Mechanics & Industry **23**, 22 (2022)

https://doi.org/10.1051/meca/2022023

Mechanics & Industry

Available online at:
www.mechanics-industry.org

Regular Article

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A new method with ultrasonic mechanism for efficient depowdering of parts produced by electron beam melting

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Received: 26 January 2022 / Accepted: 1 July 2022

Abstract. Among metallic additive manufacturing technologies, electron beam melting (EBM) requires a specific operation called depowdering once a part is built. With the help of a powder recovery system (PRS), this process consists in blowing titanium powder onto a “cake” of a manufactured part in order to separate sintered but not melted powder from the part itself. However, the depowdering of some geometries can in fact become difficult, even impossible, due to the part shape. This article aims at proposing an ultrasonic depowdering mechanism that allows to improve and to quantify the depowdering capabilities of the PRS system currently used. Experimentations are led onto geometries that include canals. A “depowderable depth”/diameter criterion is then applied for comparing the depowdering capacity of the proposed system with the traditional one. First results show that the quantity of powder removed onto samples is highly enhanced with an ultrasonic process. This outcome creates opportunities since additional tests could be implemented onto more complex shapes such as, for instance, parts with internal complex shapes.

Keywords: Electron beam melting / depowdering / powder recovery system / ultrasonic shot peening

1 Introduction, state of the art and objectives

1.1 Introduction: about electron beam powder bed fusion

Powder Bed Fusion (PBF) is a relatively recent additive manufacturing process that includes Direct Metal Laser Sintering (DMLS), Electron Beam Melting (EBM), Selective Heat Sintering (SHS), Selective Laser Melting (SLM) and Selective Laser Sintering (SLS). These technologies allow to make parts of complex shape that meet accurate specifications [1]. They push back the frontiers of part design by achieving the best possible shapes [2–5]. However, these technologies may differ in terms of manufacturing steps. For example, EBM technology encompasses seven steps, from Computer Aided Design (CAD) to Quality Control (QC), see Figure 1 [6]. This includes a critical depowdering or powder removal operation that consists in removing what is called a “part cake” of lightly bound powder so it can be recycled and reused in a further build.

Powder removal follows the additive manufacturing step and precedes support removal. For many reasons, it has a significant impact onto the part quality, post processing duration, health and safety, part surface finish... At this stage, the part is trapped into the sintered powder and needs to be taken off. To carry on the depowdering activity, a Powder Removal System (PRS) is used [7], so that the cake (Fig. 2) is blasted off thanks to the same metallic powder as the cake under air pressure of 5 bars.

The powder is afterwards sieved in order to be reused. Based on these observations, the success rate of PRS depowdering is variable according to part features or specificities. For instance, some complex shapes like internal surfaces with angular shapes and holes (blind holes or through holes) remain difficult to depowder.

1.2 State of the art

Today, few studies about depowdering are available for PBF technologies. Among them, EBM process solely has to include the specific step of depowdering in its manufacturing process. Indeed, DMLS, SHS, SLM and SLS do not encounter this issue since, during additive manufacturing, powder is not melted into a cake. As far as EBM technology is concerned, the conventional method of removing the powder is PRS [7]. Research works have been carried out by Vayre [8], making it possible to predict the capacity of

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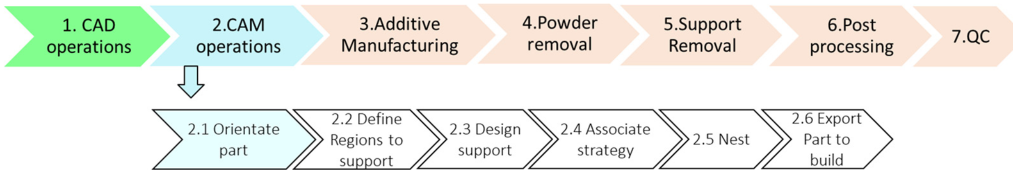

Fig. 1. EBM process steps.

Fig. 2. EBM cake to be depowdered.

