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METAL 3D ADDITIVE MACHINING FOR IN-VACUUM BEAM INSTRUMENTATION

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Abstract

3D additive machining by selective laser melting (SLM) has great potential for widespread use in the field of accelerator instrumentation. However, as with any new process or material, it must be adapted and qualified for use in the specific in-vacuum accelerator environment.

This paper outlines recent developments of this technology for beam instrumentation in CERN accelerators. It covers topological optimisation, design and production methods for SLM, validation and testing of samples and components to qualify the production process. It also reports on experience with operation in multiple machines.

INTRODUCTION

The CERN Beam Instrumentation Group manages more than 2000 in-vacuum instruments across the whole accelerator chain with several hundred different designs. With tens of designs in progress at any time for consolidation and new projects, there is a strong interest in taking advantage of emerging technologies and processes that offer either enhanced functionality or more cost effective production.

SLM offers both of these possibilities, allowing for the simple and rapid production of forms that are not readily machinable. In addition, it is a process that is well suited to the small series of parts generally required.

The capital cost of metal SLM equipment is falling rapidly and desktop plastic 3D printing equipment allows easy prototyping.

SLM LIMITS AND QUALIFICATION

There are a number of well-documented constraints that apply to SLM. Typical powder grain size of 30 µm limits feature sizes and wall thicknesses to a minimum of ~0.4 mm, as a minimum number of fused grains are required to ensure mechanical integrity. This also limits achievable surface roughness without post-machining to Ra 12.5 (ISO N10). Tolerances are limited by thermal deformations and component design, but typically are not better than 0.1 mm between two separated points. Although many geometries that are not possible using conventional machining can be produced by SLM, some forms, particularly flats parallel to the plane of product build-up are not possible. Thus an understanding of the production process is needed by the designer. A specific training course for CERN designers on 3D additive manufacture was therefore organised with a manufacturer.

Additional constraints are imposed by the application of the final component to an in-vacuum, accelerator environment. SLM uses a powder semi-product of which only a small fraction is integrated into the part. The rest is re-used in successive cycles, sometimes up to 20 times. This recycling was considered a risk factor for introducing impurities into the powder, particularly as it is an abrasive dust manipulated by technicians with plastic gloves. Any powder sintering process such as SLM tends to produce products with some porosity and reduced mechanical strength compared with smelted materials. This could also cause problems of virtual leaks if pores are open.

In order to address these potential issues, three cuboid samples were produced using SLM with dimensions 2×2×1 cm. One sample was made with new powder the second with powder after 10 re-uses and the third with powder after 18 re-uses. They were tested on a standard 'vacuum qualification' bench at CERN, measuring outgassing rate via pressure variation across a known conductance and measuring gas spectra with a Residual Gas Analyser (RGA) [1]. No difference was seen between the three samples either for outgassing or in the RGA spectrum, within the limits of the measurement (1.55×10^{-8} mbar.l.s^{-1}.cm^{-2}, limited by the background outgassing). A further test, putting all three samples together gave a value for total outgassing of 6.23×10^{-9} mbar.l.s^{-1}.cm^{-2} H_20 equivalent after 10 hours of pumping. The pump-down curve showed a 1/t slope, typical of a clean, unbaked, metallic surface. The RGA was also typical of an unbaked, metal surface with mass elements greater than 44 all 4 orders of magnitude below the 18 (H_2O) peak, indicating no heavy contamination (see Figure 1).

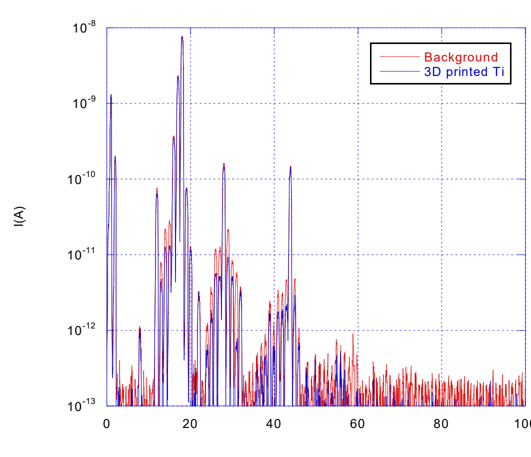

Figure 1: RGA scan of titanium blocks made by SLM from 'recycled' powder blocks.

