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Research Paper

The Evolution of a Refined Printable System for Metal/Ceramic Composite Materials

Yogishkumar S V [1], Sheshagiri A T [2], Biligirinayaka M [3]
[1] *Lecturer, Department of Department of Machine Tool Technology, S J (Govt.) Polytechnic Bengaluru, Karnataka, India.*
[2] *Lecturer, Department of Mechanical Engineering, Government polytechnic Chamarajanagar, Karnataka, India.*
[3] *Lecturer, Department of Machine Tool Technology, Government polytechnic Chamarajanagar, Karnataka, India.*

Abstract
The technique of additive manufacturing for ceramic/metal composites combines the inherent advantages of these materials with the adaptability of 3D printing. This allows for the development of complicated structures that are personalized to the individual's needs and promotes breakthroughs in lightweight design solutions. The processing and production of high-performance components involves the use of this technology, which is now being applied across a variety of industries, including the aerospace and automotive industries. For the purpose of this inquiry, we developed a material extrusion 3D printing equipment that may be used to fabricate hybrid structures made of metal and ceramic substances. The technology allows low-heat printing, which makes it possible to debind printed samples in an easy and secure manner using a procedure that is based on alcohol. This, in turn, streamlines the flow of the process and improves the efficiency with which high-performance composites are processed. Furthermore, the creation of composites of SUS316L/ZrO_2 that were printed using a 3D printer was conducted as part of this study in order to produce intricate structural components.

Keywords: *Additive Manufacturing; Low-Heat Printing; Ceramic/Metal Composites.*

I. INTRODUCTION AND LITERATURE REVIEW

Because of its remarkable high-temperature capabilities, resilience to wear, and resistance to corrosion, ceramics are a material that is desirable for use in a range of structural components (1,2). There are several reasons why ceramics are appealing for use in these components. Zirconia, in particular, is a prominent ceramic material that has important characteristics such as high stability at high temperatures, high bending strength and fracture toughness, and biocompatibility 3,4. On the other hand, ceramics are difficult to deal with due to their poor machinability and brittleness. This makes it difficult to create large and sophisticated structures, which in turn restricts its usefulness. Ceramics are difficult to work with because of their material properties. As a result, there has been a lot of interest in the method that enables ceramics and metals to be linked together. Through the process of linking metal and ceramics, it is possible to achieve improvements in material properties that are not attainable by a single material. Consequently, this paves the way for a wide range of potential applications. One of our key objectives is to create a 3D printing technique that is capable of manufacturing hybrid structures composed of ceramics and metals. This is one of our primary aims. In the fabrication of structural materials (6-7), oxygen sensors (9-11), and solid oxide fuel cells (SOFCs) (12-15), metal and ceramic each play a key role in the use of these materials. Metals and ceramics are often joined together by the process of welding, brazing, and diffusion bonding, which are all methods that are used. There are, however, a few drawbacks that are linked with these methods, such as the need for additional processes or materials in order to link. On account of this, it is desired to have manufacturing techniques that do not need any additional activities to be carried out in order to connect.

This study was conducted with the intention of developing a dispenser-based metal 3D printing technology that is capable of printing with low heat and readily debinding the material via the use of the technology. We make use of a recently created compound material that is formed of zirconia powder and stainless steel powder that have been mixed with a thermoplastic binder. This substance is used as the printing medium. The printed samples are debound and sintered in a way that is comparable to the procedure that is used in powder

metallurgy. The procedure of debinding, on the other hand, may be carried out in a safe way by using alcohol, and it does not need the use of any complicated gear. via the use of the 3D printing technique that we have developed, we also make an attempt to print hybrid structures that are composed of ceramic and stainless steel. Additionally, we investigate the interface via the utilization of the co-sintering process. Ceramics that are resistant to corrosion and have a high degree of hardness may be combined with metal components in order to generate composite materials. This procedure makes it feasible to combine these ceramics with metal components. In addition, components that include three-dimensional ceramic structures are shown, and we demonstrate that the regions that contain ceramics have a higher degree of hardness than the regions that do not contain ceramics.