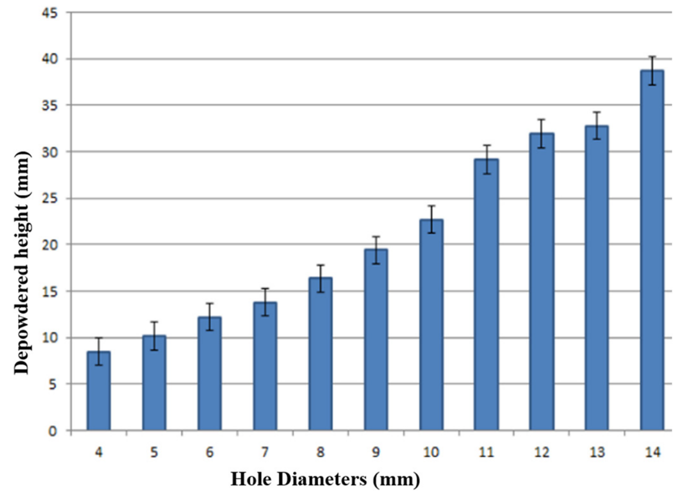

Fig. 3. Depowdered height vs blind hole diameters from [8].

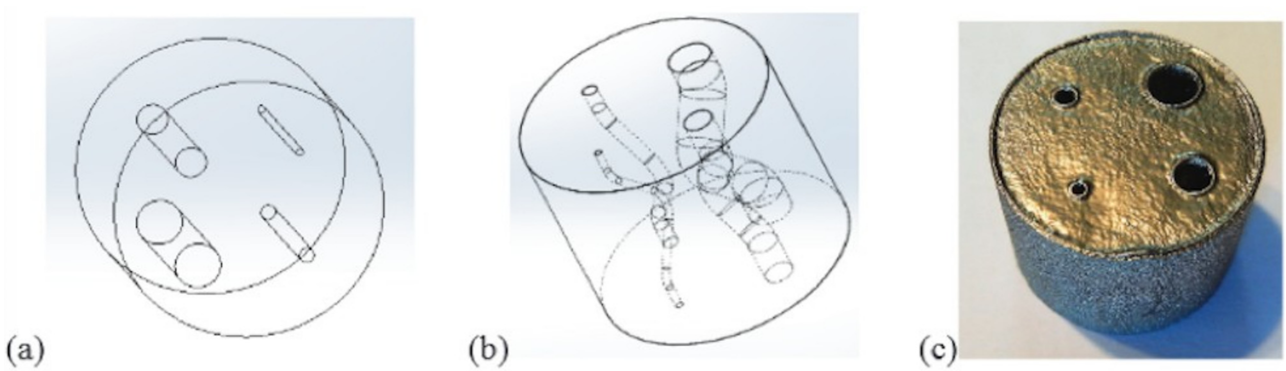

Fig. 4. (a) CAD cylinder design with straight channel features, (b) CAD cylinder design with curved channel features, and (c) Additive Manufactured Cylinder from [10].

depowdering means with a ratio between the height (i.e. depth) of the depowdered part and the diameter of cylinders. Vayre's model proposes an average depowderable height based on a cylinder diameter that contains consolidated powder. His proposition led to the "depowderable height"/diameter ratio from 2 to 3 by using PRS only, see Figure 3.

Other latest researches have also been carried out by Carre et al. [9] who predict the depowdering capacity of lattice structures based on hydraulic diameter. All these approaches characterize the ability to depowder by implementing a PRS [7], but little is described about other working approaches. Lopes et al. [10] provide a state of the art of different depowdering means for EBM technology. The authors carried out a first depowdering operation thanks to the PRS and managed to remove around 3 out of 6 grams of consolidated powder. They applied six depowdering methods to remove the remaining powder. The best results allowed to eliminate a maximum of 0.17 additional grams of remaining powder. Different diameters and shapes have been studied, all related to cylinders, Figure 4.

The same authors show that efficient solutions are liquid based, such as chemical etching. However, such actions do not allow the powder recycling mentioned in Section 1.1. In addition, they point out that further experimentations are required to remove powder from internal cavities.

Based on this review of the literature, the authors emphasize the need to design and develop a non-liquid based system for eliminating the remaining powder. This system should thereby at least be more efficient than PRS used alone or would complement PRS.

