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S Abdelkhalek

Mechanical Design and Manufacturing Department, Military Technical College, Cairo, Egypt

E-mail: Sherifabdelkhalek@mtc.edu.eg

Abstract. This comparative study aims to analyze the most relevant literature regarding Binder Jetting Additive Manufacturing (BJAM) process. The paper starts with section one to briefly introduce the process. Section two of the paper presents an overview of the technology; the main advantages and shortcomings are also addressed. Then, the materials that are mostly employed in BJ are introduced. In section four, the most important design considerations that must be taken into account in this process are presented. Section five of the paper compares the BJ systems available nowadays. Some relevant examples of components and geometries that can be created with this technology are presented next with special emphasis on applications for high-tech industries. Then, the main challenges and limitations along with the prospects of the BJ process are discussed. Finally, the main conclusions extracted from the literature review conducted are listed.

Keywords: Additive Manufacturing (AM), Binder Jetting (BJ), Digital Manufacturing.

1. Introduction

There are several motivations to make a comparative study about BJ technology, including: 1. Summarizing the state of the art: A comparative study can provide a comprehensive overview of the current state of BJ technology, including the latest developments and trends. This can be valuable for researchers and practitioners who want to stay up-to-date with the latest advances in the field. 2. Evaluating the advantages and limitations: A comparative study can evaluate the advantages and limitations of BJ technology compared to other AM techniques, such as fused deposition modeling (FDM) or selective laser sintering (SLS). This can help researchers determine whether BJ is the most appropriate technology for their specific application. most 3. Discussing potential applications: A comparative study can discuss the potential applications of BJ technology in various fields, such as aerospace automotive, biomedical, and consumer products. This can help researchers identify new opportunities for using BJ technology in their own research. 4. Identifying research gaps: A comparative study can identify research gaps and areas where further investigation is needed. This can help guide future research in the field and help researchers prioritize their efforts. 5. Providing guidance for future development: A comparative study can provide guidance for future development of BJ technology, including recommendations for improving the printing process, optimizing material properties, and enhancing the overall performance of the technology. This can help researchers and practitioners advance the field and accelerate the adoption of BJ technology in industry.

AM is a manufacturing technology based on slicing the 3D model into many layers (about 50 μm thick each) and then deposition of material layer by layer to create a three-dimensional component from scratch [1]. This material addition can be accomplished by melting the material feedstock through a heat source (mostly laser or electron beam technology) or gathered utilizing a binder agent. AM inputs vary between powder, wire, sheet, and resin that are selectively melted or gathered together to fabricate a 3D part. Figure 1. shows a classification of AM technologies depending on the source they employ to join the subsequent layers.

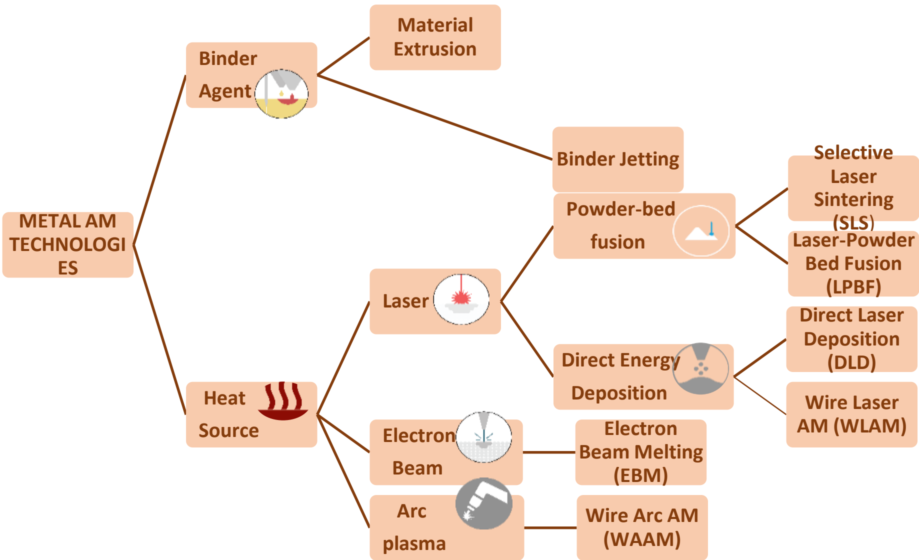

Figure 1. Classification of metal AM technologies [1].

