LASIMM - AM production of large scale engineering structures

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Abstract

Additive manufacture (AM) has great potential for having a major impact on the production of components or parts in the future. There are a wide variety of AM processes and for each application, the potential benefits need to be identified and the optimum process matched. The use of AM in the production of high strength, high integrity metals for application to large (several meters) engineering structures would have a significant impact potential. It is envisaged that if this could be achieved cost effectively it would have the potential to revolutionize major engineering sectors, such as energy (including renewables), construction and aerospace. From the several AM techniques, Wire Arc Additive Manufacturing(WAAM) is a technique with clear potential for such applications. The present paper details the concept to be developed in the LASIMM project, addresses the preliminary results regarding productivity and quality of large WAAM parts and outlines the potential of NDT techniques towards an in-line integration.

1. Introduction

Today, we are at the beginning of a Fourth Industrial Revolution, which consulting firm McKinsey describes as the next phase in the digitization of the manufacturing sector, driven by four disruptions: the rise in data volumes, computational power and connectivity; analytics and business-intelligence capabilities; human-machine interaction and improvements in transferring digital instructions to the physical world. Taken together, they will lay the foundation for a revolution more comprehensive and all-encompassing than anything we have ever seen. One of the pillars of this revolution is additive manufacturing, also referred to as 3D printing. Additive manufacturing—the industrial version of 3-D printing—is already used to make some niche items, such as medical implants and to produce plastic prototypes for engineers and designers. And while 3-D printing for consumers and small entrepreneurs has received a great deal of publicity, it is within manufacturing that the technology could have its most significant and lasting commercial impact.[1]

Looking at AM there are different technologies, all with their strengths and weaknesses and therefore generally not directly competing for specific applications. Figure 1 provides an overview of the main AM processes.

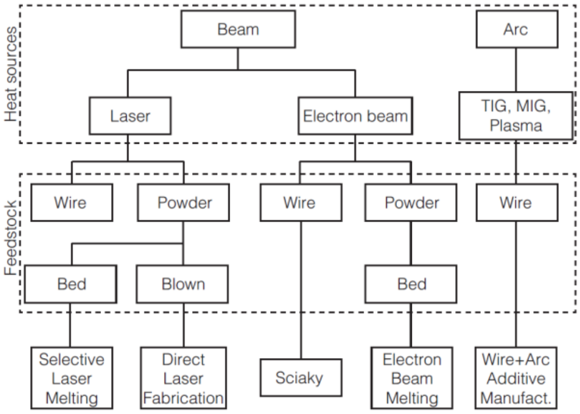

Figure 1 - Current main AM processes [1]

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Looking at metal AM, there are several processes available which can be considered for the production of engineering structures:

- Powder bed systems – These systems utilise a closed chamber with pre-placed metal powder which is then locally melted using either a laser or electron beam;
- Blown powder systems – These systems direct a stream of metal powder into a laser beam and these or the part are moved by a motion system and components are produced in a freeform manner;
- Wire + arc additive manufacture (WAAM)[2] systems – These systems are based on conventional or modified weld cladding technology combined with a motion system and components are produced in a freeform manner. This process can be combined with interlayer cold work such as rolling to give material properties in excess of those of forged or wrought materials[3,4,5];
- High deposition wire based systems – These systems are primarily based around an electron beam in vacuum chamber with multiple wire feeds which are moved with a scanning electron beam to produce components in a freeform manner.

A comparison of these strengths and weaknesses can easily be made using spider diagram as shown below.