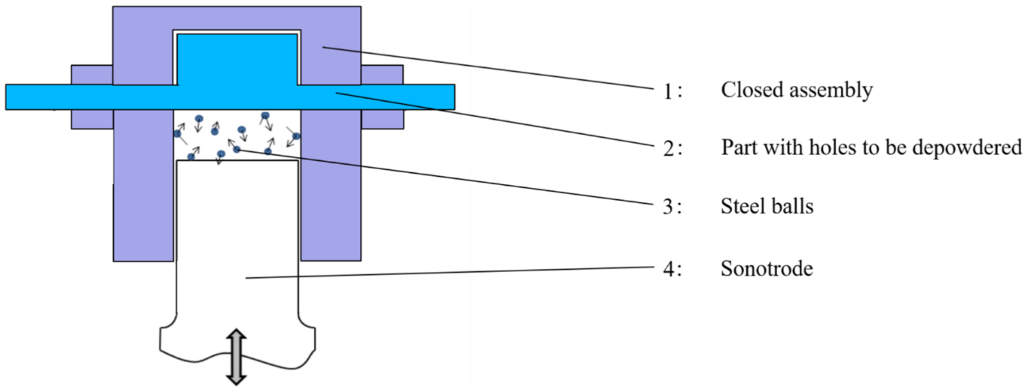

Fig. 5. Shot peening installation.

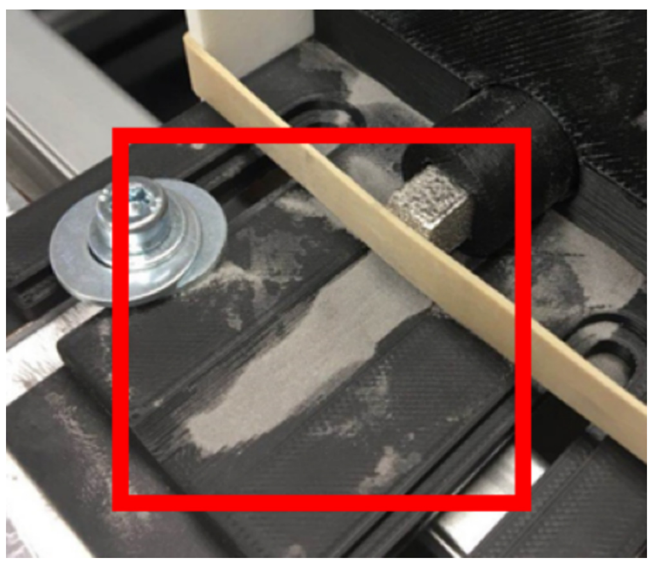

Fig. 6. Powder passed through the shot peening installation.

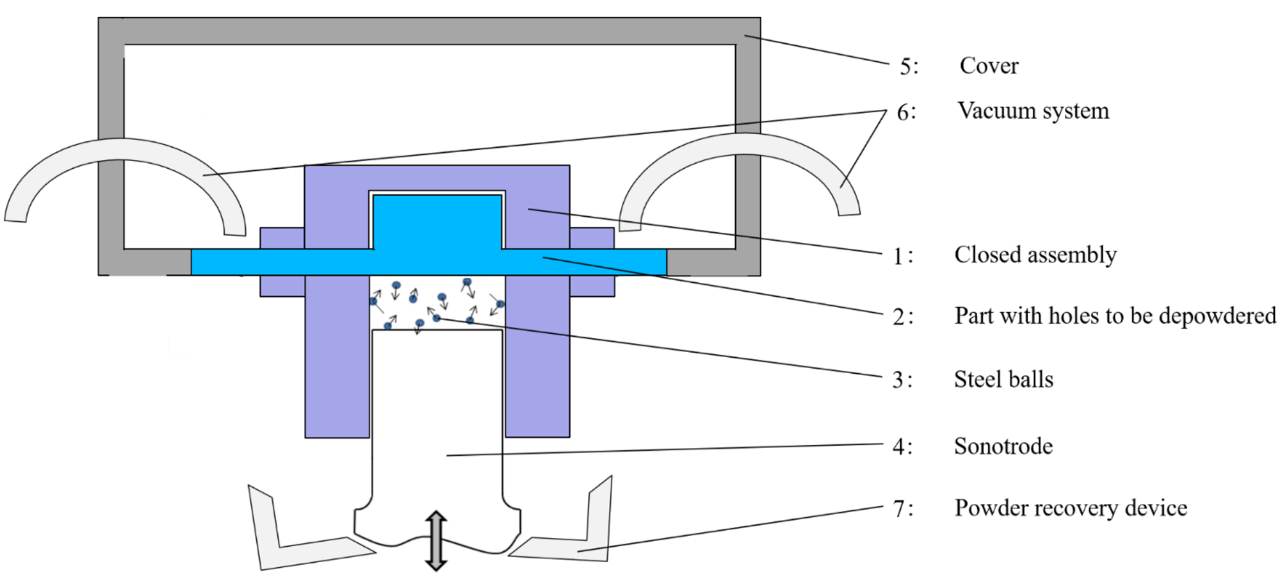

Fig. 7. Presentation of the whole operating system.

