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MANUELA
Additive Manufacturing
using Metal Pilot Line

Deliverable D1.2

Pilot Line Specifications

WP 1

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Executive Summary

MANUELA aims at deploying a TRL 7 metal additive manufacturing pilot line, overcoming identified metal additive manufacturing process limitations, including:

- Limited manufacturing speed
- Limited capability of right-first-time production
- Limited number of qualified materials
- Lack of controlled quality monitoring at line level
- Lack of automated data analytics at line level for part, process and material parameters with tested functionality
- Lack of an easy-to-use, comprehensive user-interface with access to all pilot-line facets for both expert and non-expert users
- Lack of integrated technical solutions along the whole value chain from pre-processing via printing to post-print processing

MANUELA provides the coordination of printing facilities including the two powder bed fusion techniques laser powder bed fusion (LPBF) and electron beam melting (EBM). MANUELA hence is set to cover the full range of needs from smallest possible to largest possible parts of varying complexity and materials of interest as defined by first set of predefined use cases as well as generic capacities to address additional use cases. The pilot line specifications outlined in this report summarises the materials, processes, process parameters, line monitoring, post-process and associated simulation software included in the MANUELA concept. The report also outlines the potential strategy for the facilitation, demonstration and selection of solution for matching of use cases to pilot line specifications and the concept of single entry point.

1 Introduction

In order to facilitate the realisation of the predefined use cases it is important that the MANUELA pilot line has the specifications to meet the requirements set by these use cases. It is also important that the MANUELA line has the specifications in order to meet the needs set by next series of use cases to be addressed based on the open call which will be launched by the MANUELA consortium. This open call aims at attracting further use cases to demonstrate the capabilities and to gain further learning and understanding to be able to provide future solutions for great variety of design, materials and performance criteria with quality and control of processing. Below, the report provides first short review of the outcome of use cases descriptive work (extracted from D1.1) as generic input to the assessment and description of pilot line specifications, the correlation to the generic input from simulation/pre-process preparation (as extracted from D1.4) and the connection to post-AM specifications (as extracted from D1.3). Then, a short review of the specifications of the AM-machines to be used for the predefined and additional use cases follows, followed by the analysis of the potential match and duplication of process solutions selected for the different use cases. Finally, the single entry point concept is shortly addressed in its initial concept, although not yet being fully developed.

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2 Use cases manufacturability

The pre-defined use cases are summarised in public form in Table 1. As can be seen these use cases define the initial materials, process capabilities and product performance criteria. The indication of possible processing solution(s) is also shown in the table and explained further in Section 4.

Table 1. Summary of pre-defined use cases and potential solutions

Use case	Material	Dimension	Complexity	Post-AM	Method	Process monitoring
Housing	Al-alloy Possibly need for materials development	Small	High	Yes	LPBF	Benefit
Slip ring	Al-alloy or Cu-alloy	Small	High	Yes	LPBF (Al) EBM (Cu)	Benefit
Implant	Ti-alloy	Medium	Medium	Yes	EBM LPBF	Benefit
Liner and injector	Ni-alloy	Large	Medium	TBD	LPBF (large)	Not possible
Brake bell and rocker	Ti-alloy Possibly for LPBF need for materials development	Medium	High	Yes	EBM LPBF	Benefit
Gas turbine heat shield	Ni-alloy	Medium	High	TBD	LPBF	Benefit

When not commented in the table above, the AM-material for the indicated processes is established. In case comment is provided, the first hand choice would require development of new material for the application, whereas existing AM-material may be possible subject to fulfil the material properties. In one case alternative material solutions (Al/Cu) are possible, but with different technologies (LPBF and EBM) being the choices. In general post-AM processing is required, including processes that are not AM specific, but more general for any kind of product realisation. As most products are complex, process monitoring is a benefit. The process monitoring is a measure that can be applied to make sure that the product being printed will be defect free and that processing parameters for the process applied (either being LPBF or EBM) can be efficiently set to facilitate rapid product realisation with the vision of first part right. It should be noted here that we talk about advanced on-line monitoring and at present certain capabilities in on-line controlling of the process. However, the full scale of implementing feed-back looping including the application of machine learning is not yet a reality and hence the input and development of the analytics tool-box and associated measures constitute an important part for the development of the pilot line specifications. For large scale product realisation using LPBF, process monitoring is not possible owing technical limitations of connected machine solutions and hence will not be applied.