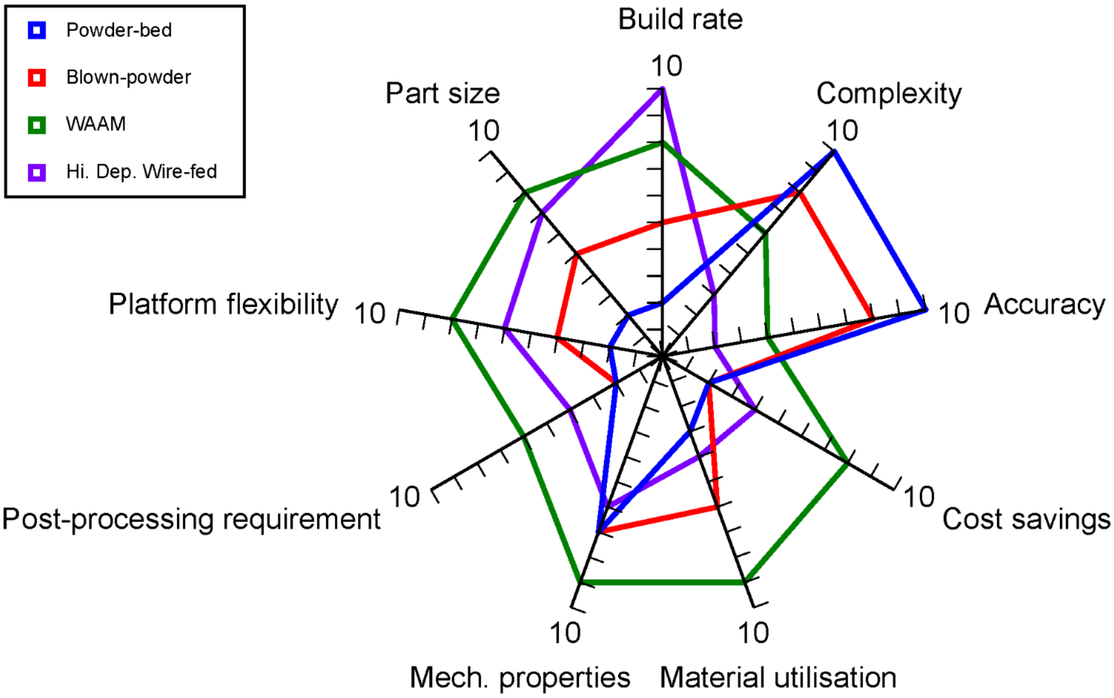

Figure 2 - Comparison of strengths and weaknesses of different metal AM processes [5]

For the envisaged AM production of large scale engineering structures an analysis of the requirements above indicates that the most important features required from the process are: mechanical properties, build rate, build envelope and cost savings. Therefore, it is clear from **Error! Reference source not found.** that the process of choice for this application is WAAM. Typically, the WAAM process is carried out using one or more standard industrial articulated arm robots combined with part manipulation.

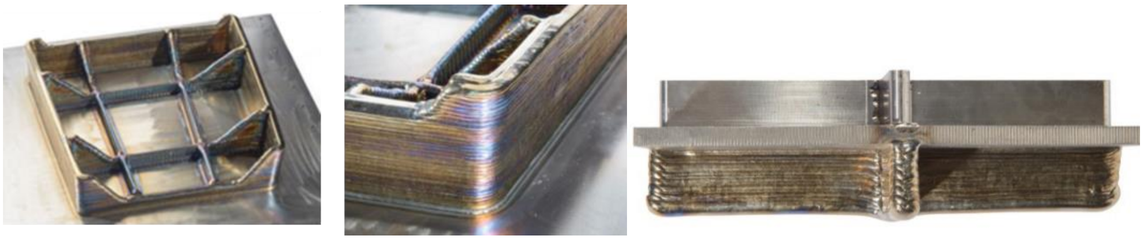

Figure 3 - 20 kg landing gear rib built in titanium and the detail of the surface finish. Small part as deposited and machined. [6]

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It will be noted from **Error! Reference source not found.** that all metal AM processes have some post processing requirements. In the case of WAAM this is only finish machining, as material integrity is inherently very high, with no defects, provided everything is done correctly. However, parts are generally built with typically 1 mm of extra material over all surfaces to allow for the scalloped surface profile of the WAAM process (typical depth of this is 0.4 mm). Figure 3, shows an outboard landing gear rib in titanium produced at Cranfield University. The detail of the surface finish can be observed as well as a part with machined surfaces.

Currently the deposition, measurement and finishing is done in different stages, on three machines, which greatly increases the cost and time of production. After manufacture by WAAM, the component is then measured for form, transferred to a CNC milling system, relocated and then finished through machining. Considering that the prime motivation for the manufacture of parts using the WAAM process is cost saving. Therefore, there is a major requirement for the development of a WAAM based machine that produces large scale finished large engineering structures and this is where the LASIMM concept comes in play.

