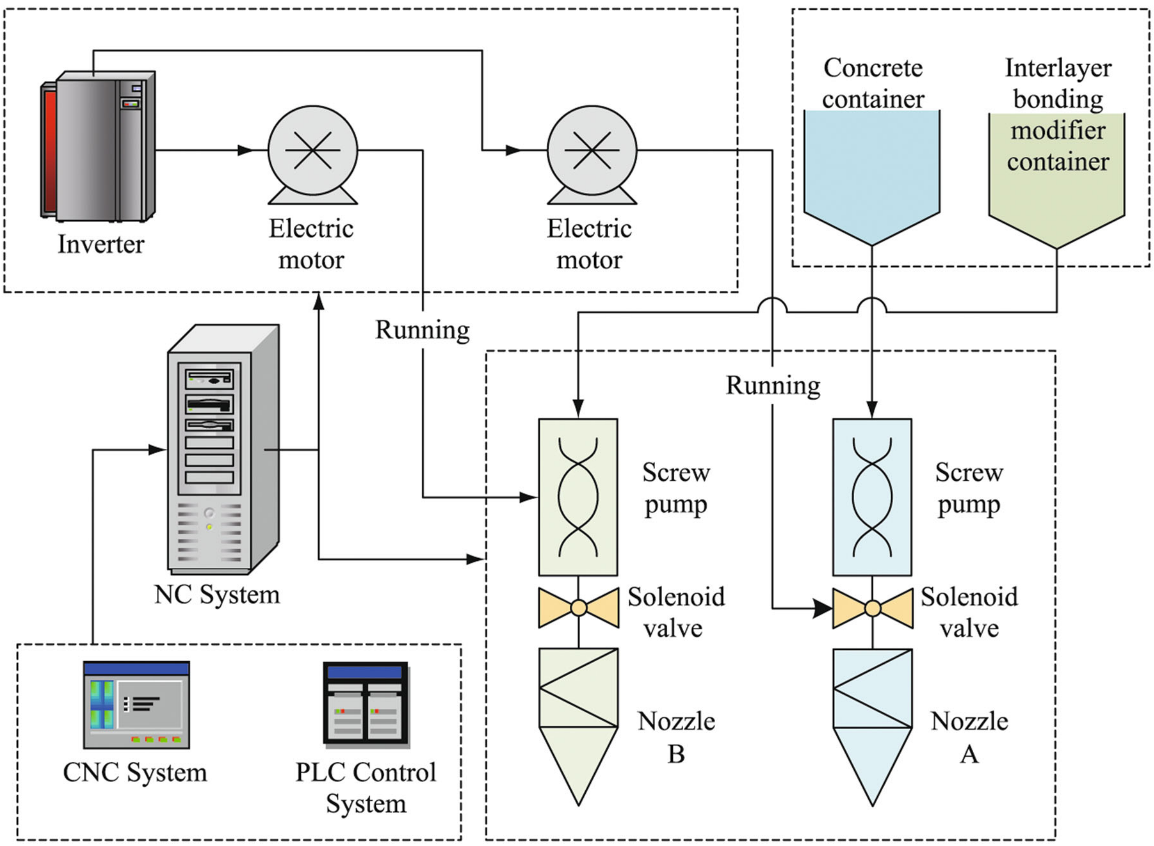

FIGURE 8 The working mechanism of the double-nozzle 3D printing system for physical models. PLC, programmable logic controller; CNC, computer numerical control; NC, numerical control.

