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# Robot-based chiselling for the removal of support structures from PBF-LB/M manufactured Haynes 282

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**Abstract**
This study explores a robotic chiselling method for the automated removal of support structures from metal workpieces produced by Powder Bed Fusion by Laser Beam. Current methods for the removal of support structures face challenges such as manual and complex process chains and costly machine tools. In this study, robot-based chiselling of support structures from additively manufactured test specimen was performed and the removal of support structures was analysed. The experiments demonstrated over 95 % removal efficiency of support structures under optimal conditions, showcasing the potential for safe support structure removal and reduced manual labour. A chiselling strategy was developed for geometrically complex specimens, ensuring complete support structure removal. This work contributes to advancing automated post-processing in additive manufacturing, aiming to enhance efficiency and product quality while laying the foundation for future research on optimizing chiselling processes.

Additive Manufacturing, Support Structure Removal, PBF-LB/M, Automation

**1. Introduction**

Removing support structures from metal workpieces manufactured by Laser Powder Bed Fusion (PBF-LB/M) poses significant challenges. Currently, these support structures are removed using manual or automated processes. Various methods are used depending on the material and geometry. Popular methods and tools include Wire Electrical Discharge Machining (WEDM), milling, mechanical band saws and manual removal with handheld grinders, pliers and sandpaper [1]. Often a WEDM machine, milling equipment and a band saw are required to first separate the workpiece support from the build plate before the actual removal of the support structures from the part [2].

These methods for support structure removal face several challenges. Often, post-processing steps are time-consuming and cost-intensive, impacting the efficiency of the entire manufacturing process. Although various approaches exist for the removal of metal support structures, manual separation remains the most widely used method. More sophisticated technologies are gaining traction but are still at a relatively low technological level [2]. Manual processes can damage the workpiece due to inadequate handling and often impose physical strain on the user.

Automated processes, such as milling or WEDM, require precise control to accurately remove the support structures without damaging the workpiece. They are also limited in working space and may have mechanically restricted accessibility. Investigations reveal that the design and process parameters during the additive manufacturing of Ti-6Al-4V overhang structures significantly affect the removability of the support structures [1]. Moreover, the design of the support structures not only has an influence on the stability and build time $t_b$ during additive manufacturing, but also affects the post-processing parameters during milling [3, 4]. Bending and vibrations are particularly common when milling thin-walled components, potentially impacting the accuracy of the machining process or damaging the workpiece. [3]. The machining strategy during milling also influences the surface roughness and the machining time $t_m$ [3].

Unconventional approaches have also been explored for the removal of support structures. Etching after sulfidation has been investigated as a chemical method for the automated removal of support structures from workpieces manufactured from Ti-6Al-4V. Etching dissolves the support structures and reduces the surface roughness. It offers the advantage that it is independent of the parameters of the printing process and can even be applied to mechanically inaccessible supports [5]. Another approach involves semi-automatic support removal using dry ice blasting. This mechanical process ensures gentle processing of sensitive components and represents a significantly lower physical strain on the user compared to manual processes [6].

Automated processes are still underdeveloped, yet essential for the series production of PBF-LB/M workpieces. These automated systems could not only reduce processing time $t_P$, but also improve consistency and accuracy by delivering reproducible results. The use of pneumatic chiselling tools for the automated removal of additively manufactured support structures can provide a cost-effective approach compared to other methods. Chiselling can be effective for large quantities of support structures, as these have a defined weak point that breaks when chiselling force $F_{Ch}$ is applied [7]. This method is often used in manual post-processing. PLAKHOTNIK ET AL. [2] investigated robotic chiselling of different types of support structures in IN718. It was demonstrated that removal can be carried out in an automated manner. However, not all investigated support structure geometries could be removed [2]. This study focuses on investigating the influence on the chiselling force $F_{Ch}$ and the development of a processing strategy for support structure removal on geometrically complex surfaces.