Depending on the source employed to join the layers, AM technologies can be divided into two groups: (1) those that use a binder agent to join the material and (2) others that are based on a heat source that melts the feedstock material together. As shown in fFigure 1. this classification can be in turn subdivided into different and more specific technologies. Recently, parts with complex geometries, also parts made from advanced materials (ex. high temperature alloys, structural materials, ceramics, biomaterials, high entropy alloys, and shape memory alloys) which have great importance, have been successfully manufactured using various AM techniques.

AM technologies are the best ways to manufacture geometries with complex features in most metallic alloys or refractory materials that cannot be obtained by traditional methods. Many studies have been done making comparisons about the life cycle between AM and traditional methods [2]. The conclusion is, AM technology has many merits in reducing manufacturing time which leads to reduce cost as well because of reducing manufacturing procedures. Also, AM end the requirement to make design for special molds, patterns, and tooling [3]. The AM technologies have disadvantages for components manufactured by AM techniques, like high porosity and low mechanical properties, especially regarding surface quality and dimensional accuracies. That is why the components created by AM need a post-processing step to improve their surface qualities and dimensional accuracies. This kind of post-processing includes machining to reach the required accuracy or to clear the support structures used during the building process [4]. Also, surface and heat treatments will be needed as post-processing techniques as well [5].

2. Metal BJ Process

2.1. Process Overview

My focus will be on the BJ method which is one of the AM technology types in which the component is created by selectively depositing a binding agent on the powder bed to join the powder particles within about 50 μm layer sick then repeating the same process for the rest of layers. The resulting is called the “green part”, which should be de-binded and cured later to increase its strength. Sintering into a furnace gives the final strength also to reduce porosity and improves its dimensional accuracy, density, and mechanical properties [2],[4]. Figure 2 illustrates the steps of the BJ technology process.

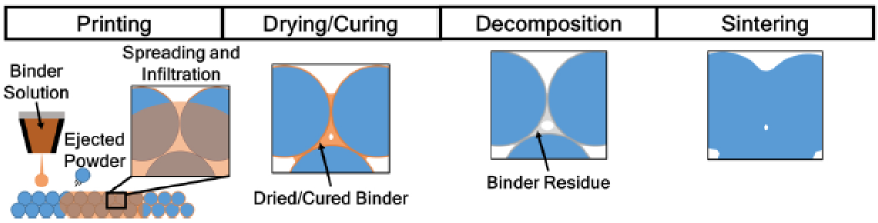

Figure 2. The steps of the BJ technology process [6].

Recently BJ Technology was adopted for building components with different materials (metals, ceramics, and refractory materials) because of its advantages regarding the other AM technologies as there is no requirement for a heat source to melt the powder particles during the building process. These advantages avoid common problems in laser-based technology like vaporization, cracking and weld-ability issues [7]. Another advantage is that it avoids using the temporary support structure used during building the complicated geometry parts [8].

2.2. Influence of process parameters

As shown in the previous section, MBJ is a multi-stepped technology. Therefore, the parameters controlling the process should be optimized to obtain the best results. Numerous works had been done to figure out the most effective parameters on the process quality. Regarding the literature the main parameters affecting the characteristics of the built parts are: (1) Powder characteristics (2) binder agent characteristics and (3) printing parameters [9]. Regarding the powder characteristics, the most important properties to be controlled that affect the final result are the powder morphology, particle size distributions (PSD), flow-ability and spread-ability [10].

Concerning the binder agent characteristics, proper rheology, stability, proper penetration, strength, clean burn off, proper binder droplet size must be ensured to get best performance [11]. Most employed binders are polymers (colloidal latex, polyethyleneimine for tungsten, aqueous acrylic and polyvinyl alcohol (PVA)). About binder delivery, print-head types also influence the process. There are two main types of printheads, the so-called drop-on-demand and the continuous-jet print-heads [12].

Finally, during printing itself, layer thickness, printing rate, drying time and heated power, component orientation and binder saturation play an important role in the final result [13]. Powder spread must be also controlled in terms of recoating speed or oscillator speed (depending on the powder delivery system), roller rotational and traverse speeds.

2.3. Post-processing techniques and their influence

Last step of the metal BJ operation, is subjecting the green part to a post-processing technique that aims to improving its density and mechanical properties. The main post-processing techniques applied.

2.3.1. Sintering

Sintering process is conducted in a furnace, where the green part is enclosed in a controlled atmosphere and subjected to a specific temperature during certain period [13]. In the following, research works that analysis the influence of sintering parameters on the results obtained in binder jetted metal components are presented.