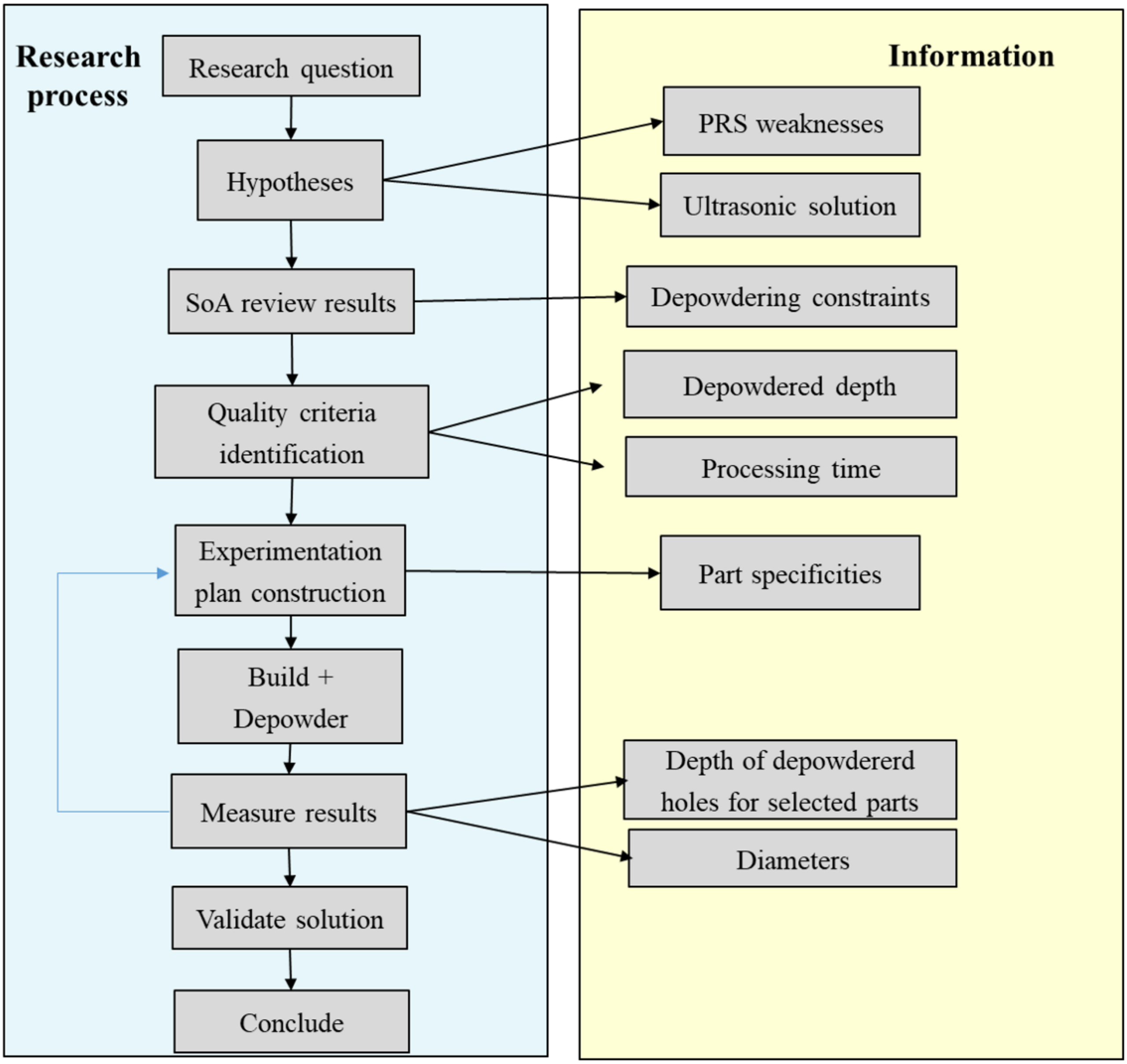

Fig. 8. Research approach.

1.3 Objectives and research question

This paper aims at proposing a method for depowdering complex internal part geometries more efficiently than with PRS solely. Indeed, it is currently easy to depowder external surfaces with PRS, which in not the case for internal surfaces such as holes. It strives to analyze the depowdering of various part hole depths so as to overcome the current limitations of EBM part depowdering process.