## 2. Methodology

### 2.1. Experimental setup

A robotic cell with an industrial robot Smart NJ 320 2.7 manufactured by Comau S.p.A., Grugalisco, Italy, was utilized to perform the chiselling experiments. The industrial robot was equipped with a clamping device to position the sample workpieces, while the pneumatic chisel hammer MLH-MLM by Schneider Airsystems GmbH, Reutlingen, Germany, remained in a fixed position. This setup allows sequential processing of workpieces in one clamping, which reduces the effort required to measure the position of the workpiece. A chiselling stand was constructed from aluminium profiles and firmly anchored to the ground. The mount, which secures the pneumatic chisel hammer, was machined from aluminium blocks to ensure rigidity. A cover protects essential components, such as pneumatic tubes, from potential damage caused by debris. The chiselling force $F_{Ch}$ is regulated by a pneumatic air regulator with a maximum pressure $p_{max}$ = 0.8 MPa.

### 2.2. Specimen

Chiselling experiments were performed on two types of test specimen. The specimens are additively manufactured by PBF-LB/M from Haynes 282 material. All test specimens feature a multistage support structure. Volume supports were applied to the interface to the build plate, and lattice supports were applied on the interface of the test specimens. A simple rectangular specimen was used to identify potential processing parameters. The rectangular specimens measure a length $l_r$ = 75 mm, a width $w_r$ = 25 mm, and a thickness $d_r$ = 5 mm, as shown in Figure 1.

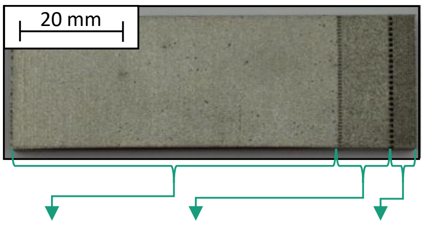


**Figure 1.** Rectangular test specimen with multi-stage support structure

Geometrically intricate demonstrator specimens were used to evaluate the selected parameters under more realistic conditions. These demonstrator specimens feature various geometries, such as convex and concave surfaces, and the same multi-stage support structure as the rectangular test specimen. The demonstrator specimen are divided into three versions A, B, and C as seen in Figure 2.


**Figure 2.** Demonstrator test specimen

### 2.3. Parameters

The parameters air pressure p,and the chisel tool were systematically varied in the chiselling process. Experiments were performed with pressure $p_1$ = 0.3 MPa, $p_2$ = 0.5 MPa and $p_3$ = 0.7 MPa. The tilt angle was set at α = 90 °. The experiments were performed with a straight and a curved chisel tool.

### 2.4. Evaluation of chiselling efficiency

To evaluate the efficiency of support structure removal, gravimetrical analysis of the separated mass of the support structures $m_S$, as well as the remaining mass of the workpieces with residues of the support structure $m_W$ was performed. The proportion of the separated mass of the support structures $\Delta m_S$ was determined by dividing the separated mass of the support structures $m_S$ by the difference between the mass of the workpiece with support structure $m_{W+S}$ and the theoretical mass of the workpiece $m_W$, as seen in Equation 1. The theoretical mass of the workpiece $m_W$ was determined by the workpiece volume $V_W$ = 750 mm³ and the density of the material $\rho_{H282}$ = 8.18 g/mm³ with a relative density of $d_{rel}$ = 99 %.

$$\Delta m_S = m_S / (m_{W+S} - m_W) \quad (1)$$

## 3. Results

### 3.1. Chiselling experiments of rectangular specimens

The experiments carried out with the curved chisel did not allow the support structure to be removed from the specimens. This was attributed to the unfavourable effects of the chiselling forces $F_{Ch}$. With the flat chisel at a tilt angle α = 90 °, the support structures could be successfully removed. The results of the support structure removal are shown in Figure 3 shows the specimen of the first trial run at $p_1$ = 0.3 MPa, $p_2$ = 0.5 MPa and $p_3$ = 0.7 MPa with removed support structures, as well as the specimen of the second trial run at $p_2$ = 0.5 MPa where the support structures remained attached to the workpiece.