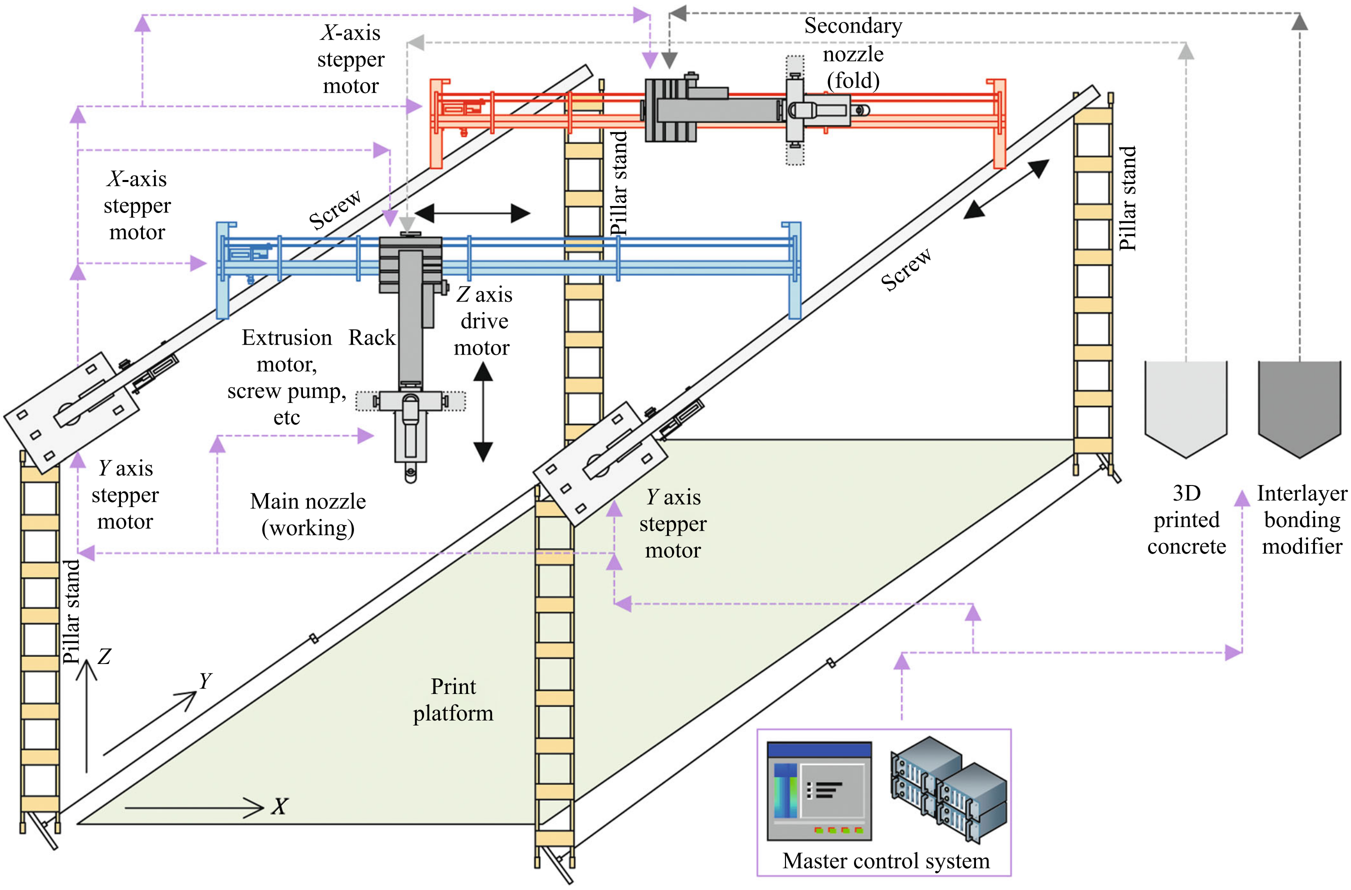

FIGURE 9 The sketch of the overall double-nozzle 3D printing system.

laboratory. The failure pattern indicates a high degree of similarity with the prediction rendered by the existing theories.

Based on the tests on the materials, applications, and equipment of the 3D concrete printing, it can be concluded that the 3D concrete printing can also be utilized in the retaining wall construction in gob-side entry retaining work, and underground dams in the underwater environment for abandoned mines to prevent disasters. Nowadays, even the 3D models with complex geometrical structures can be fabricated by materials such as powder gypsum or concrete (Ban et al., 2020; Song et al., 2018), which greatly expands the range of application of 3DP in these areas. Moreover, the key part of mining engineering components can be digitized and stored for a potential replica in the future.

A scaled 3DP bolt can effectively reproduce the reinforcement mechanism by the interfacial bonding of the ribbed surface. 3DP bolts in joint-separated rock specimen have similar failure patterns with PT ones, which demonstrates the accuracy of 3DP exploitation to some extent.

In spite of its high precision, 3DP is often labeled with its high cost. Comparatively speaking, with technological advancement, 3D concrete printing and 3D PLA printing can be very cheap, although the cost of 3D metal printing is still high. To be specific, a 20-time-scaled 3DP bolt costs 5 US dollars, while a real one costs 3 US dollars. The cost of 3DP bolts could be further lowered according to the quantity. Nonetheless, the trustworthy results from the tests can be more meaningful and important, which can make the cost acceptable to some extent.

In a word, 3DP can be considered a suitable and promising technique to assist mining research. Although more efforts are needed in the exploration of 3DP in the mining area, it is certainly an alternative approach to investigate engineering problems with remarkable accuracy.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

Data are available on request.

ETHICS STATEMENT

Not applicable.

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