2. Concept for a machine for Hybrid manufacturing (WAAM + Subtractive)

A consortium of 10 companies and RTD organisations from six countries is collaborating in a European project, LASIMM, which targets the development of a robotic hybrid, completely integrated, machine based in WAAM as the key enabler for a flexible hybrid manufacturing environment. It combines and automates WAAM with other processes such as machining, in-line NDT and cold-working. Figure 4 presents the concept of the system under development.

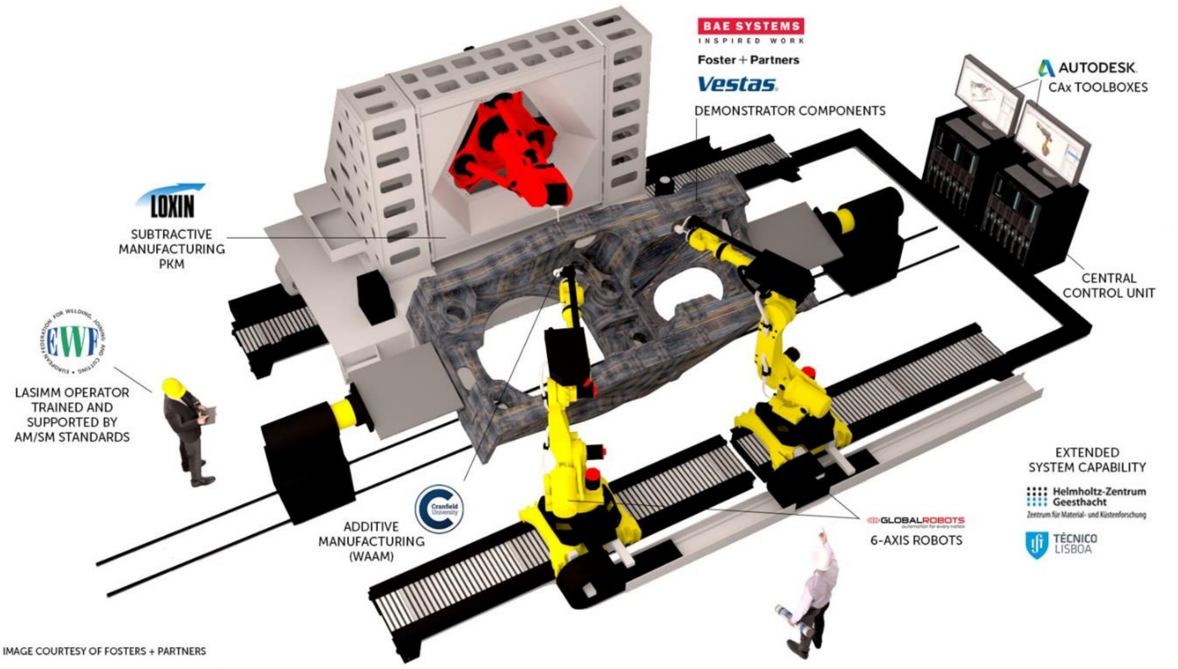

Figure 4 - Envisaged LASIMM featuring parallel processing and multi-head deposition

This machine is being developed with the following objectives:

- The mechanical properties are at least equal to or preferably better than that of the materials used currently;
- High quality, high integrity material is produced without defects of flaws;
- The build envelope is not restricted;
- The production cost is at least similar to or preferably much less than that of the current manufacturing methods;
- Build rates are sufficiently high that production times are similar to or less than that of current processes;
- The equipment capital cost is not prohibitive.

The Large Additive/Subtractive Integrated Modular Machine (LASIMM) is based on a scalable open architecture framework with associated software enabling full parallel manufacturing. The machine will feature capabilities for AM, machining, cold-work, metrology and inspection.

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These processes will need to be implemented in a symbiotic and smart way to achieve the multiple goals of high productivity, flexibility, structural integrity, and superior performances. The long-term goal is a system capable of producing fully finished, inspected and quality assured components straight from Computer Aided Design (CAD) models at a high productivity rate.

