Ref. Ares(2019)1364947 - 28/02/2019

This project has received funding from the European Community's
Horizon 2020 Framework Programme under grant agreement 820774

MANUELA
Additive Manufacturing
using Metal Pilot Line

Deliverable 1.3

Post AM specifications

WP 1

Deliverable Status	FINAL
Type	REPORT
Dissemination level (according to the proposal)	PUBLIC

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Horizon 2020 Framework Programme under grant agreement 820774

Project Name:	MANUELA - Additive Manufacturing using Metal Pilot Line
Grant Agreement:	820774
Project Duration:	1 October 2018 – 30 September 2022

Document Information

Work package	WP1
Lead beneficiary	RISE IVF AB

Due Date	2/28/2019	**Due date in months**	5
Date of submission	2/27/2019	**Month of submission**	5

Status	**Authors name and Company/Organisation**	**Date**
Prepared by	Emil Johansson, RISE IVF AB	2/25/2019
	Seyed Hosseini, RISE IVF AB	2/25/2019
Reviewed by	Daniel Gage, FAU	2/26/2019
Approved by	Emil Johansson, RISE IVF AB Seyed Hosseini, RISE IVF AB	2/27/2019

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Terms and definitions

Acronym	Description
AM	Additive manufacturing
EBM	Electron beam melting
LPBF	Laser powder bed fusion

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Executive Summary

The project MANUELA "Additive Manufacturing Using Metal Pilot Line" aims to advance and assure that metal Additive Manufacturing (AM) will live up to its long-term potential, concentrating on Laser Powder Bed Fusion (LPBF) and Electron Beam Melting (EBM) as the most developed and industrially relevant metal AM technologies at the current state-of-the-art.

Metal AM allows, by enabling use of advanced design, production of high added value components, at levels that cannot be reached with conventional manufacturing techniques. However, after manufacturing of a part by metal AM several manual operations remain including for example powder removal, part removal from build platform, heat treatment and machining of critical surfaces. These steps represent a major part of the total cost and lead time of an AM part. Additionally, manual operations involving handling of metal powders and lifting of heavy components represent a health and safety risk.

To address this, MANUELA will develop and deploy automated and tailored post AM processes. This deliverable provides an overview of the requirements and proposed approach for the post AM setup in MANUELA. The specifications have been based on the six industrially relevant use cases which are part of the project.

1 Introduction

Among the desired impacts of MANUELA are significant ***reduction in production time***, ***reduced exposure to metal powder*** for AM operators, ***reduced need for heavy lifts***, and an overall ***increase in the robustness of metal AM***. Currently, metal AM and subsequent post-processing of manufactured parts generally require a large number of manual operations including for example powder removal, extraction of build platform, support removal, part removal from build platform and 3D scanning. These tasks contribute to both long production times and high cost. The manual operations increase variations in quality and performance between parts which in turn affects the process robustness.

In order to achieve a state-of-the-art pilot line for metal AM, MANUELA will need to develop and deploy an optimized and automated post AM workflow. To guide the development, six use cases have been selected from the participating partners. This document details the fundamental requirements on the post AM workflow and proposed approach based on these use cases.

1.1 General requirements on the post AM supply chain

MANUELA aims to create an agile, scalable, robust, safe and automated workflow AM machine operation and subsequent post-processing. This requires a cost-effective automation solution which can serve both large-scale and small-scale AM users as well as multiple different AM and post-processing equipment. Fundamental requirements are therefore a high degree of interoperability between different subsystems and flexibility. In order to ensure part quality, complete traceability of individual parts and associated data from for example quality assurance and heat treatment is required. Later, this can be used to introduce a digital certification for metal AM parts.

1.2 Summary of use case requirements

The six use cases in MANUELA are within avionics, space, medical, energy and automotive and have intentionally been selected to offer a broad set of requirements. To meet both the needs of the use cases and future needs of the pilot line the anticipated requirements are generalized in Table 1 below.

Table 1. Pilot line requirements based on the six identified use cases and expected future use cases.