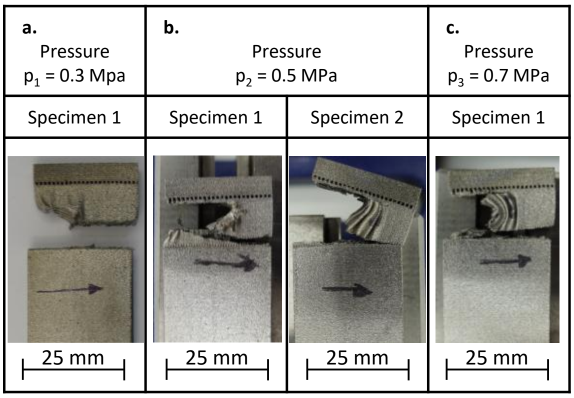


**Figure 3.** Results of the support structure removal with a. pressure $p_1$ = 0.3 MPa, b. pressure $p_2$ = 0.5 MPa and c. pressure $p_3$ = 0.7 MPa

Figure 4 shows the proportion of separated mass of the support structures $\Delta m_S$. At a pressure $p_1$ = 0.3 MPa, a proportion of separated mass of the support structures $\Delta m_{S1}$ > 95 % was achieved. As shown in Figure 3a, the separation of the support structure shows fracture of the lattice supports close to the surface of the test parts. This indicates that the support structures in the attachment area to the component were torn off, resulting in almost complete removal of the support structures. At a pressure $p_2$ = 0.5 MPa, the support structures could only be removed from one of three test specimens. A proportion of separated mass of the support structures $\Delta m_{S2}$ = 90 % was achieved. The lattice support structure material was not completely removed. Support structure material remained at the start of the machined zone. It is considered that the chiselling force $F_{Ch}$ led to cutting of the support structure material rather than tearing off the support material from the part surface. At a pressure level of $p_3$ = 0.7 MPa, the support structures were successfully separated. A proportion of separated mass of the support structures $\Delta m_{S3} > 90$ % was achieved. On all test specimen, residual material that had not been removed from the part remained attached to the part surface.

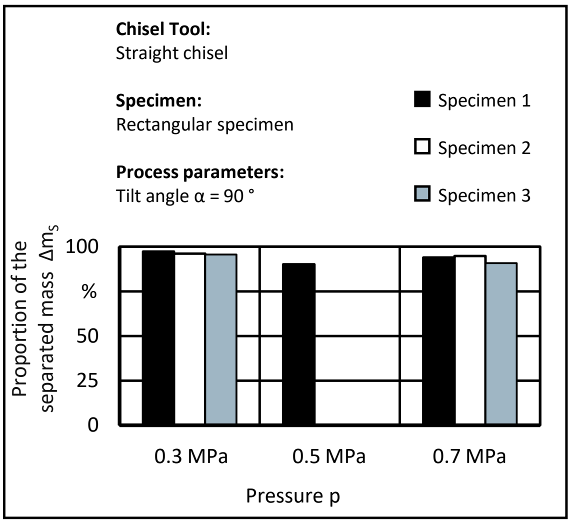


**Figure 4.** Proportion of the separated mass of the support structures after chiselling

The results show that support structures of the additively manufactured components can generally be removed using the chiselling process. Tearing off the support structures was identified as advantageous, as this results in almost complete material removal, whereas residual material from the support structures remains on the workpiece during cutting.

### *3.2. Machining strategy for demonstrator specimens*

Building on the parameters and findings from the flat specimens, a general processing strategy for complex specimens was developed. The strategy, applied across all three demonstrator units, is depicted in a flowchart in Figure 5.