A feature of the machine is the capability for parallel manufacturing including either multiple deposition heads or concurrent addition and subtraction processes. However, the machine is designed to allow different configurations totally aligned with the end-user requirements. To ensure that the surface finish and accuracy needed for engineering components is obtained, a parallel kinematic robot is employed for the subtractive step. A key aspect is the ICT infrastructure and toolboxes needed to programme and run the machine.

The equipment will be modular and scalable: it can be tailored to different needs, depending on its desired use and applications. The number of industrial and parallel kinematics motion robots, as well as part positioners can be decided to match the production specifications.

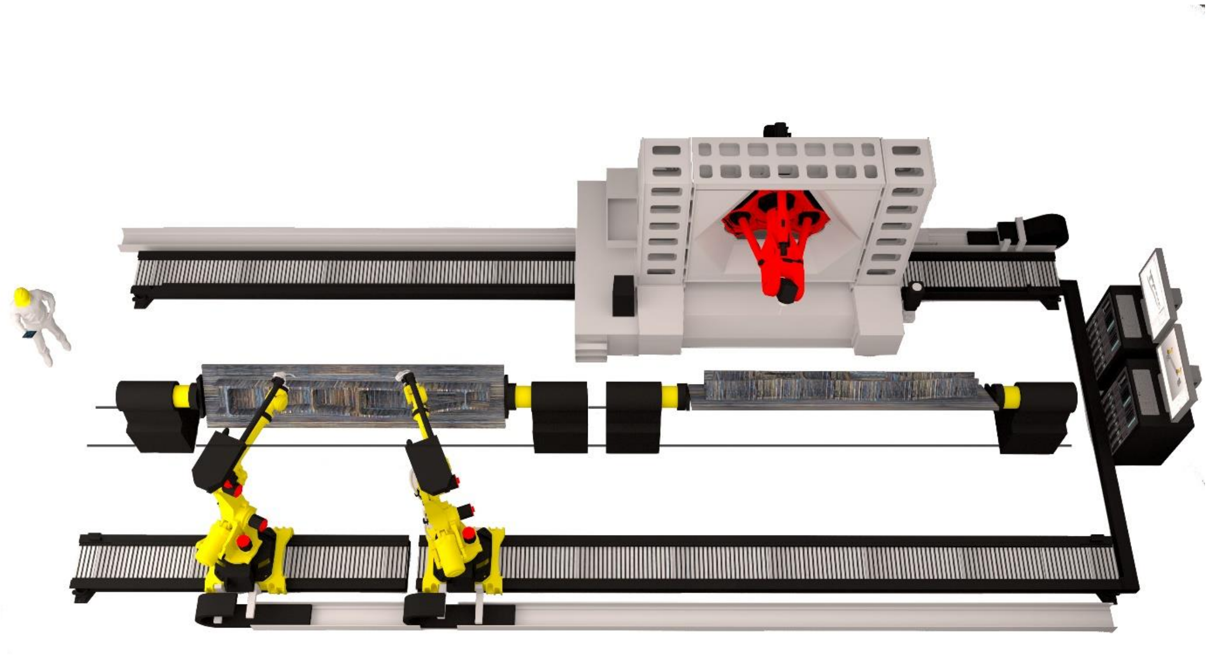

Figure 5 - Modular System

3. WAAM performance and capabilities

One of the main reasons for choosing WAAM is mainly related to the deposition rates that are achieved. These can vary from 1Kg/h to 4 Kg/h for Aluminium and steel respectively, this allows producing parts in an acceptable time frame. It is also possible to achieve higher deposition rates (for example 10Kg/h for steel), but this has a negative effect on the part and would mean that more machining is required, making the process less attractive from an economical point of view [7].

One of the first aspects to decide upon is the path generation as this will influence the productivity that the system will be able to reach and quality of the parts produced. The LASIMM machine will use the know-how developed at Cranfield University in terms of path generation for WAAM. This will be done based on two approaches, as described in figure 6. In the traditional approach the CAD model of the 3D component to be produced by WAAM is sliced into a number of 2D layers of defined thickness. Each layer of deposition may consist of a number of tool-path passes. Each tool-path pass is defined as a continuous deposition of metal, with a single start and stop.