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As can seen, the pre-defined use cases include specific Al-alloy, Ti-alloy and Ni-alloy grades. This means that the pre-defined use cases will not test the capacity of the pilot line to its full extent and hence the consortium would need to execute additional development cases for non-real parts to cover other materials like 316L, tool steel and engineering steel to be prepared for additional use cases.

3 Analytics and post-AM correlations

MANUELA will develop an analytics tool-box that should provide faster design for AM as well as better predictive capacity in tuning and assessing optimised processing of intended parts for the different use cases. The so-defined dashboard is further described in deliverable D1.4. From the pre-processing perspective this means the loop from CAD to build preparation including the multiscale modelling of potential outcome of part distortion and residual stresses, build optimisation with respect to orientation, support structures, etc., will be beyond the state-of-the-art at project end. In addition, there is an ELM data model to structure and gather all digital information for the given case. Now, the measuring capabilities implemented in the machines come in, with the electron-optical-observation (ELO) for the on-line monitoring of the EBM process and the Eostate monitoring for LPBF process including real time optical tomography, imaging and meltpool monitoring. The information received from these systems will feed back to the pre-process analytics/modelling as well as it constitutes an input for machine learning solutions that ultimately will provide on-line advanced corrective measures.

Concerning the LPBF process, post-AM processing will include for the most built parts initial stress-relief by annealing before removing parts from the build plate. Prior to this, surface cleaning will be applied by e.g. blasting. Thereafter follows heat treatment if required from product performance criteria and also further post-processes like machining or grinding to set surface characteristics, in particular for functional surfaces and critical measures. Subject to application, further processing like surface treatment (e.g. anodizing, plating, etc.) follows. The post-AM processing can then be divided into two categories, i.e. stages that are specific for the AM process chain, like the removal of support structures, the monitoring of stress-relief before removing the parts, their removal and the recycling of surplus powder from the build process, and general processes that are not AM specific but application specific like surface treatment. Figure 1 below represents an extract from the deliverable report D1.3 concerning the generic post-AM processing. This constitutes an integral part of the pilot line capacity.

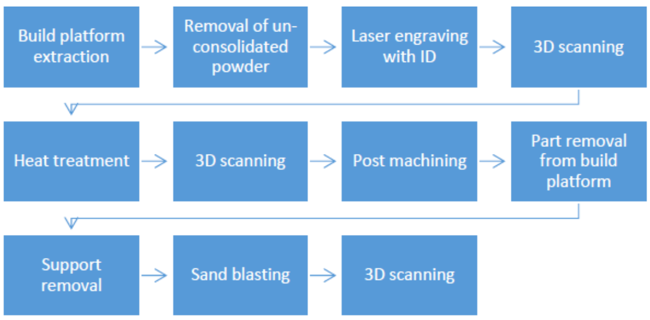

Figure 1. Generic post-AM processing for basically all cases of powder bed fusion.

4 Manufacturing capabilities

4.1 EBM at FAU

The EBM machine provided at FAU is a retrofitted Arcam S12 Machine. The specific capacity of this machine is that it has a maximum power of 6 kW, which is double that of commercial EBM-machines. The build envelope constitutes 120x120x200 mm^3. The beam diameter is around 400 μm and the build layer thickness is 50-100 μm. The special capacity of the EBM technology is the high build rate compared to the LPBF technology. The EBM technology in general has been developed for lesser number of alloys than the LPBF technology. Usually, material solutions provided by EBM include Ti-6Al-4V alloy, pure Titanium, Co-Cr alloys as well as Ni-base alloys like the Alloy 718. There is also evidence of in-house development for specific alloys in different laboratories and industries, but these alloys are not generally provided as qualified alternatives to public and commercial basis.

For the EBM machine provided at FAU, the specifics include the qualified provision of solutions for Ti-6Al-4V alloy, pure Cu and Cu alloys. The Cu-base is a unique feature and an important capability of EBM as this technology does not have the limitations set by the laser reflection that would be the case for wavelength used for mainstream laser technology of today.