More recently, Zheng et al. [14] compared the results obtained after sintering of Inconel 625 components at both sub-solidus (1270ºC) and super-solidus (1285ºC) temperature ranges and considering different powder size distributions. Regarding the influence of sintering temperatures tested, authors observed that super-solidus sintering promoted a uniform microstructure and improved final component density. Among other MBJ process parameters, Lecis, et al, [15] made an analysis to study the influence of the de-binding and sintering atmospheres and there effect on the microstructure, material composition and mechanical properties of the built part. They also simulated the phase formation during the sintering process. For the sintering stage, they found that vacuum sintering improves component densification as it reduces the risk for gas entrapment. Additionally, this avoids the need for extra sintering aids and reduces the dwelling times needed. In an attempt to increase the final density of components made from Magnesium. Su et al. [16] also proposed a tow-step sintering process that consists on rapidly increasing the density of samples in a first short sintering stage and a second sintering stage at a temperature slightly higher than the liquidus temperature. They noticed that the best density result was obtained when the first sintering step was done at 680ºC during 30 minutes and a second step at 610ºC during 6h. In fact, this two-step sintering parameters also led to the best mechanical properties and the best corrosion resistance.

2.3.2. Infiltration

The second post-processing technique could enhance the MBJ-ed components to reduce component porosity is the infiltration. This process is based on adding a second alloy with a melting temperature lower than the main part material aiming to cover the pores produced during the MBJ [16]. By using the infiltration technique, a composed material with enhanced properties is formed.

Many researchers worked on the infiltration techniques. Mudanyi, et al. [17] made a comparison between the results obtained after infiltration of Zr_2Cu into both sintered tungsten samples and un-sintered tungsten samples. They found that the un-sintered samples performed better and formed fewer unwanted phases when compared to the sintered samples.

S.L. Lu [18], used parts made from stainless steel 420 that had different ranges of porosities (6: 54 %) all made by the technology of BJ 3D printing. The post processing had been done by sintering the parts in temperatures varying between 1000 °C to 1400 °C. At 1150 °C, they observed symptoms of the neck formation. After they pre-sintered at temperatures between 1300 °C and 1350 °C, they found 3D interconnected open porous channels. Last step was sintering at 1400 °C, this step led to closed/isolated pores inside the parts. They made another trail by infiltrating bronze inside the as-built samples then pre-sintering to temperature < 1350 °C. The presence of 3D interconnected open porous channels, leaded to more uniform bronze infiltration which could be achieved for the pre-sintered parts at temperatures between 1300 °C and 1350 °C. By making the comparison with the as-built parts, they discovered that the pre-sintering at temperature of 1350°C, following by infiltration with bronze combination increase the tensile strength (σ_{yield} = 647 MPa, and $\sigma_{ultimate}$ = 1053 MPa, respectively).

Corson L. Cramer, et al, 2019 [19] used BJAM technology to produce complicated parts made from Tungsten Carbide Cobalt (WC-Co) on two steps, first sintering the "WC" powder then infiltration with "CO". They studied the shape retention, infiltration height, and parts properties. They found that mixing between BJAM and infiltration of the metal phase like Cobalt reduced the shrinkage and the grain growth in Cermet (Ceramic metal) composites like Tungsten Carbide. They characterized properties such as density, microstructure, grain size, and hardness of the parts with respect to the infiltration height.

S.L. Lu, et al, 2020 [20] Divided their research to two parts. First was applying sintering to parts made from stainless steel 420, all by BJAM which had different porosities within (6% to 54%) with three different heating ranges. Sintering with temperature (1000:1400 °C). a) The stainless steel 420 powder particles had Neck formation phenomena when sintering with 1150 °C. b) At higher temperatures 3D open-porous interconnected channels were found when sintering at (1300: 1350 °C). c) By temperature of 1400 °C, a complete close of the pores inside the parts occurred which isolated them. Second was following sintering by infiltration with Bronze into the finished parts. Increasing tensile strength can be achieved from optimizing the infiltration and sintering.