Each material layer may be made using straight-line, raster, zigzag, contours, space-filling curves, and hybrid tool path. After generating the code the part is ready to be produced by WAAM, and finished with machining operations. The new approach aims too automatically recognize all the features of the solid model including freeform surfaces and to extracts its parameters to design an algorithm capable of generating the tool path according to the identified feature and also to be capable of automatically selecting the tool path type to be generated with respect to the feature.

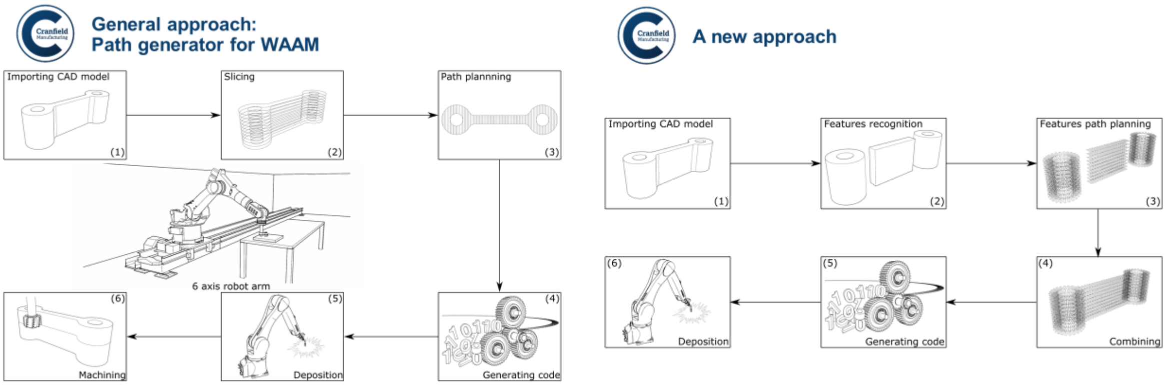

Figure 6 - Path generator for WAAM - courtesy of Cranfield University [6]

As referred previously for the part to be considered finished it has to be subject to subtractive operations, layer after layer of metal deposition or at the end. Independently of the approaches chosen the machine for Hybrid manufacturing (WAAM + Subtractive) will include sensing, metrology, non-destructive testing and cold-working methods to produce fully quality assured parts with superior mechanical properties. To support the WAAM deposition process monitoring and sensing requirements were identified, namely a welding monitoring camera, insensitive to arc light.

Another challenge to address is the integration of non-destructive testing in the LASIMM machine. Two options are being addressed:

-Testing layer after layer in combination with deposition, and/or

-Testing the final part after machining.

Non- destructive testing of AM parts faces many challenges such as geometry of the part, surface finishing, location of defects, size and shape of minimum detectable defects and others. Also, the need for implementation during manufacture as opposed to post operation, in order to save time, is a key aspect when selecting the correct NDT techniques.

Currently there are no standards regarding NDT for AM, the urgent need for them has put together cooperation between the International Organization for Standardization (ISO) and ASTM for the first time enabling the joint development of AM standards in the area [8].

In [9] the mapping of the NDT techniques with respective advantages and disadvantages for application in large scale WAAM parts is presented.

A fist set of experiments was conducted at IST in WAAM parts in aluminium and steel. Radiographic Testing (X-ray), Liquid Penetrant Inspection (LP), Ultrasonic Testing, Phased Array UT (PAUT), Eddy Current Testing (ECT) and four-point Potential Drop testing (PD) were applied. Figure 7 and Figure 8 give examples of results obtained with X ray and UT.

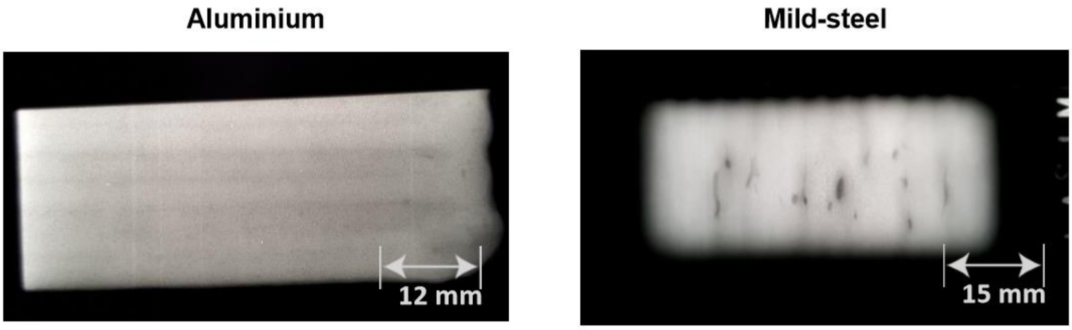

Figure 7 - X-ray testing of Aluminium sample (left) and mild-steel sample (right) [9].