Materials	Aluminium alloys, titanium alloys, nickel based super alloys, stainless steel and tool steels.
Minimum wall thickness	Down to 0.6 mm
Surface roughness	< 1 µm for critical surfaces
Part size	Up to ca. 190 mm x 190 mm x 420 mm
Tolerances	Down to ±0.01 mm
Post treatment steps	• Removal of residual powder • 3D scanning • Heat treatment • Wire EDM

	• CNC machining • Sand blasting • High precision turning • Hot isostatic pressing (HIP) • Laser ablation • Chemical surface modification • X-ray Computer Tomography

2 Specification of automated 3D printer operation

2.1 Manual tasks involved in powder bed based metal AM

The pilot line in MANUELA will include LPBF and EBM which are both powder bed based AM processes and use laser and electron beam respectively for selective consolidation of the metal powder. Despite some principal similarities between the processes, the equipment operates in very different ways. Consequently, automation of manual tasks must be tailored for each equipment.

2.1.1 Laser Powder Bed Fusion (LPBF)

Basic tasks involved in LPBF vary between different machine brands but generally include:

1. **Build setup**
   This step involves (1) filling the machine with metal powder, (2) loading the build file into the machine, (3) levelling of build platform and the powder dispenser, (4) checking homogeneity of the first powder layers, and finally (5) starting the build job.
2. **Powder cleaning**
   After opening the door to the build chamber, black powder condensate is first removed using a wet separator vacuum cleaner in order to reduce the risk of fire. Used un-sintered powder is then removed and collected for future recycling. The time required for this step depend on the complexity and height of the built part.
3. **Build platform extraction**
   The build platform is typically held in place with four bolts which need to be removed before extraction.
4. **Part removal from build platform**
   Built components can be removed from the build platform in several ways. Two common approaches are wire EDM and by using a band saw.
5. **Removal of support structure**
   Support structures are typically removed manually using pliers or in some cases with help of CNC machining.
6. **Reconditioning of build platform**
   In order to allow re-use of the build platforms the surface must first be restored. This is usually achieved through CNC machining.
7. **Powder recycling**
   Used powder is generally re-used by first sieving to remove agglomerates and then mixing it with virgin powder before re-introducing it to the machine.

2.1.2 Electron beam melting (EBM)

Basic steps involved in operation of equipment for EBM generally include:

1. **Build setup**
   The build platform is prepared by ultra-sonic cleaning with solvent, insertion of temperature sensors and finally by winding it with copper wires. Metal powder is poured into the EBM equipment and the build platform is positioned, levelled and centred onto the powder. Metal powder is poured around the build platform and the powder deposition unit is calibrated. Finally, the build platform surface is cleaned from loose powder and a protection shield is positioned in the machine.
2. **Build process**
   During the building process, the powder deposition mechanism and layer pre-heating sequence may require adjustments.
3. **Build platform extraction**
   In order to remove a build, the protection shield is first removed and unconsolidated powder is removed through vacuum cleaning. The build platform is raised and the temperature sensors removed. The build platform including manufactured samples and surrounding sintered powder block is removed as a single piece.
4. **Part removal from build platform**
   First sintered powder is removed by powder blasting. Subsequent the part including the support structure is removed by manual break off.
5. **5. Removal of support structure**
   Support structures are typically removed manually using pliers.
6. **Reconditioning of build platform**
   In order to allow re-use of the build platforms the surface must first be restored. This is usually achieved through grinding.
7. **Powder recycling**
   Used powder is generally re-used by sieving to remove agglomerates.

2.2 Environment, health and safety assessment

AM using powder bed based processes such as LPBF and EBM have several associated risks which must be considered and minimized. AM equipment used in MANUELA has built in safety mechanisms which prevent operation of the built in high power laser and electron beam systems unless the equipment is sealed. The primary security risk for operators is instead exposure to metal powder during standard operation. Typical metal powders for LPBF and EBM are in the range 10 – 150 µm and may cause eye and skin irritation as well as pulmonary fibrosis if inhaled. The long-term inhalation exposure risks are not fully understood and handling therefore requires respirators.

Another concern is the flammability and potentially explosive nature of many metal powders which may burn in the presence of oxidizing substances or release heat when exposed to moisture. Metal condensate generated during the AM process which is deposited on the chamber walls and in the filter unit is particularly flammable. After a build is finished, the build platform and unconsolidated powder may still be hot. This is especially relevant for EBM where a build requires significant cooling down before it can be removed.

In order to minimize the potential environmental impact, metal powder waste should be collected and treated as potentially hazardous waste. Unconsolidated powder may remain on the surface or inside channels of manufactured parts and risks being released during handling of the components. To minimize risk of exposure, manufactured parts will be kept in sealed off environments until residual powder has been removed.