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APPLICATIONS FOR BEAM INSTRUMENTATION

Fast Beam Wire-Scanner Forks

The first application selected for this process was a 'fork' for fast Beam Wire-Scanners (BWS). A BWS functions by rapidly passing a thin (~30 µm) carbon filament, held in place with a fork, across the beam (see Figure 2). The intensity of the secondary particle shower produced by these interactions is measured downstream of the scanner with a scintillator outside the vacuum chamber. By combining an accurate measurement of the wire position with the shower intensity, a transverse beam profile measurement is achieved. A new generation of BWS is being built at CERN for the high brightness beams foreseen following the LHC injector chain upgrade [2]. These require wires that can scan the beam at 20 ms^{-1} and a wire position measurement accurate to within 10 µm, which is a factor of 50 more precise than the existing fast scanners. The scanner must accelerate the wire to its maximum speed in ¼ of a rotation, giving a peak acceleration of 15600 $rad.s^{-2}$. These two requirements imply an optimised fork design with a high stiffness in two planes and low inertia to minimise motor torque requirements.

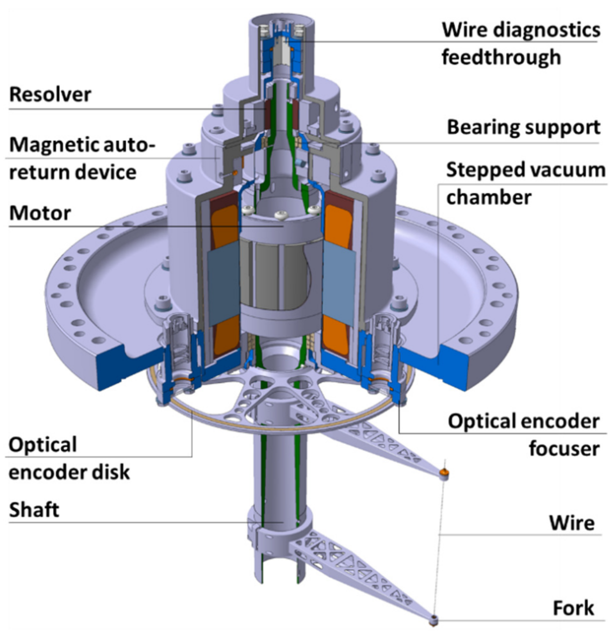

Figure 2: Part-section of the new wire scanner design showing the fork and wire.

The approach taken was first to use a topological optimisation code to generate a fork shape, iteratively removing material to converge towards an optimum for the given loads and displacement maxima (see Figure 3a) [3]. This shape was then refined into a 3D model which was further optimised based on dynamic stress analysis using the ANSYS FE code (see Figure 3b). The design was then adapted for production by SLM. The direction of 'growth' was defined along the long axis of the fork, and horizontal surfaces either removed or reinforced with removable tabs. Considering the requirements for high stiffness and low inertia, the Titanium alloy Ti6Al4V was selected as the most suitable from the limited choice available (Figure 3c).

Figure 3(a-d): Design and production process for titanium wire scanner forks, showing successively: Optimisation; analysis; SLM product and finished fork.

Overall form tolerances and surface roughness from production were sufficient for the application, however, grain size limitations, thermal distortions and stress relaxation heat treatment meant that tightly-toleranced interface features needed to be post-machined (Figure 3d).

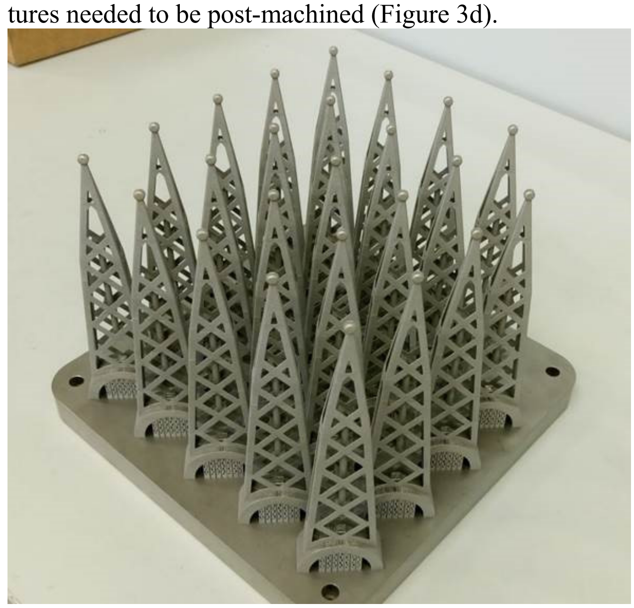

Figure 4: Series production of wire scanner forks.

Some prototypes and samples were produced for process development and test. A series of 56 forks with slightly different lengths and geometries was then produced in three batches using this process (see Figure 4). The series production was highly cost-effective, with each high-precision fork costing ~35% of the original, conventionally fabricated part.