II. PRINTING SETUP

2.1 Material

As part of this research study, a fresh new material was developed that could be printed at a temperature that was far lower than the previous one, which was around 80 degrees Celsius. Additional components that were used in the manufacturing process of the binder were stearic acid, rapeseed oil, and a synthetic wax thermoplastic resin known as PALVAX, which was manufactured by Nippon Seiro Co., Ltd. These components were mixed together, and then heated in a microwave until the synthetic wax was entirely dissolved in the rapeseed oil while being agitated. This was done in order to finish the creation of the binder. It was with the assistance of stearic acid that the gelatinization of the rapeseed oil was achieved. Stearic acid not only helps to keep the shape of the printed sample, but it also helps to ensure that the combined metal and ceramic powders are distributed evenly throughout the sample.

Next, the compound was manufactured by adding metal or ceramic powder into the binder, heating the mixture to 80 degrees Celsius in an oven, and stirring it using a planetary mixing apparatus (SK-350T, Shashin Kagaku Co., Ltd.). This process was repeated until the compound was produced. It was after the production of the substance that this procedure took place. In the course of this study, powder materials were used. These powder materials included stainless steel powder (SUS316L, Daido Steel Group) with an average particle size of around 10 μm, as well as zirconia powder (TZ-3Y-E, Tosoh Corporation) with a particle size of 40 nm. Both of these powder compounds were employed for the aim of their respective investigations. The binder was manufactured by mixing rapeseed oil, synthetic wax, and stearic acid in a mass ratio of 89:9:2, respectively. This was done in line with the description that was provided earlier. Within the course of the printing procedure, the powder and the binder were mixed together in a proportion of one volume to one volume.

2.2 3D Printing System

Obtaining data that defines the print path by dividing the 3D model into separate layers is a prerequisite to carrying out 3D printing. We used PrusaSlicer, developed by Prusa Research, a popular slicer program for resin filament 3D printers, to accomplish this goal. This research also made use of the dispenser device's control software, MuCAD (Musashi Engineering, Inc.), for its printing procedures. Our in-house Python application was responsible for converting the G-code code produced by the slicing software into the code needed to operate the dispenser.

The 3D printing equipment used for this study is shown in Figure 1(a). The 3D printing equipment was a dispenser device, more precisely a SHOTMASTER 300SX from Musashi Engineering, Inc. Moving the stage along the y-axis and moving the dispenser along the x- and z-axes at the same time allows this printing technology to create a three-dimensional design. In addition, the material was extruded using an air pulse type dispenser (ML-5000XII, Musashi Engineering, Inc.) that allowed for the simultaneous manipulation of the geometry, speed of movement, and compound extrusion pressure. Two ceramic heaters were attached to the nozzle component and a silicone rubber heater to the syringe part since heating is necessary for the printing substance used in this experiment. To maintain an exact temperature of 80 °C, a digital fine thermometer (DG2N, Hakko Electric) was used. Before the printing procedure, the composite material was heated in an oven to 80 °C and then injected into the syringe. After that, the substance-containing syringe was attached to the printing device after being heated to 80 °C. The dispensing equipment applied pressure to the contents of the syringe, which were then expelled via a nozzle with a diameter of 0.50 mm. An alumina board was fastened to the stage for printing, and the compound was inscribed as the procedure progressed according to the predetermined printing schedule.