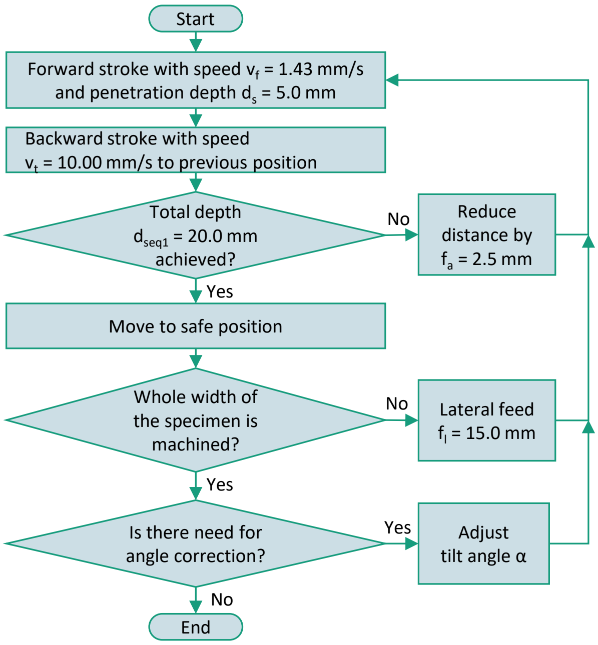


**Figure 5.** Flowchart of the developed machining strategy for demonstrator specimen with complex geometry

For demonstrator C, the chiselling process is carried out according to the following two machining phases. First, a cyclic forward and backward movement is performed. The forward stroke is performed at a speed $v_f = 1.43$ mm/s, with a penetration depth $d_s = 5$ mm. The backward stroke is performed at an increased travel speed $v_t = 10.00$ mm/s. After each stroke, the distance between workpiece and chisel tool is reduced by the axial feed distance $f_a = 2.5$ mm. This sequence is repeated until a total depth $d_{seq1} = 20$ mm is reached. At the end of each chisel path, a lateral feed of $f_l = 15$ mm is performed. This process is repeated until the entire width of the workpiece has been machined. To machine the rear support structures, the tilt angle α is adjusted to prevent collisions and damage to the component. This involves tilting the demonstrator to a tilt angle of approximately $\alpha = 100$ ° while adjusting its position to optimize the reach of the chisel tool to the remaining support structures. The described chiselling strategy is applied again without changing the machining parameters. In this second processing sequence, however, the target depth is $d_{seq2} = 45$ mm. This ensures that the rear support structures are also completely removed. Due to the reduced component width, a total of three machining paths are carried out.

### *3.3. Chiselling experiments of demonstrator specimens*

The chiselling experiments conducted with demonstrator specimens indicated that the removal of the support structure at $p_2 = 0.5$ MPa yielded better results compared to removal at $p_1 = 0.3$ MPa and $p_3 = 0.7$ MPa. In contrast, the rectangular specimen exhibited the best results at $p_1 = 0.3$ MPa. This variation can be attributed to the engagement of the chisel tool, which spans the entire chisel tool width $w_c = 20$ mm, whereas in the previous tests on the rectangular specimen the engagement was restricted to the workpiece width of $w_r = 5$ mm. Complete removal of the support structures from all three demonstrator workpieces was successfully performed. As seen in Figure 6, the workpieces have a rough surface after the chiselling process. In some cases, residues of the support structures remain on the workpiece. Residual support structure material is pressed against the workpiece by the chisel and deformed. The low guiding tolerance and lateral deviation of the chisel tool during the machining process results in damage to the edges of the workpiece. The separated support structures exhibit deformation and tearing from the workpiece. However, it is not observed that support structures were cut by the chisel tool as seen in Figure 2b.

Despite the identification of suitable process parameters for separating the support structures, complete removal was not possible for small and intricate features due to limited accessibility. In particular, the accessibility of the chisel to the support structures at the rear edge of the workpiece was identified as a challenge. By applying the developed machining strategy and adjusting the tilt angle α, the removal of the support structures in the rear area of the workpieces was achieved for the demonstrator parts subject to this study. Furthermore, a high degree of process instability was observed. This is attributed to the high wear on the cutting edge of the chisel tool. A frequent change of the chisel tool was required.