Ji-Ho Ahn, et al, 2021, [21] investigated the possibility of 3D printing of applications of the hard tissue engineering, especially the composite scaffolds which are biodegradable. So, they proposed a type of composite scaffold with a high percentage of ceramic polymer-based used for biodegradable applications. They can be manufactured by using the method of BJAM followed by infiltration on the way of capillary rise. They fabricated a scaffold made from the Calcium Sulfate Hemihydrate (CaSo4 – ½ H2O) by using BJAM. Afterward, the hydrothermal treatment was applied to convert (CaSo4 – ½ H2O) into Biphasic Calcium Phosphate (BCP), then heat treatment was used. Infiltration had been done by using Melted Polycaprolactone (PCL) into the BCP scaffold formed, which was made BCP dispersed in a matrix formed from PCL. The percentage of PCL that existed in the matrix which made from BCP override 40 % of the volume. The resultant scaffold which is made from the composite (PCL/BCP) earned the biggest value of the toughness, compressive strength, and moduli. Also, the mode of the fracture was reclassified to be brittle instead of less brittle. Their results referred to the existence of a very stable composite (PCL/BCP) surface which affect and increased the initial cell responses and showed a sufficient proliferation and differentiation of pre-osteoblast cells.

2.3. Advantages of Metal BJ
Many problems faced the other AM methods when printing some composite materials like for example tungsten with nickel, iron, and copper as matrix alloy elements. Because of the big difference in melting temperature and the limited solubility. Laser build parameters are considered as a significant challenge during seeking to produce Tungsten heavy alloy (WHA). That's why Binder jet printing became a suitable alternative AM method that can beat these significant challenges. BJ showed one of its merits in printing this type of powder successfully after that sintering was made to obtain higher density. The used material was tested in the condition of the as-sintered and it fulfilled all the ASTM-B777 demands related to the tungsten heavy alloy [22].

3. Materials
In this section, an overview of the materials that are most commonly employed in the MBJ process is presented. Stainless steels, Inconel super alloys, titanium alloys, copper, and composite materials are among the most employed [8]. Parts from these materials are common in all AM processes, in the following section, works focusing on materials that are used in the MBJ process will be discussed.

3.1. Bimetallic materials
As mentioned above, infiltration is one of the post-processing techniques employed to enhance component density in MBJ. It is based on the addition of a different material that will fill the pores left from the MBJ process, improving the properties of the generated component. Apart from the improved properties of the generated components, this infiltration process also enables the generation of biomaterial or bimetallic components through MBJ. In the following, a review of works focused on the generation of bimetallic materials through MBJ is conducted.

Recently, Cui et al. [23] analyzed the wear resistance of three different bimetallic materials generated by using the infiltration of Bronze in metal BJ technology stainless steel 316, stainless steel 420, and WC parts. They observed that all composites behaved similarly to those manufactured by traditional processes.

Zhanqi Liu, et al, 2020, [24] gave a special interest in 3D printing of materials used in the field of aerospace engineering like structures from bimetallic (BS) and titanium aluminum alloys which have wide applications in the manufacturing of the turbine blades in the aero-engine and TC4 which are used in turbine disks.

3.2. Ceramics
Fabrication of Al2O3 parts can be produced by the BJ technology using the ExOne M-Lab system machine by binder saturation of 60% and various layer thicknesses [25]. manufacturing using BJ is classified as an emerging technology with the merit of printing many of the materials already existing in the market, including metal, sand, and ceramics (316SS, 420SS, Inconel625, Iron, Silica). In their work, they fabricated parts by using the powder of aluminum oxide (Al2O3). They optimized the building parameters (e.g., layer thickness, saturation, particle size) also different sintering profiles were investigated to reach a density of (96%). They characterized materials' micro structure and physical properties. They subjected all parts to many tests like compression testing, dielectric testing, and full XRD. They were able to obtain sintered alumina parts with compressive strength of about 131.86 MPa (16h sintering profile). Filters and membranes are products classified as complex parts

which can be easily offered by AM of aluminum oxide, which is considered as one of the highest energy value components. Also, aluminum oxide can be considered as biomedical implants inside the structures of the integrated reticulated to enhance the Osseo integration.