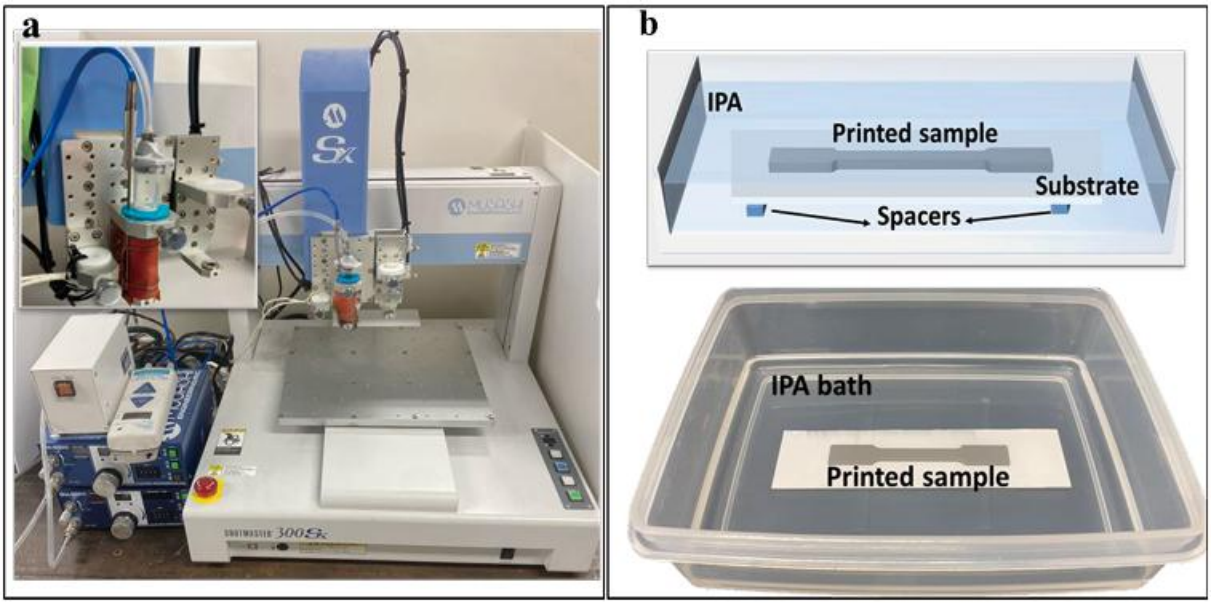


Fig .1. (a) 3D printing system, (b) Degreasing system.