Moreover, this research takes into consideration Titanium powder as material, i.e. Ti-6Al-4V alloy.

Given EBM-related constraints, the research question is then the following: how to improve the depowdering process of EBM parts and which criteria could help to evaluate and characterize any new performances?

2 Context and approach

2.1 Context

After manufacturing and depowdering parts with EBM it is usually necessary to carry on post process operations so as to improve the surface finish. As finishing process, an Ultrasonic Shot Peening (USP) installation (Fig. 5) highly enhances the surface finish of EBM parts [11]. During research work related to this finishing process, it is observed that some powder escaped from parts that, therefore, have not been previously depowdered correctly with PRS (Fig. 6). This leads to the conclusion that USP could contribute to complete the depowdering process initiated by PRS. It is then decided to study the USP installation and compare it with results obtained solely with PRS.

2.2 Description of the USP installation

The part that is subjected to shot peening (2) is maintained by the closed assembly (1) which prevents the steel balls (3) from escaping. The sonotrode (4) vibrates in the ultrasonic domain, 20085 Hz, which is the default frequency of the shot peening installation. This helps to set in motion the steel balls and shot peen the whole part (2). The ball projecting onto the part surfaces with consolidated powder allows to remove the remaining powder.

However, this device cannot be used as it is because the device is not enough sealed and lets the powder pass between (1) and (2), but also (1) and (4) of the shot peening installation (Fig. 6).

As titanium powder is risky for AM operators, it necessary to improve the system in order to avoid any contact with it. A cover (5) has been designed, as well as a vacuum system (6) and a powder recovery device (7) to prevent any projecting risk. Figure 7 presents the whole operating system that is used in the following experimentations for comparing its efficiency with the PRS performance.

Based on this context, an approach is proposed in the next section and relies on the identification of criteria for defining the conditions of several cases studies.

2.3 Approach

The following approach consists in identifying for each research step the critical information that would lead to the conclusion about a solution proposition (see Fig. 8). Hence, considering the research question and the context, some hypotheses related to PRS weaknesses and ultrasonic solution have been made. Completed with a state of the art review, few depowdering methods showed some constraints and led us to list the depowdering quality criteria, namely the "depowderable depth"/diameter ratio after depowdering as well as the processing time. Several experimentations are thus prepared in order to study different types of part specificities. The complementary depowdering results are finally compared with the classical PRS system solely used.

Next section presents in details experimentations done with ultrasonic shot peening system characteristics as well as their results.

3 Trials and results

The "part cake" containing samples used in our different trials has been depowdered with PRS. Attention is paid on the holes of the samples which were purposely not depowdered. Indeed, the objective is to characterize the depowdering process of USP only (without PRS) for depowdering holes, i.e. the internal part geometries of the samples.

3.1 Preliminary trial

In order to validate the performance of the USP system for depowdering EBM parts, various samples with

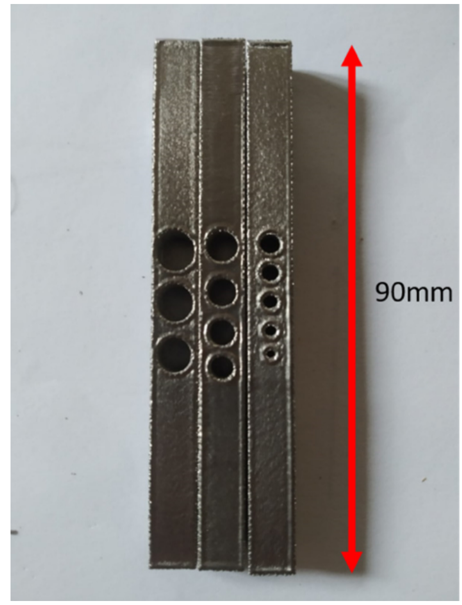

Fig. 9. Samples containing holes with diameters from 1mm to 6.5 mm with a pitch of 0.5 mm.

through holes are designed, see Figure 9 (left). The samples contain holes with diameters from 1 mm to 6.5 mm with a pitch of 0.5 mm and a depth of 7.5 mm. Indeed, the maximum part width in the USP installation is 7.5 mm, which requires a minimum thickness of 0.5 mm at each side of holes. Hence, the maximum possible diameter of holes is 6.5 mm.