Another important means of the EBM machine at FAU is the specially developed electron-optical observation system (ELO) that enables the assessment of build result at high lateral resolution owing the detection of so-called backscattered electrons generated by the electron beam interacting with the material in the powder bed. Hence, this constitutes a one to one detection of the result of the electron beam as it generates the melt pool and the material is built up layer by layer. Consequently, there is a unique capacity in process monitoring to generate process optimisation with increased build speed and first part right capability.

The EBM process has specific benefits such as the in-situ stress relaxation owing to high temperature (kept by the electron beam heating of the powder bed around the build), high building speed due to the high scanning and deflection speed (given by the physics of electron beam technology), processing in vacuum that may secure less contamination from gases.

The simulation input includes:

- Material properties
- Scanning strategy
- Electron beam characteristics
- Temperature measurements
- The ELO imaging
- The processing window

By using process parameters centered in the processing window (see Fig. 2), the process can kept more robust against possible influences that may cause a shift of the processing window. For example, the size and geometry of the melting area can influence the processing window in this regard.

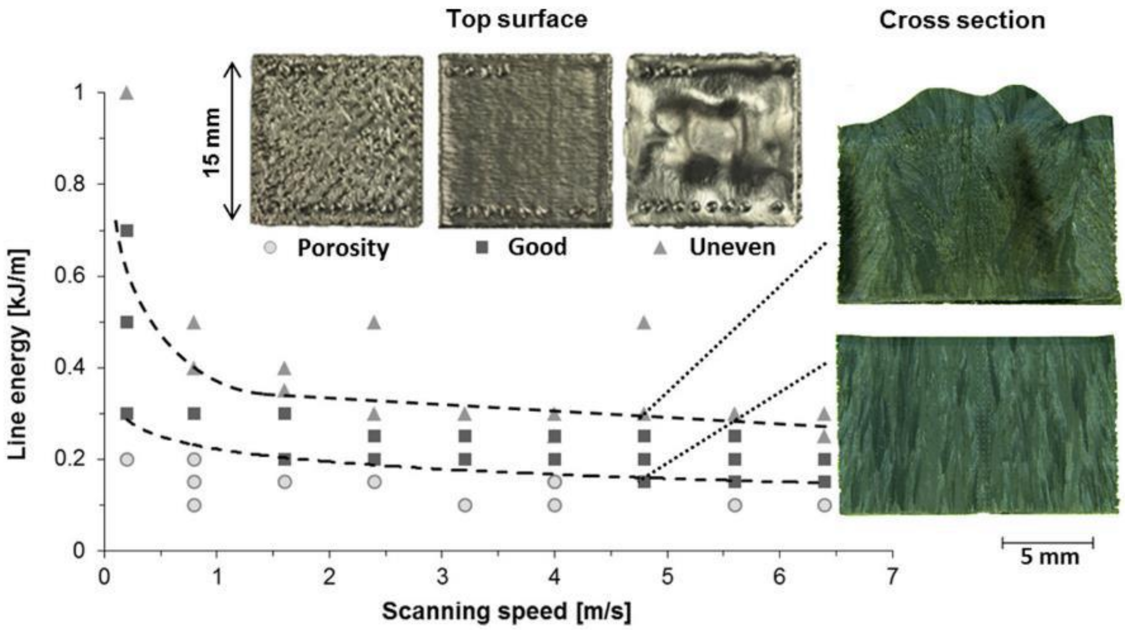

Figure 2. EBM processing window for Ti-6Al-4V. Line offset: 100 µm. Layer thickness: 50 µm. (V. Juechter et al. / Acta Materialia 76 (2014) 252–258 / "Processing window and evaporation phenomena for Ti–6Al–4V produced by selective electron beam melting")

For processing window determination, cube samples with edge length of 15 mm are used, normally. Further processing window determinations should use the same or similar samples. Other geometries can be used for the determination of the geometry influence on the processing window. Samples produced can be used for hardness measurements as first measure as well as density measurements. For further evaluation, tensile test bars, impact test bars, fatigue test bars, etc. can be built.