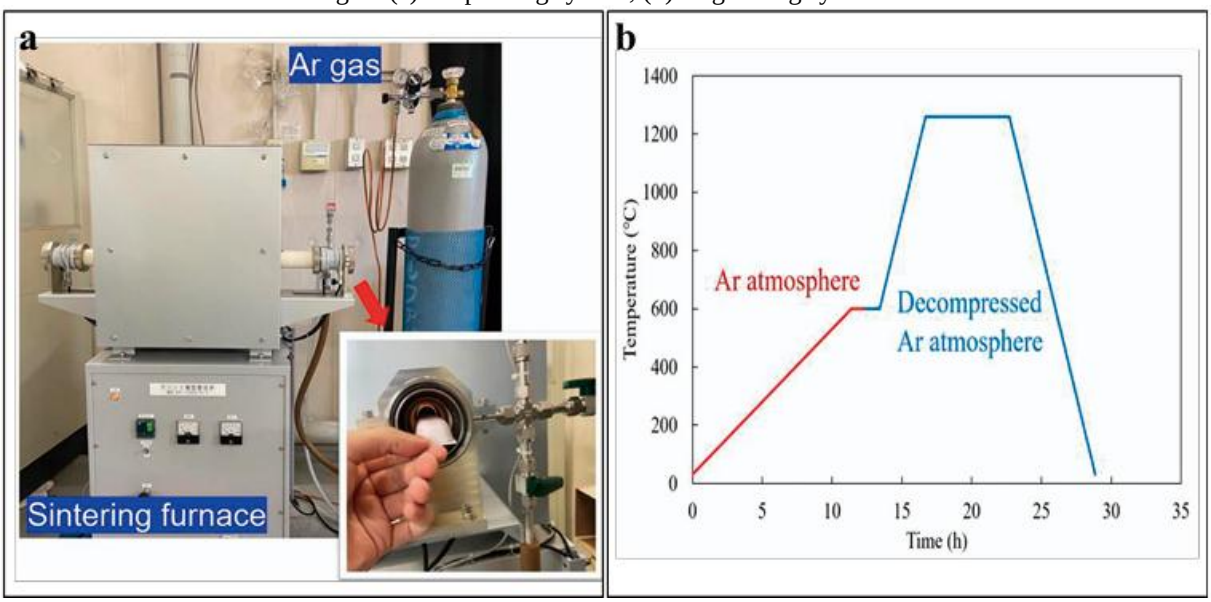


Fig.2. (a) Sintering system, (b) Variation of sintering temperature

2.3 Debinding and Sintering

The procedure of solvent debinding often calls for the use of specialist equipment as well as solvents that are considered to be hazardous solvents. On the other hand, in this particular investigation, the prepared binder may be easily debound by submerging the sample in an isopropyl alcohol (IPA) bath. This eliminates the need for any specialist gear from being used. In accordance with the illustration in Figure 1, the printed sample was kept in the bath at room temperature for about 86 ks, which is equivalent to one day. It is (b). During this time period, the IPA was responsible for dissolving the major component of the binder, which was rapeseed oil, and then removing it. On the other hand, the synthetic wax that was included in the binder displayed insolubility in IPA, which allowed the printed sample to maintain its form without any damage. Spacers were strategically placed underneath the alumina board that was supporting the sample in order to prevent the buildup of the extracted rapeseed oil at the base of the IPA bath, which may potentially hinder the operation for debinding the solvent. In an electric furnace, the sample that had been debound was subjected to sintering. For the purpose of this experiment, the sintering procedure was carried out using a horizontal tube furnace that was fitted with molybdenum silicide heaters (HF-1500-S-T, Crystal Systems Co., Ltd.), as shown in Figure 2.(a). An argon gas cylinder and a vacuum pump were connected to the furnace in order to control the atmosphere in which the sintering process took place. Following the completion of the solvent degreasing process, the samples were positioned in the middle of the tubular furnace so that the sintering process could take place. The sintering

process is shown in Figure 2(b), which shows the temperature and ambient conditions that are present during the process. The necessary criteria were determined via a series of preliminary evaluations that were carried out before the primary analysis was carried out. In the beginning, the sample was heated to 600 degrees Celsius at a pace of fifty degrees Celsius per hour in an atmosphere of argon for a period of 7.2 thousand seconds, which is equivalent to two hours. It was via the process of heat breakdown that the residual binder that was present in the sample was removed during the whole of this operation. Due to the fact that the adhesion between the metal and ceramic powders was improving over this time period, the shape continued to be unaltered even after the binder was removed. After that, the environment was changed to a low-pressure argon setting (ranging from 1 kPa to 100 kPa), and the specimen was heated to a temperature of 1350 °C at a rate of 200 °C/h. This temperature was maintained for a duration of 21.6 ks, which is equivalent to six hours, in order to facilitate the bonding of the powder particles and enhance the density of the sample. After that, at a pace of 200 degrees Celsius per hour, the sample was brought down to room temperature.

III. RESULTS AND DISCUSSION

Hardness and Tensile strength

A Vickers hardness instrument was used in order to determine the level of hardness shown by the SUS and MIX samples, which included ZrO2 volume fractions of 10%, 20%, 30%, and 40% respectively. The tests were performed with a load of 1.96 Newtons (0.2 kgf) and a loading duration of thirty seconds throughout the whole process. An illustration of a cross-section of the SUS sample may be shown in Figure 3a. For the purpose of measuring the sample's hardness, ten test spots were chosen at random. As a result of the hardness measurements, the indentation diagram is shown in Figure 3b. Figure 4 depicts the indentation diagrams that were obtained after hardness tests were performed on the surface of MIX samples that included varying amounts of zirconia. Zirconia was found in the regions that were bright, while SUS316L was found in the parts that were dark. The fact that the indentations are becoming smaller and the diagonal lengths of the indentations are getting shorter is a clear indication that the hardness is getting higher as the brilliant regions become bigger.