The aim of this experiment is to check if the USP is able to remove the consolidated powder from the holes and to determine the minimum diameter of the holes that can be depowdered. The results show that through holes are depowdered, with the exception of holes with diameters from 1 to 2.5 mm; the reason is that the diameters of these holes are too small for the 1mm balls to fit in and remove powder.

3.2 Final trial

3.2.1 Design of samples and experimentation method

To characterize the USP process, new samples are designed, with a minimum diameter of 3 mm due to the fact that smallest diameters cannot be depowdered. The length of the samples is imposed by the size of the EBM build chamber (200 × 200 × 180 mm). Thus, samples are designed with vertical holes, diameters from 3mm to 5 mm (sample a.) and from 5.5 mm to 6.5 mm (sample b.) and a length of 180 mm due to space constraints, see Figure 10.

Throughout the experiment, the depth of the holes concerned is measured with a caliber every 2 min along the depowdering operation. From the moment when this depth is below 2 mm, the timestep is modified from 2 to 20 min. Indeed, the depowdering phenomena being logarithmic, there is no more evolution of the depowdering process when the powder inside the holes cannot be any longer removed. For this experimentation, the operation is stopped after 220 min.

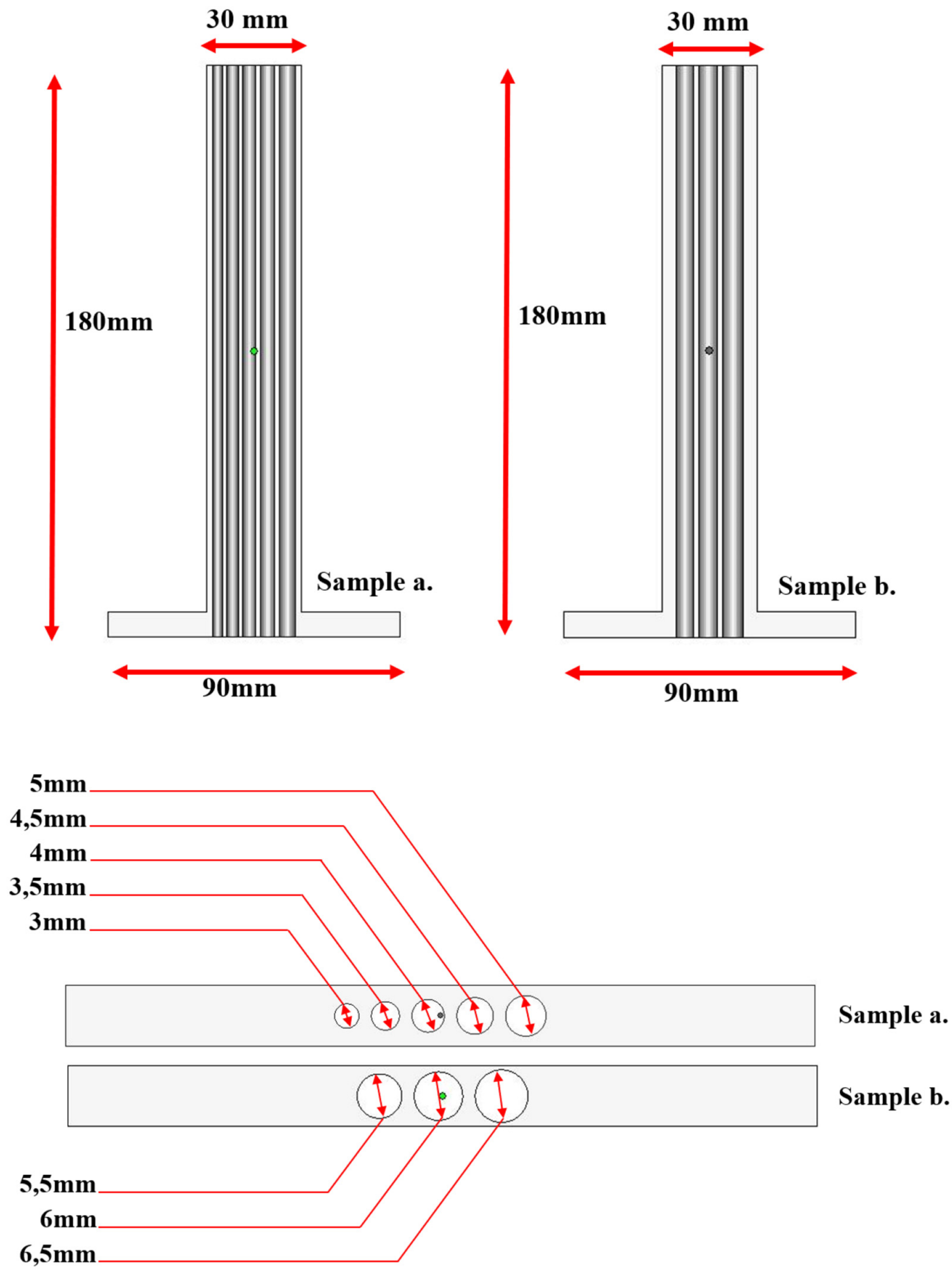

Fig. 10. Samples with holes (sectional view and bottom view).