Jimenez, et al, 2019, [26] made a parametric study containing 18 experiments that explored the effect of seven inputs of the BJ process on the proportional densities of parts in the green status (as-printed) made from aluminum oxide. They compared the effect of each parameter on the density of the green part and they showed the sensitivity analyses. They provided mathematical models to predict the green densities as a formula containing the input parameters of the BJ process. They found that the oscillator speed and the recoating speed were the most affecting parameters on the green density of any part made by BJ process. They concluded that by decreasing the value of the recoat speed and increasing the value of oscillator speed the alumina parts green density will be increased. There mathematical models showed that the other BJ process parameters had a nonlinear relation with the green density. Their produced models help in the selection of the process parameters which result to the best green part density, also allow reducing the percentage of porosity in the printed green parts. Their study can be considered a corner stone for extracting the input parameters and control the percentage of the porosity in the green parts fabricated by BJ process. The printable ceramic materials using BJ are [Ca5(PO4)3(OH), Ca3(PO4)2, Bioactive glass, Si/SiC, Dental porcelain, TiC/TiO2, CaO, LAS, Zr, Quartz/Mullite, Chromite, Plaster, Wax, SiO2, Si3N4, Al2O3, BaTiO3) [27], [28], [29].

3.3. Refractory materials

Refractory is the terms employed to refer to materials that are resistant to high temperatures and are used predominantly as furnace linings for the processing of materials at elevated temperatures [22], [30]. The BJAM is the only method capable of printing refractory materials because sintering is done outside the machine in HIP furnaces which can reach high temperatures easily. Many researchers used In their work, Oh, et al, 2021, [31] studied the possibility of using BJAM process for the generation of SiC because it is a very important industry material and very hard to be manufactured. The properties of SiC summarized in two points observed thermal stability, and high hardness. The normal production method is made in several steps which cost tools and materials wastes which are not recommended for lean manufacturing. They used phenolic resin during building the green part then the strength is modified by infiltering the cured phenolic resin to synthesized SiC by decomposing with carbon through the densification step. Marco Mariani, et al, 2021, [32] made a successive trail to create WC/Co (12%Co) parts using BJAM. They adopted the strategy of building the green part from a mixture of fine particles and coarse particles then sintering was made in ssintering furnace at 1400oC. The resultant parts reached density of almost 99.3%. They discovered the existence of layer-oriented porosity after sintering. The resultant Vickers hardness was 1205 HV and transverse rupture strength (TRS) was 2257 MPa.

3.4. Ni-based alloys

Metal BJ has also been used for the manufacturing of Ni-based alloys that are considered as difficult materials due to their outstanding properties that are maintained even in harsh environments and at high temperatures. Mostafaei, et al, 2018, [33] were the pioneers to evaluate the microstructure of parts printed by BJAD using ball milled Ni-Mn-Ga powder followed by sintering for two hours in 1020^{o}C in HIP resulting to density about 80% also they measured the magnetism saturation which was 68.4 Am2/kg. In the case of γ' Ni-based alloys, conventional powder bed fusion AM technologies (L-PBF and EBM) led to the formation of samples that are prone to cracking and with high residual stress fields. As an alternative to these technologies, in their work, Martin, et al, 2021, [34] used MBJ to manufacture RENÉ 105 Ni-based ultra-high strength super alloy. They achieved a 96% density sample after sintering that was later improved to fully dense by applying HIP treatment.

3.5. Magnetocaloric materials
Recently new materials attracted the AM researchers to work on. The Magnetocaloric (MC) materials, or ferromagnetic shape memory alloys (FSMA), or Magnetic Shape Memory Alloys (MSMAs) these type of alloys react with forces or deformations as response to a magnetic field. One of the applications of these alloys is the field of the solid-state magnetic refrigeration. Stevens, et al, 2022, [35] worked on manufacturing the designs for solid state cooling from (MSMAs) with low cost. They used NiMnCuGa alloy powder for binder jet process. They proved the viability of BJAM as an effective fabrication method for functional magnetocalorics, also the outstanding MC characteristics of a low-cost Ni-Mn (Cu)-Ga Heusler FSMA type.

4. Design considerations/rules in Metal BJ
In order to obtain optimal results when manufacturing a component through MBJ, there are certain design considerations that must be taken into account that are related to process limitations.

4.1. Shrinkage
Definition of shrinkage in MBJ is the dimensional and geometrical change produced by the anisotropic dimensional variation during sintering which appears very clearly on the cylindrical holes, which are produced with different sizes and different inclination axes' using BJ technology. An analytical model has been proposed for calculating the diameter shrinkage percentage, the circularity error, and the error of the axe inclination angle, which happened during the sintering of the green part. The calculation was done by comparing to the nominal dimension in the green state and also by the anisotropic dimensional change in the reference system of the fabrication as shown in figure 3.