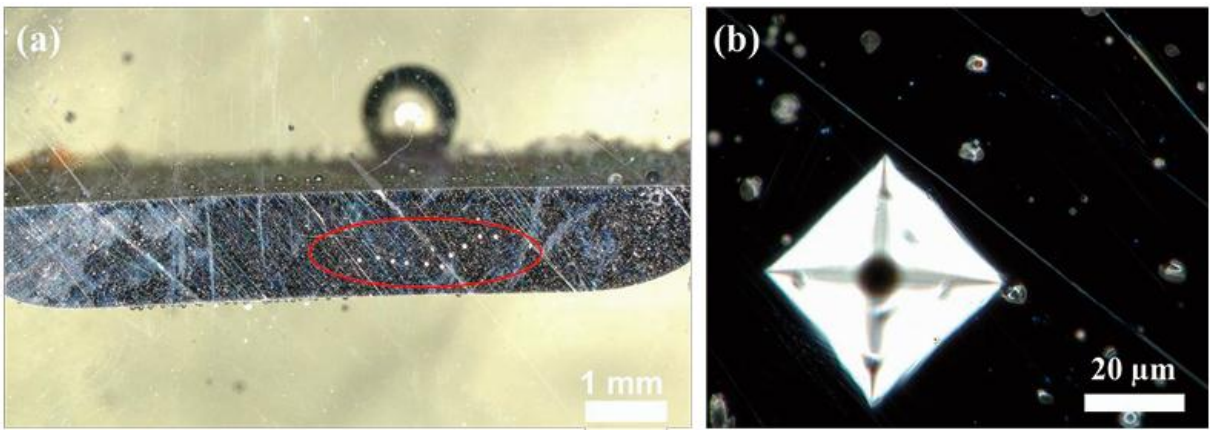
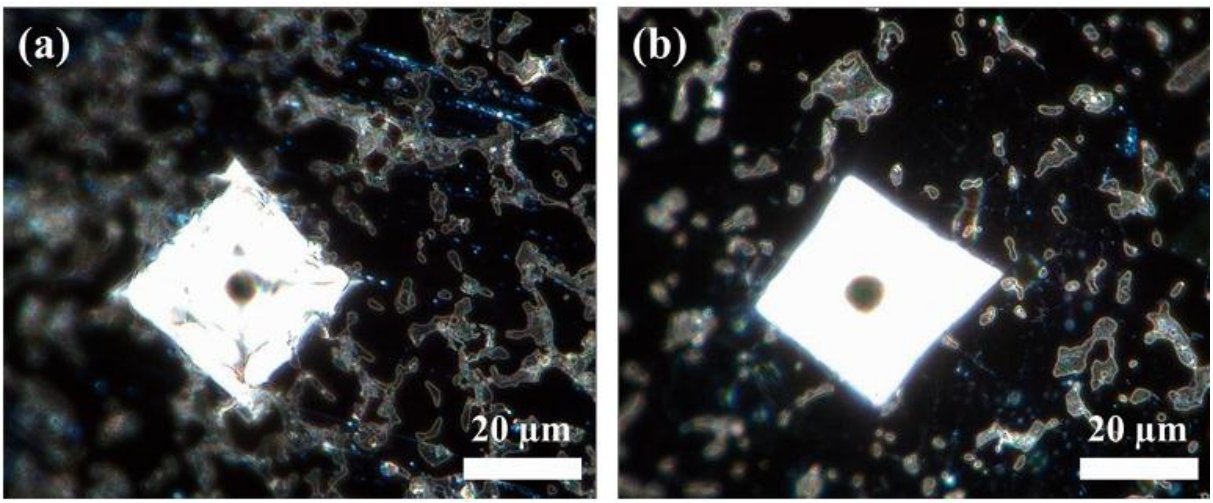


Fig.3. (a) Cross-section of the SUS316L sample; (b) Randomly selected indentations after hardness measurement.



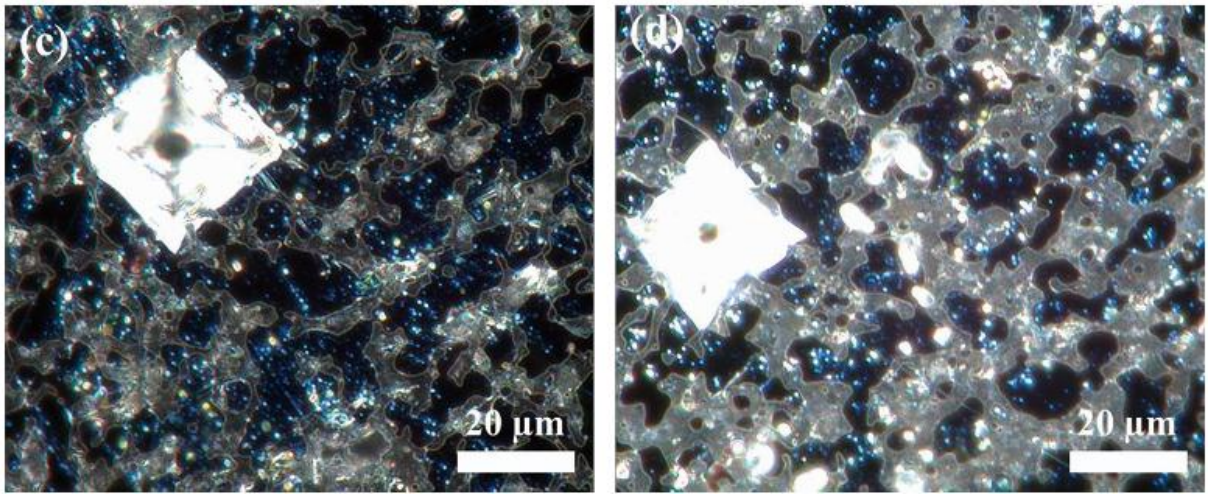


Fig.4. (a)-(d) Indentation plots of randomly selected surfaces of MIX samples with zirconia content.