3.2.2 Results

The evolution of the depowdered depth based on the depowdering time can be seen in Figure 11. For instance, it take 220 min to depowder 124 mm out of 180 mm for a 6 mm diameter hole and to depowder 45 mm for a 3 mm diameter hole. In addition, we can observe an impact of the holes position onto the depowdering performance. Indeed, the "depowderable depth"/diameter ratio becomes smaller for holes that are located at both ends of the sample. An explanation can be that there are statistically more balls which are projected in the holes close to the center than on the ends, thus contributing to a better depowdering of the centered holes.

In Figure 12, the maximum "depowderable depth" in function of each hole diameters of our experiments is represented. A linear regression is calculated in order to propose a model for predicting the "depowderable depth" of

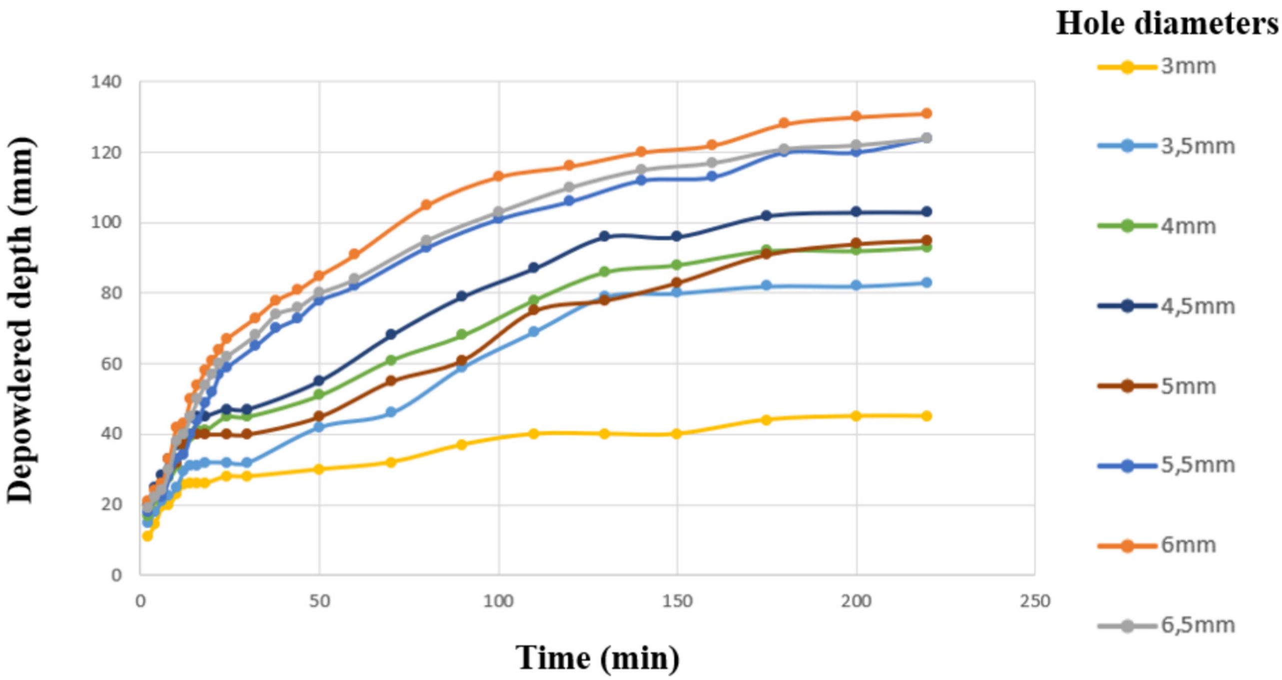

Fig. 11. Holes with diameter range of 3–6.5 mm.