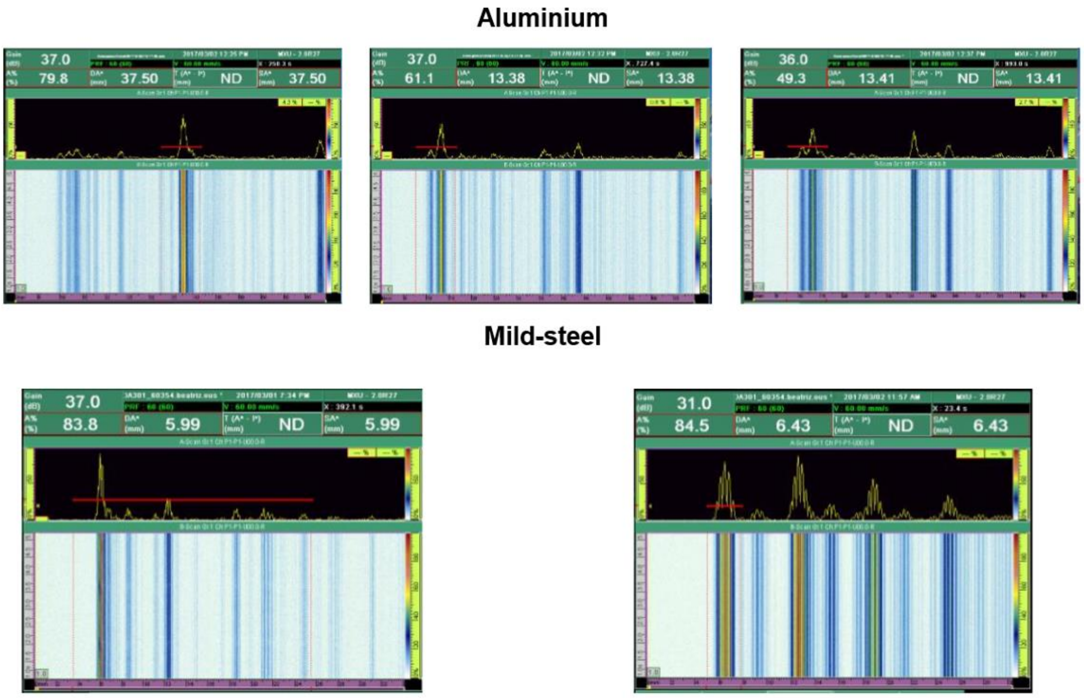

Figure 8 - Ultra sonic results for Aluminium and Mild-steel [9].

Based on the inspections carried out it was demonstrated that not all techniques can give correct information on the defects location. PAUT is the most flexible one regarding the relative position of the inspection equipment and the part, and proved the capability to detect and scale WAAM defects. X-ray presents stringent safety limitations and involves a more demanding procedure, in addition to the difficulties in defects detection that are associated with the angle between the crack and the radiation. ECT performed better at lower frequencies but presents the limitation of only detecting near surface defects. Potential Drop Testing will require further computer simulation to evaluate the best probe arrangement as well as depth capabilities. Further work on analysis and optimisation of NDT for large WAAM parts in aluminium and steel is being developed [9].

5. Conclusions

LASIMM is a highly ambitious concept, which will culminate in the world's largest metal hybrid machine, capable of producing quality assured finished components directly from a CAD drawing to a final machined part. Also, with the possibility of adding other processes and techniques to the machine, for example cold rolling and on-line NDT.

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However, there are several challenges that need to be addressed in order to have a hybrid working machine for large parts.

The main challenges identified so far relate with the fixturing of the large parts, the distortions and the irregularities/roughness of the surface, characteristic of WAAM, which makes it difficult to apply on-line NDT. These will be addressed by adding "extra" functionalities to the developed machine.

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