Figures 5 contrasts the Vickers hardness values obtained for every sample. SUS: 123.5 HV, MIX (ZrO2 10 Vol%), 176.5 HV, MIX (ZrO2 20 Vol%), 203.4 HV, MIX (ZrO2 30 Vol%), 227.6 HV, MIX (ZrO2 40 Vol%), 350.3 HV, This suggests that the hybrid material MIX has more hardness than SUS316L, offering a new approach to get high hardness and wear-resistant zones on metal surfaces. The zirconia concentration of the MIX material employed in this work was regulated at 40 Vol%. This helps to prevent bending of the SUS-MIX composite and the visible cracking at the interface.

Nonetheless, zirconia's normal Vickers hardness is about 900 HV, hence raising the percentage of zirconia should help to further enhance the mechanical characteristics in the future.

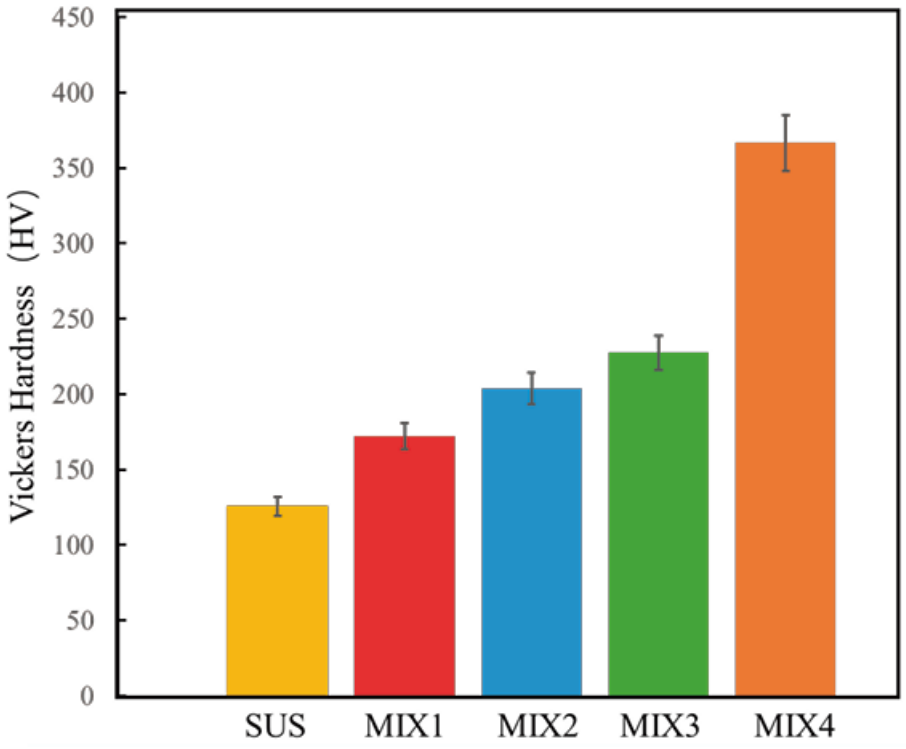


Fig. 5. Vickers hardness of SUS and MIX

IV. CONCLUSION

It has been discovered that a unique substance can be created that can improve the process of low-temperature 3D printing and make the debinding technique easier to do. In addition to that, we built a material extrusion 3D printing method that makes use of this compound. By using our cutting-edge technique, we were able to effectively achieve high-density samples via the process of co-sintering. This was accomplished by fabricating hybrid structures using zirconia powder and stainless steel powder. Through the employment of an IPA bath, the new chemical, which was composed of rapeseed oil, wax that was manufactured, and stearic acid,

exhibited its effectiveness in easing the debinding of solvents throughout the process. Furthermore, we accomplished the successful construction of a metal-ceramic hybrid structure by the amalgamation of stainless steel and zirconia with the compound, ending in a sintered body that displayed no problems. Taking into consideration the inherent challenges of this technique, the accomplishment of co-sintering metals and ceramics via the use of 3D printing is a significant improvement.

Furthermore, the substantial hardness that is shown in the ceramic regions is indicative of the potential for applications, such as the manufacturing of mechanical components that have better wear resistance on their surfaces. Consequently, this technique offers a convincing method for the production of hybrid structures that are composed of ceramics and metals. It demonstrates the possible applications that may be made use of the favorable properties that are inherent to both materials.

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