4.2 LPBF at Polito

The LPBF machines at Polito include a medium size system (EOS M270) and the dedicated machine for large part manufacturing. The medium machine has a build dimension capacity of 230x230x180 mm^3 with a scan speed up to 7 m/s and a 200 W Yb-fibre laser with a laser beam diameter of 100 µm. This system can work in nitrogen or argon atmosphere on the basis of the material to be processed. The large machine uses a high laser power of 1 kW with a build dimension capacity of 400x400x350 mm^3. This machine has a focus diameter of 90 µm, it allows scan speeds up to 7 m/s and can run in nitrogen atmosphere. The LPBF technology has in general much broader spectrum of possible alloys than the EBM technology. The actual solutions that can be provided depend however on the availability of a processing window for the alloys of interest. Also, for the large AM system, the material processing capacity depends on the possibilities, avoiding cross contamination of materials, and the need to keep separation of material flows. Hence, even if the processing window capacity would be there, this does not mean that a certain material as such can be produced considering the need to avoid multiple use of different materials in one machine and along its manufacturing chain. At present, the possible materials at Polito are:

Large System EOS M400

- In718
- CoCrMo

Medium size system EOS M270

- AlSi10Mg
- A357
- Ti-6Al-4V
- In718
- In625
- 316L

The high amount of available materials, for which the process parameters are known, for the medium size system is possible, thanks to the reduced size of the building chamber and therefore the reduced contamination issues.

There is also the possibility to develop new materials such as the A20X and Ti6246, which are useful to meet end users requirements.

The development of new materials is performed on the basis of the following approach. At first as received powders are characterised, then the optimisation of the main building parameters (P, v, h_d, t) will take place. This step will be carried out by using a design of experiment (DoE) and by the measurement of the samples densities. On samples built with the optimised parameters, microstructural and mechanical analyses will be carried out. Finally, the optimisation of a specific heat treatment designed for the alloy processed by AM can be accomplished.

4.3 LPBF at Chalmers

The LPBF machines at Chalmers includes two capacities. There is a smaller machine (EOS M100) used for materials development and used to test manufacturability and set up of processing parameters for different alloys including novel materials. Furthermore, there is a medium size machine of industrial/pilot capacity (M290) that constitutes the main resource of the MANUELA line. The machine has a build dimension capacity of 250x250x325 mm^3 with a scan speed up to 7 m/s and 400 W Yb-fibre laser with a laser beam diameter of 100 μm. The gas supply includes pure argon, pure nitrogen as well as nitrogen of lesser purity through the internal generator.

Of specific concern is the on-line process monitoring provided by the EOSTATE system including real time optical tomography, imaging and melt pool monitoring. The resolution of the on-line measurement is of the order of magnitude of the melt pool generation/beam diameter. The system stores all data from the mentioned signal sources and allows the stopping of defect parts so that the building of other parts can continue. The data stored can then be used for analytical purposes to assess the quality of a build and hence in that sense be used as means for future integration of pre-processing analytics, in-line measurement, in-line control and parts specification, modelling and assessment.

Significant number of materials solutions are provided with generic processing windows for the LPBF machines including Al-Si-10Mg, Co-Cr, maraging steel, Ni-alloy HX, Ni-alloy 625, Ni-alloy 718, stainless steel CX, stainless steel 316L, stainless steel 17-4PH, Ti-6Al-4V, Ti-6Al-4V ELI, CP Ti grade 2. The powder size range is typically 20-50 μm and build layer thickness is usually 20 μm. Greater build layer thickness can be implemented but with the risk of not having full density components. Part design and case of application would govern whether it is viable to go for greater build thickness to accommodate faster production.

Again, the risk of cross-contamination and separating material flows must be considered, which means that the full range of materials listed above is not available. Also, the build quality capability relates strongly to the specific experience at Chalmers, which at present includes Ni-alloy HX, Ni-alloy 625, Ni-alloy 718, stainless steel 316L, stainless steel 17-4PH as well as stainless steel 420. Processing parameters for Al-Si-10Mg, Ti-6Al-4V and Ti-6Al-4V ELI and CP Ti grade 2 are possible to implement, subject to prioritization of use case between the different facilities of Chalmers, FAU and Polito. Also, the provision and expertise from the project partner EOS constitutes an important part of the realization of the LPBF capabilities of MANUELA.