## 4. Conclusions

This study successfully demonstrates the effectiveness of a robotic chiselling method for the automated removal of support structures from metal workpieces manufactured via PBF-LB/M. Through a series of experiments utilizing a robotic cell equipped with a pneumatic chisel, a systematic investigation of key parameters affecting the chiselling process, including air pressure p, tool type, and tilt angle α was performed.

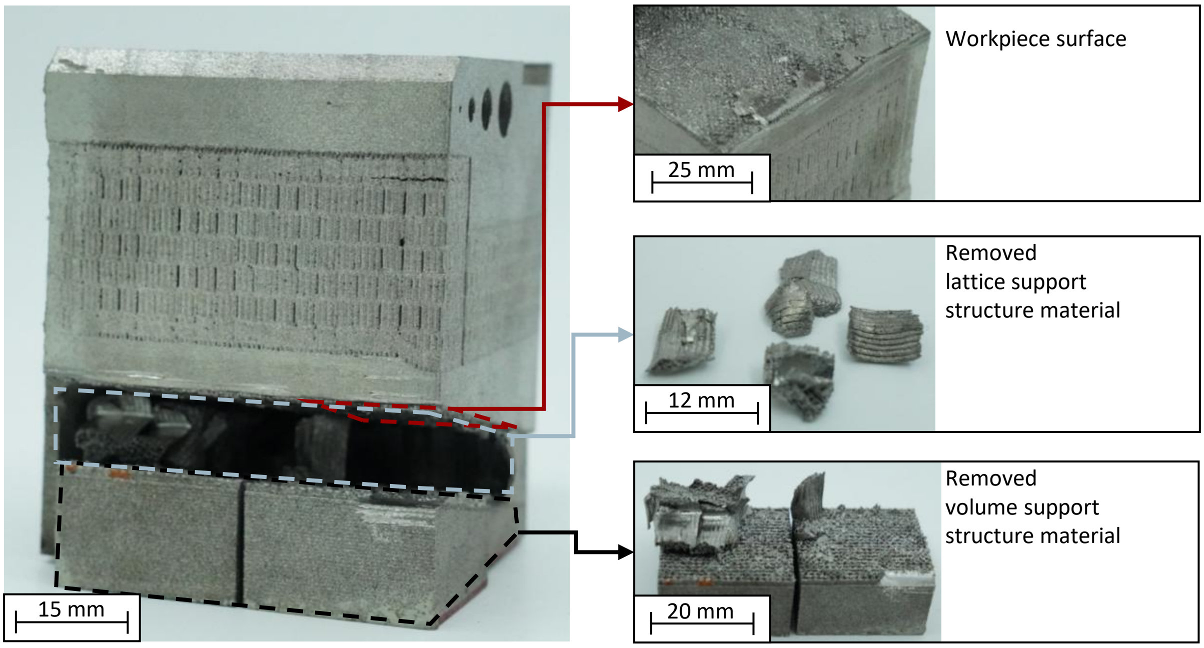


**Figure 6.** Results of the support structure removal for demonstrator A

The experimental results indicate that optimal chiselling parameters significantly influence the removal efficiency. Notably, a pressure of $p_2$ = 0.5 MPa yielded the best results for geometrically complex specimens, achieving substantial support structure removal. For smaller specimen, a lower pressure $p_1$ = 0.3 MPa resulted in the most efficient support structure removal. It can be concluded that the parameters must be chosen according to the workpiece and machining situation. Overall, the results demonstrate that automated chiselling with industrial robots is an efficient method for removing support structures, achieving removal of over $\Delta m_{S1}$ > 95 % of the support structure material. However, challenges remain, particularly concerning the accessibility of the chiselling tool to intricate geometries and the wear on the chisel, which necessitates frequent tool changes.

Overall, this research contributes valuable insights into the development of automated support structure removal technologies. Further investigations into optimizing chiselling strategies and exploring complementary automated techniques are essential to enhance the robustness and applicability of this method in industrial settings.

## Acknowledgement

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