In MANUELA, the ambition is to remove as many of the manual steps involved in metal AM as possible in order to avoid the above mentioned environment, health and safety risks.

3 Specification of AM post-processing supply chain

3.1 Required post-processing steps and functionality

Automation of loading and unloading operations is required in order to minimize manual operations and waiting times between different post-processing steps. This will be accomplished using industrial robotics with flexible gripper tools in order to allow handling multiple different build platform types as well as individual components. While the robot cell is not operating it should be possible to work manually with the equipment in the cell.

Removal of residual powder from components is required both from an environment, health and safety perspective and to allow heat treatment operations. In MANUELA, this will be done in a custom built, hermetically sealed chamber, where the build platform and manufactured samples are subjected to movement and vibration in multiple orientations.

Various forms of ***heat treatment*** cycles, including stress relieving, annealing and ageing, are necessary to achieve the final properties of manufactured parts. The majority of the heat treatments will be performed in box furnaces using inert atmosphere. The specific thermal cycles will vary depending on the selected alloy but may include:

- *Nickel alloys:* Each Ni-based alloy has their own special heat treat recipe, where for example Hastalloy X (HX alloy) suffers from high crack susceptibility during the laser powder bed fusion (LPBF) process, why extra care needs to be taken both during the printing process as well as during the heat treatment operation to relax the internal stresses. HX alloy is a solid solution hardening alloy, which usually are solution treated to 1175 °C, to create a microstructure with equiaxed grains and primary Mo-rich carbides. So, the heat treatment solution for this alloy involves solution treatment after printing at temperature around 1175 °C.
- *Aluminium alloys*: Like Ni-based alloys, also for Al-alloys the heat treatment strategies vary depending on the chemical composition. But for Al-alloys, it involves solution annealing with quenching in water followed by age hardening. In some cases, a simpler stress relief heat treatment for 2 hours at 300 °C can be enough. But for each alloy that will be studied here a heat treatment process will be optimized to reach maximum strength/elongation/hardness, etc.
- *Titanium alloys:* For EBM, in-situ heat treatment is possible during the AM process due to the high temperature (> 700°C) in the build chamber. For LPBF, heat treatment must be done externally using either i) a vacuum furnace and maximum temperature of approximately 800 °C or ii) hot isostatic pressing with a maximum temperature of approximately 920 °C.

Machining of manufactured parts will be required for most use cases in order to meet requirements on tolerances and surface finish. This will primarily be accomplished through CNC machining with the component is still attached to the build platform in order to reduce the need of fixtures and alignment. In some cases, where tighter tolerances are required, high precision turning will be used.

Removal of parts from the building platform can be achieved either with wire Electrical discharge machining (EDM) or by using a band saw.

Sand blasting using glass, zirconia or other media will be used to improve surface finish of manufactured parts.

In cases which require improved surface modification, ***surface laser treatment*** from OSAI Automation System S.p.A. will be used. This will allow to perform different processes, for example chemical surface modification, texturing, ablation or finishing, at the same time. This may also be used to ***engrave unique identification tags*** into the products in order to allow full traceability.

Quality assurance will be performed by 3D scanning multiple times during post-processing in order to verify the geometrical integrity of the parts and as a support for machining operations. This will be done inline in the robotized post-processing cell using a GOM Atos 3D scanner. When new materials and process parameters are introduced, test specimens will be sent for evaluation through X-ray tomography.

3.2 Post-processing integration and automation

In MANUELA, a fully automated cell with the ability to perform a majority of the required post-processing and quality assurance steps will be developed. The cell will use industrial robotics to load and unload both build platforms and individual parts in post-processing equipment. A pick–and-place station able to handle parts from both LPBF and EBM systems will be used.

In order to facilitate automation of the workflow, post treatment of parts will be defined already during build job preparation. This will allow optimization of both design and build setup, such as part orientation, in order to facilitate the post-processing steps. The post-processing workflow for each build and part will be communicated from an Engineering Lifecycle Management (ELM) platform which will be used in MANUELA. Each build platform and individual part will be marked with a unique ID in order to enable full traceability.

3.2.1 General post-processing workflow

The post-processing workflow in MANUELA will be adapted for each use case depending on its specific requirements. For the initial identified use cases, Figure 1 illustrates the following general workflow.