Figure 3. Structural alumina part before (left) and after (right) sintering with shrinkage [36]

Shrinkage is mainly consequence of binder agent removal and densification of the green part by sintering. Wang, et al, 2017, [37], studied the effect of different sintering profiles on the shrinkage rate on parts made by BJ process. They applied different sintering parameters values and checked the accuracy of linear dimension. The study was made on stainless steel 316L parts. They came up with a recommended set of parameters' values.

Marco Zago, et al, 2021, [38], focused on cylindrical holes made during producing parts by BJ which are the most affected during the sintering process. Dimensional and geometrical precision for five different parts each had four holes made from AISI 316 were done. Different holes orientations according to the direction of printing. They applied their model on different geometries and building orientations. The model results were matched with the realty.

4.2. Part dimensions
Printer characteristics must be taken into account from the first steps when designing the component. Apart from the machine characteristics, there are other considerations regarding component dimensions. There is a maximum wall thickness that the system will be able to print. The upper limit of the wall thickness is determined by the ability of the binder agent to diffuse through the wall during the sintering process. As an example, in the Desktop Metal BJ system, manufacturers suggest a maximum wall thickness of 25 mm and not to exceed 25 mm in more than two axes. Additionally, the recommend a minimum wall thickness above 0.75 mm, as lower values may result in insufficient strength in the brown part. According to these manufacturers, even 2mm wall thickness might be still fragile during the de-powdering process. Finally, the relation between dimensions in different direction must also be taken into account. Especially, the width of certain features may limit the maximum achievable height, slot depth or whole depth.

5. Challenges, limitations and future prospects of the technology
In spite of all the benefits provided by Metal BJ process, as it is still an immature technology, there is still much to study and research. In this section, a review of the main process shortcomings and challenges that the researchers will have to face in the near future, will be presented.

5.1. Dimensional accuracy
Distortion of manufactured components is a common issue in all metal AM processes and it is also a problem to consider in MBJ. There are works in the literature focused on the analysis of the influence of different process parameters and geometric features on the distortions generated. Additionally, some authors had also tried to minimize these distortions based on the results obtained in numerical simulations of the process.

Recently, Maximenko, et al, [39] investigated the effect of powder spreading on the resulting distortion on the walls printed at different inclination angles both numerically and experimentally. They observed that by increasing the heights at the final layers, distortion of samples also increases.

5.2 Powder recycling
As in other AM processes, the cost of feedstock material limits sometimes the applicability of the process in a larger scale. Therefore, some researchers have focused their efforts on the analysis of reusability or recyclability of unused powder.

Mirzababei, et al, [40] analyzed the characteristics of unused 316L stainless steel powder particles after MBJ. Additionally, they generated a new component with recycled powder in order to assess the feasibility of powder reusability. Authors observed an increase of coarse particle percentage with respect to virgin powder. Regarding powder morphology, they noted a more irregular shape probably due to particle agglomeration. The component produced with reused powder showed a slightly lower density when compared to the one created with virgin powder and similar hardness and yield strength.

6. Conclusions
BJ started thirty years ago; the method has been applied to a wide range of materials. Different commercial applications are adopting this technology. BJ technology is a potential solution where conventional methods fail because it is suitable for most powdered materials. There is a growing body of knowledge increasing because many researchers give attention to this method which guides the process and the powder material development. As long as the knowledge base is increasing, the wider range the feasible industrial applications. As soon as the knowledge base is stronger, and the early patents will be expired, the machine manufacturers' competition will be increased in the future. Many researchers worked to optimize the process, but despite, these efforts there are still many points that need to be emphasized.