Scanner Cable Chains

A major programme of instrumentation consolidation is in progress at CERN's ISOLDE (on-line isotope mass separator) facility. This includes the re-design of several beam needle scanners which function by scanning a needle across the beam and measuring the deposition of electrical

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charge from the beam on the needle. These scanners cover 350 mm horizontal apertures at speeds of up to 100 mm.s^{-1} with the signal extracted through a coaxial cable that must be properly constrained in order to avoid interfering with the beam. The redesign of these scanners is described in detail in another contribution at this conference [4], with the focus here being on the 3D additive machining used in their manufacture.

Cable-carrying chains are widely used for moving machinery. At ISOLDE, vacuum and radiation-tolerance requirements coupled with space constraints imply that off-the-shelf chains cannot be used. The solution was to design and produce a custom metallic chain.

The first step was to print several single links using thermoplastics. The links could be easily assembled together and used as a proof-of-concept. Typically, ABS or PLA are used for plastic 3D printing, the latter was used for this application. Soluble PVA supports were added to the holes. The chain links were then placed in water such that these could dissolve and the final part was ready to be tested.

In order to fully validate the design, two small chains composed of six pre-assembled links were then made in Ti6Al4V using SLM. The clearance between any two moving surfaces was 150 µm, which was found to be too small for the chain links to move smoothly. Additionally, the holes on each link had slightly collapsed as the top of the hole was not supported. The chain was saw cut from the base plate rather than using wire Electrical Discharge Machining (EDM) cutting as the former option was faster. A new chain was designed to address the aforementioned issues. The clearance was increased to 200 µm and a keyhole feature was added at the top of all holes. Additionally, the length of the printed chain was increased from 6 to 32 links, to validate the full-length design. In this instance, the chain was cut from the base plate using wire EDM cutting which is more precise.

The resulting chain had a good clearance between parts and the hole geometry was accurately reproduced, however, the chain had almost no bending radius, collapsing onto itself and rendering it unusable. This was found to be caused by the change in cutting process. Saw cutting removes less material from the chain and therefore the final result does not fully represent the nominal design. This masked a fault in the original design.

Taking this into account, two new designs were made to ensure the bending radius was properly defined. One design included a feature to limit the rotation of each link to 15º as seen in Figure 5. In the second design the chain height was increased by adding material at the chain base – as it proved to be useful in the first prototype.

The final chain prototypes have a full length of approximately 280 mm and were printed as a whole assembly. The links move smoothly relative to one another and the individual link features as well as the chain bending radius are well defined.

This validated design can now be adopted for similar applications in moving instruments.

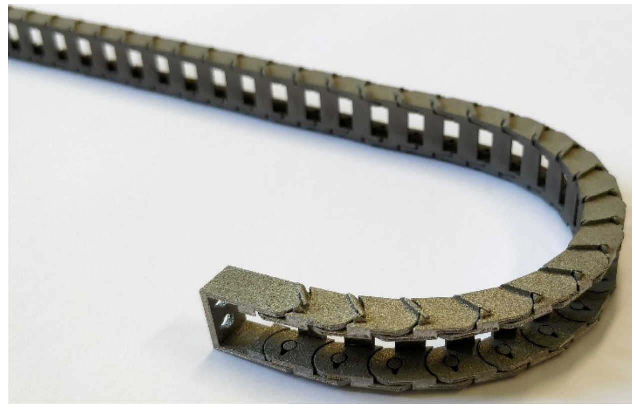

Figure 5: Titanium cable chain made by SLM.

EXPERIENCE WITH ACCELERATOR OPERATION

Wire scanner forks produced by SLM have been used in fast wire scanner prototypes installed in operating CERN accelerator rings, each scanner fitted with one fork composed of two SLM supports. The first prototype was installed in the Super Proton Synchrotron (SPS) ring in January 2015, with a second installed in the Proton Synchrotron Booster in 2016 and a third in the Proton Synchrotron (PS) in 2017. The three prototypes have slightly different fork designs to accommodate the different beam apertures in the machines. SPS and PSB installations used forks produced by an external company (3T-RPD Ltd.) with the PS and subsequent series produced in-house at CERN. A total of 6 prototype scanners were produced, with all forks passing vacuum qualification for installation without issue, irrespective of production path.

These prototype scanners have been extensively used with more than 100,000 cycles on test benches and 10,000+ cycles with beam. No issues – mechanical, vacuum or machine impedance related – have been encountered with the forks. A series of 25 scanners is now in production for installation in 2019.

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