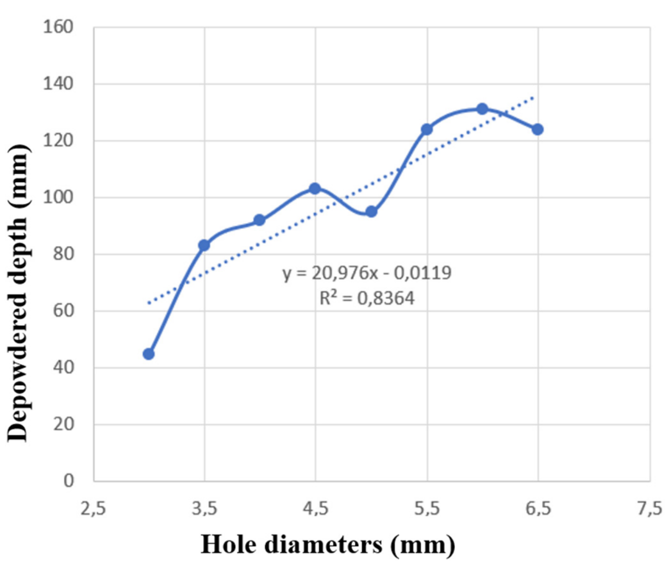

Fig. 12. Depowdered depth vs hole diameter and resulting linear regression.

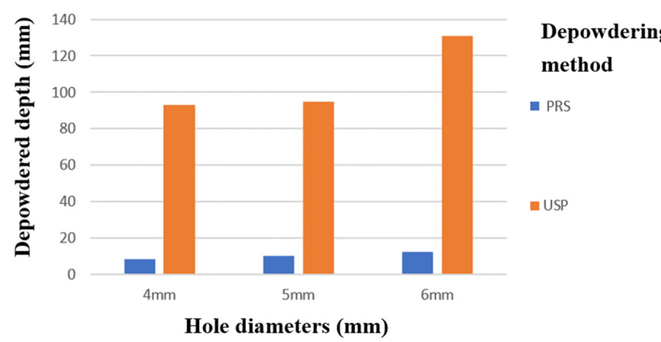

Fig. 13. Comparison of the results of parts depowdered by PRS [8] with the parts depowdered by USP.

straight holes according to their diameters, and for hole diameters from 3 mm to 6.5 mm. This information could be used during the design process of EBM parts in order to ensure that the holes in the designed parts can be depowdered. Figure 13 shows the depowderable depth depending on the hole diameters. It compares the results of parts depowdered by PRS [8] with the parts depowdered by USP. The "depowderable depth"/diameter ratio ranges from 2 to 3 for parts depowdered with PRS and from 15 to 23 for part depowdered using USP.

4 Conclusion

4.1 Contribution

This research strove to complete the PRS method for depowdering EBM parts. As a start, the comparison of the various depowdering solutions currently proposed in the scientific literature highlighted weaknesses in terms of depowdering mechanisms and lack of study results. The analysis of current process needs in terms of quality, compared to this state of the art, has led to the identification of depowdering quality criteria. These criteria concern the depowdering ratio ("depowderable depth"/diameter), after PRS and USP, as well as the processing time for depowdering. The selected samples range from 3 mm to 6.5 mm diameter and 180mm length. After depowdering process with the ultrasonic system, the depth of removed powder based on the depowdering time is measured. These experimentations enabled us to propose a model for predicting the depowdered depth of holes relatively to their diameters.

As a conclusion, this methodology can enrich current researches in PBF depowdering systems and provides perspectives for future researches about EBM part quality. These trials give indeed promising results that highlight the main assets of this new method.

4.2 Perspectives

From an industry point of view, to enhance the depowdering system of EBM technology will have high beneficial effect. For instance, it could be interesting to make mono-bloc heat exchangers that contains conformal cooling channels, or else, to build lattice structures with a density above the boundaries highlighted by [9]. To do so, additional research work would be required for tackling needs such as to determine the depowdering limits for parts with internal complex shapes or to extend the method to a depowdering device with bigger dimensions. Moreover, this study has been conducted using the default frequency of the USP installation. Studying the variation of this frequency onto the depowdering performance could be investigated.

Lastly, it would be interesting to test this depowdering mechanism with more complex internal geometries, for instance conformal cooling channels.

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Cite this article as: P.-T. Doutre, C. Grandvallet, M. Museau, A new method with ultrasonic mechanism for efficient depowdering of parts produced by electron beam melting, Mechanics & Industry **23**, 22 (2022)