For processing window determination, cube samples as well as specific thin wall design samples are used depending on intended application. The processing window determination for a new or tuned material is often very fast and can be delivered in quite short time starting from good position (scan speed, laser power, hatch distance, etc.) and then a design of experiment (DoE) study is centered around to set process point and window. Other geometries can be used for the determination of the geometry influence on the processing window. Samples produced can also be used for hardness measurements as first measure as well as density measurements. For further evaluation, tensile test bars, impact test bars, fatigue test bars, etc. can be built and be tested.

4.4 Capabilities for predefined use cases

The predefined use cases are supposed to provide two types of impact. First, through the successful development and fabrication of the demonstrator parts for the use cases, the capabilities of the MANUELA pilot line is proven. Second, the use cases define the necessary development needs and strategies for the AM of the different nodes of the MANUELA pilot line, regarding the manufacturability.

Based on the inventory of use cases, the input from framing of the analytics toolbox development has to be done as well as the analysis/assessment of post-AM specifications. It is concluded that the combined capacity at FAU, Polito and Chalmers can match the development needs for the predefined use cases, see Table 1 for preliminary assessment. The conclusion is based on the following aspects:

- The material should be possible to process with machine in question
- Then, there should be a material solution that exists where processing window is established or possible to realise with appropriate effort for the machine in question
- In case there would be more extensive need for combined materials and process development, the MANUELA consortium as a whole should use its capacity to solve this
- The design for the use cases should be feasible for the machine in question
- The generic post-AM processing should be possible to accommodate within MANUELA

- The consideration of cross-contamination risk and need to separate material flows is taken into account
- The actual business case analysis as such is not a factor for the matching of machine capability with a specific use case

For the EBM at FAU the conclusions are summarized in Table 2. For LPBF at Polito and Chalmers the same analyses are presented in Tables 3 and 4.

Table 2. Analysis of use case matching capacity for EBM at FAU

Use case	Material	Comment, material	Comment, design	Conclusion
Housing	Al-alloy, not possible	If Ti-6Al-4V, possible	Processing set-up tuneable	Maybe
Slip ring	Al-alloy, not possible	If Cu, possible	As above	Maybe
Implant	Ti-6Al-4V ELI	Alloy in use, possible	-	Yes
Liner and injector	Ni-alloy HX	No solution	-	No
Brake bell and rocker	Ti-alloy (different)	If Ti-6Al-4V, possible	As above Rocker OK, bell too large	Yes
Gas turbine heat shield	Ni-alloy HX	No solution	-	No

Table 3. Analysis of use case matching capacity for LPBF at Polito

Use case	Material	Comment, material	Comment, design	Conclusion
Housing	Al-alloy, new for AM	If other Al-alloy, possible	-	Maybe
Slip ring	Al-alloy	Alloy in use, possible	-	Yes
Implant	Ti-6Al-4V ELI	Possible	Supports have to be carefully designed	Maybe
Liner and injector	Ni-alloy HX	If Ni-alloy 718, possible	-	Maybe
Brake bell and rocker	Ti-alloy (different)	Development of parameters, possible	-	Yes
Gas turbine heat shield	Ni-alloy HX	No solution	-	No

Finishing is needed in all cases. The support structures have to be designed in order to be easy to remove.

Table 4. Analysis of use case matching capacity for LPBF at Chalmers

Use case	Material	Comment, material	Comment, design	Conclusion
Housing	Al-alloy, new for AM	If other Al-alloy, possible	-	Yes
Slip ring	Al-alloy	Possible	-	Yes
Implant	Ti-6Al-4V ELI	Possible	-	Yes
Liner and injector	Ni-alloy HX	Alloy in use, possible	Liner OK, injector too large	Maybe
Brake bell and rocker	Ti-alloy (different)	Possible	-	Maybe
Gas turbine heat shield	Ni-alloy HX	Alloy in use, possible	-	Yes

As can be seen from the tables above, the facilities at FAU, Polito and Chalmers have jointly capabilities to address the predefined use cases, albeit with significant development efforts. The other remark is that from material handling perspective, focusing on different materials at Polito and Chalmers would be feasible in the development phase.