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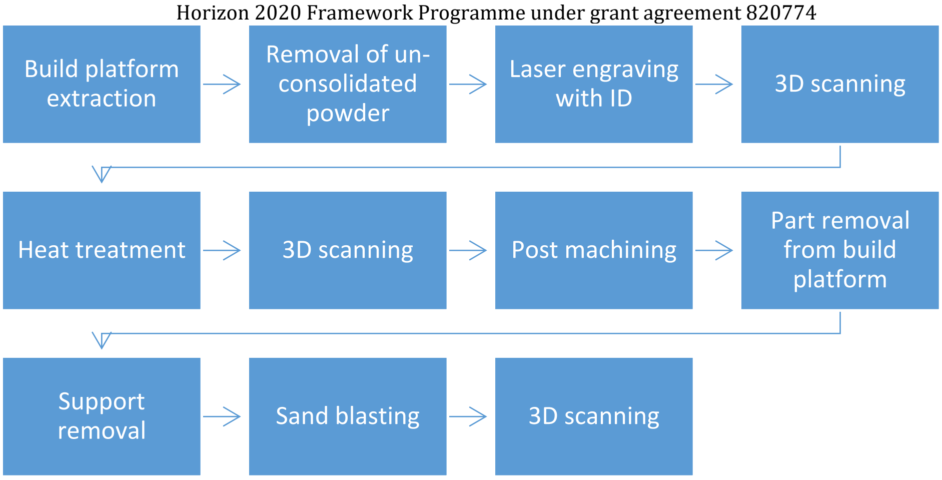

Figure 1: General post AM workflow in MANUELA.

3.2.2 Traceability

Traceability of all data generated during the post AM supply chain is necessary to validate the quality of produced parts. The data can for example include 3D scans, images, process parameters, mechanical evaluations and the order of which the post-processing steps are executed. Data for each build and part will be stored in the ELM platform and tied to a unique ID which will be laser engraved into each component. The automated post AM system will communicate with the ELM platform using a REST API which allow data query and retrieval via RESTful URLs (REpresentational State Transfer). The specifications of the ELM platform and the data management procedures are further elaborated in Deliverable 1.4, Analytic Toolbox Specification.

3.3 Environment, health and safety assessment

Post-processing of metal AM parts pose many of the same risks as traditional metal working including ergonomic concerns, cutting, grinding and crushing injuries, burns, noise and heat generation, fire/explosion and chemical exposures. These risks are mostly tied to specific equipment, such as box furnaces or machining equipment, which have security measures installed and handling procedures in place to prevent injury. A major concern is also exposure to residual raw metal powder from the AM process, especially during manual post-processing tasks such as powder removal and support removal. Risks include inhalation and dermal contact, fire/explosion hazard and environmental contamination. It is therefore necessary to ensure containment of the metal powders and appropriate air filtering throughout the post AM supply chain.

In order to minimize exposure to metal powders and improve overall efficiency, MANUELA will use an automated post-processing workflow which will be accomplished using industrial robotics. The use and integration of industrial robotics is regulated in several standards, for example:

- *ISO 10218-1:2011, Robots and robotic devices -- Safety requirements for industrial robots -- Part 1: Robots,* which specifies requirements and guidelines for the inherent safe design, protective measures and information for use of industrial robots.
- *ISO 10218-2:2011, Robots and robotic devices -- Safety requirements for industrial robots -- Part 2: Robot systems and integration,* specifies safety requirements for the

integration of industrial robots and industrial robot systems including the design, manufacturing, installation, operation, maintenance and decommissioning of the industrial robot system or cell.
- *ISO/TS 15066:2016, Robots and robotic devices -- Collaborative robots,* which specifies safety requirements for collaborative industrial robot systems and the work environment.

In MANUELA, the ambition is to deploy a robot cell where an operator can work manually with equipment when the robotized cell is not in use. The robot cell will therefore be designed with this in mind.

Thorough risk assessments will be crucial for safe and successful implementation of both post-processing equipment and industrial robots in MANUELA.

4 Conclusions

Deploying an efficient and automated post AM configuration involves many different aspects as detailed in this report. It is necessary to eliminate as many manual operations as possible, both to reduce overall lead times and to minimize health and safety risks involved in metal AM today. To ensure long-term usability, the proposed solutions must be cost-effective, scalable and flexible in nature. MANUELA will therefore rely primarily on general industrial robotic solutions rather than custom built automated systems which are optimized for specific AM equipment.