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References

[1] Gibson I, Rosen D, Stucker B, Khorasani M, Rosen D, Stucker B and Khorasani M 2021 *Add. Man. Tech.* **17** 1
[2] Swetha R, Krishna L, Kiran B, Reddy P and Venkatesh S 2022 *Materialstoday Proc. To.* **62** 4332
[3] Raoufi K, Haapala K, Etheridge T, Manoharan S and Paul B 2022 *J. Man. Sys.* **62** 202
[4] Malakizadi A, Mallipeddi D, Dadbakhsh S, M'Saoubi R and Krajnik P 2022 *Int. J. Mach. Tools Man.* **179** 103908
[5] Motallebi R, Savaedi Z and Mirzadeh H 2022 *J. Mat. Res. Tech.* **20** 1873
[6] Oropeza D and Hart A 2021 *Add. Manuf.* **48** 102448
[7] Stawovy M, Myers K and Ohm S 2019 *Int. J. Ref. Met. H. Mat.* **83** 104981
[8] Lores A, Azurmendi N, Agote I. and Zuza E 2019 *Pow. Met.* **62** 267
[9] Bartual C, Pitarch M, Martínez E and Gómez-Tena M 2022 *Open Ceramics* **11** 100285
[10] Capozzi L, Sivo A and Bassini E 2022 *J. Mat. Pro. Tech.* **308** 117706
[11] Deng H, Huang Y, Wu S and Yang Y 2022 *Manuf. Proc.* **74** 365
[12] Liu H, Lei T, Ma C and Peng F 2021 *Add. Manuf.* **37** 101627
[13] Crane N 2020 *Add. Manuf.* **33** 101127
[14] Zhang M, Yang Y, Wang D, Song C and Chen J 2019 *Mat. Des.* **165** 107583
[15] Lecis N, Mariani M, Beltrami R, Emanuelli L, Casati R, Vedani M and Molinari A 2021 *Mat. Sci. Eng.* **828** 142108
[16] Ahsan M, Fan X, Seo G, Ji C, Noakes M, Nycz A, Liaw P and Kim D 2021 *J. Mat. Sci. Tech.* **74** 176
[17] Mudanyi R, Cramer C, Elliott A, Unocic K, Guo Q and Kumar D 2021 *Int. J. Ref. Met H. Mat.* **94** 105411
[18] Crane N 2020 *Add. Manuf.* **33** 101127
[19] Cramer C, Wieber N, Aguirre T, Lowden R and Elliott A 2019 *Add. Manuf.* **29** 100828
[20] Lu S, Meenashisundaram G, Wang P, Nai S and Wei J 2020 *Add. Manuf.* **34** 101266
[21] Ahn J, Kim J, Han G, Kim D, Cheon K, Lee H, Kim H, Kim Y, Jang T and Jung H 2021 *Add. Manuf.* **41** 101988
[22] Stawovy M, Myers K and Ohm S 2019 *Int. J. Ref. Met. H. Mat.* **83** 104981
[23] Cui S, Lu S, Tieu K, Meenashisundaram G, Wang L, Li X, Wei J and Li W 2021 *Wear* **477** 203788
[24] Liu Z, Ma R, Xu G, Wang W and Liu J 2020 *Mat. Let.* **263** 127210
[25] Gonzalez J, Mireles J, Lin Y and Wicker R 2016 *Cer. Int.* **42** 10559
[26] Jimenez E, Ding D, Su L, Joshi AR, Singh A, Reeja-Jayan B and Beuth J 2019 *Add. Manuf.* **30** 100864
[27] Lv X, Ye F, Cheng L, Fan S and Liu Y 2019 *Cer. Int.* **45** 12609
[28] Du W., Singh, M and Singh D 2020 *Cer. Int.* **46** 19701
[29] Moghadasi M, Du W, Li M, Pei Z and Ma C 2020 *Cer. Int.* **46** 16966
[30] Zhuo L, Liu C, Yin E, Zhao Z and Pang S 2022 *Comp. Part A: App. Sci. Manuf.* **162** 107147
[31] Oh J, Park J, Nahm S and Choi H 2021 *Int. J. Ref. Met. H. Mat.* **101** 105686
[32] Mariani M, Goncharov I, Mariani D, De Gaudenzi G, Popovich A, Lecis N and Vedani M 2021 *Int. J. Ref. Met. H. Mat.* **100** 105639
[33] Mostafaei A, De Vecchis P, Stevens E and Chmielus M 2018 *Acta Mat.* **154** 355
[34] Martin E, Natarajan A, Kottilingam S and Batmaz R 2021 *Add. Manuf.* **39** 101894
[35] Stevens E, Kimes K, Salazar D, Mostafaei A, Rodriguez R, Acierno, A, Lázpita, P, Chernenko V and Chmielus M 2021 *Add. Manuf.* **37** 101560
[36] Zago M, Lecis N, Vedani M and Cristofolini I 2021 *Add. Manuf.* **43** 102007
[37] Wang Y and Zhao Y 2017 *Pro. Manuf.* **10** 779

[38] Zago M, Lecis N, Vedani M and Cristofolini I 2021 *Add. Manuf.* **43** 102007
[39] Maximenko A, Olumor I, Maidaniuk A and Olevsky E 2021 *Pow. Tech.* **385** 60
[40] Mirzababaei S, Paul B and Pasebani, S 2020 *Jom* **72** 3070