The detailing of the prioritizing will also include for which process monitoring is more important.

4.5 Capabilities for additional use cases

It is yet too early to set the final capacities with respect to additional use cases. However, it is clear from materials perspective and expected future needs that there should be efforts placed on the development of process capabilities for more materials with on-line process monitoring, connection to data analytics and prospective post-AM processing. This work should be set up around a few materials of known and expected importance:

- Stainless steel like 316L
- Tool steel like H13
- Engineering steel for high strength applications

The strategy will follow the same set-up as for predefined use cases, but without focus on real part. In second stage, it is envisaged that additional use cases, being brought in, will connect to the listed materials as well. For example, stainless steel is used in heat exchangers, tool steel for moulds and engineering steel is used for different automotive components and spare parts. The materials listed are all materials for which the expertise and processing capabilities are found jointly by Polito and Chalmers.

5 Manufacturing flow

When a use case is supposed to be handled, addressed and facilitated by the MANUELA pilot line there are some distributed capacities along the pre-processing, AM processing and post-AM processing as outlined in Figure 3.

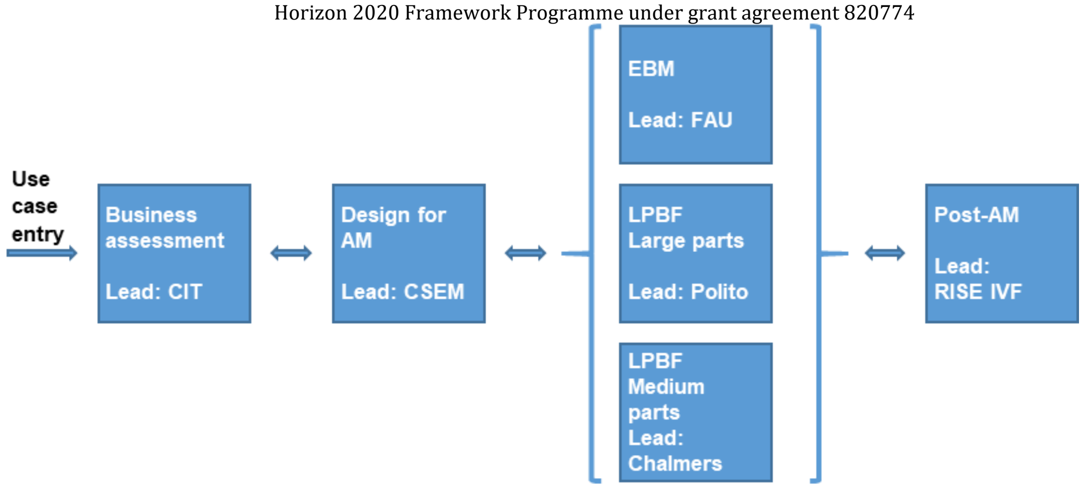

Figure 3. Manufacturing workflow for the processing of demonstrator parts for use cases.

The key message from Figure 3 is how a joint AM metal pilot line can be configured with distributed facilities across Europe taking advantage of the specialisation of different nodes. It should be noted that there are many solution providers besides the nodes in Fig. 3. These include specialists in modelling and analytics like Simufact, equipment and AM process solution provider as EOS, powder supplier as Höganäs, robotics expertise from ABB, etc. Also, CIT (Chalmers Industriteknik), being an independent body that can act under commercial conditions, will take a role as entry point. The set-up will also ensure the independent and transparent access to competence and capacities.

6 Conclusions

MANUELA provides the coordination of printing facilities including the two powder bed fusion techniques laser powder bed fusion (LPBF) and electron beam melting (EBM). MANUELA hence is set to cover the full range of needs from smallest possible to largest possible parts of varying complexity and materials of interest as defined by first set of predefined use cases as well as generic capacities to address additional use cases. The machines involved have the capacity to address the predefined use cases and also to broaden to further materials and application subjects to set-up of internal development activities for such purpose. The pilot line specifications outlined in this report summarises the materials, processes, process parameters, line monitoring, post-process and connection to analytics included in the MANUELA concept. The report also outlines the potential strategy for the facilitation, demonstration and selection of solution for matching of use cases to pilot line specifications and the concept of single entry point.