

D3.2



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D3.2 – Technical and non-technical toolkit

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Contributing beneficiaries: Peter Alešnik (UL), Andrej Lebar (UL), Joško Valentinčič (UL), Edvard Govekar (UL), Jithinraj Edaklavan Koroth (UL), Andrej Jeromen (UL), Hammad Ur Rehman (UL), Henning Zeidler (TUBAF), Toni Böttger (TUBAF), Shmuel Osovski (TECHNION), Keren Zohar-Hauber (TECHNION), Jernej Kovač (UL), Andre Uhlmann (TUBAF)

Reviewer(s): Joško Valentinčič (UL), Edvard Govekar (UL), Peter Alešnik (UL)

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1 Executive Summary

SEAMAC D3.2 brings together a non-technical development guide and a technical training toolkit to support knowledge transfer in additive manufacturing (AM) of functionally graded materials (FGMs). The main output is an editable, modular reference that connects the manufacturing process chain with the competences needed to develop research results towards practical use. It supports the project's capacity-building purpose by making this knowledge usable for researcher onboarding, training and cooperation with industry.

The non-technical part (Sections 3–7) helps researchers assess and plan the development of an idea across six KTH Innovation Readiness Level™ dimensions: technology, customer/user, business, intellectual property, team and funding readiness. It provides self-assessment guidance, development-planning tools and routes to specialist support. These resources help users identify evidence gaps and select practical next steps without requiring researchers to become legal, financial or commercialisation specialists.

The technical part (Sections 8–16) contains eight modules covering AM and FGM fundamentals; feedstock materials and powder preparation; laser metal deposition (LMD); plasma electrolytic polishing (PeP); characterisation and evaluation; defects, risks and troubleshooting; training delivery; and good practice from SEAMAC activities. It connects powder preparation, manufacturing, post-processing and evaluation so that learners can understand how decisions at one stage affect the subsequent stages.

The intended users are new and experienced researchers primarily at UL, but also at other institutions, doctoral and postgraduate students, trainers, technical staff and industrial users interested in AM and post-processing. Research managers, knowledge-transfer personnel, administrative staff and Commission Services can use the introductory guidance and task mapping to understand the toolkit's scope and its relationship to other SEAMAC deliverables. Section 2 provides audience-specific routes through the document.

The toolkit consolidates knowledge exchanged through partner training and project activities into material that can be selected and adapted for lectures, supervised practical sessions, summer schools and industrial workshops. Its exploitation route is the reuse of this training and development resource, including onboarding new researchers and preparing structured discussions with industrial partners. Module 7 explains training formats and adaptation; Module 8 records transferable good practice.

The two parts are complementary: the technical modules explain capabilities, process choices and evaluation needs, while the non-technical guide helps users consider application needs, intellectual property, team competences and resources. Together they support an informed pathway from research knowledge towards further development and use.

D3.2 presents reusable knowledge and training guidance. D1.1 and D2.1 provide the complementary manufacturing, post-processing and demonstrator results; D3.1

reports administrative capacity development; and D4.1 reports outreach activities and proposal outcomes. D3.3 addresses continuation, while D5.1 and D5.2 provide the data-management and dissemination/exploitation frameworks. This allocation avoids repeating detailed activity and experimental reporting in the toolkit.

D3.2 is classified SEN (Sensitive). Consortium members and Commission Services are its authorised audience under that classification. Reuse or external sharing of the document requires the approvals stated in its copyright notice and respect for third-party rights. Section 2 explains access and reuse conditions. Despite the classification SEN, this deliverable (D3.2) is published and publically available on SEAMAC webpage (<https://www.seamac.si/deliverables/>).

Table of content

1	Executive Summary.....	3
2	Introduction.....	10
3	From a research idea to industrial use.....	12
4	Self-assessment framework for the holistic development of a research idea.....	15
5	Preparation of a development plan across KTH Innovation Readiness Level™ dimensions.....	17
5.1	Technology readiness level.....	18
5.2	Customer readiness level.....	21
5.3	Business readiness level.....	24
5.4	Intellectual property readiness level.....	27
5.5	Team readiness level.....	30
5.6	Funding Readiness Level.....	33
5.7	Toolbox - Innovation methods and techniques to progress.....	37
6	From individual initiative to the right support network.....	40
7	Reflections on Innovation Readiness.....	45
8	Introduction to Technical Part of the Toolkit.....	46
9	Module 1: Fundamentals of AM of Functionally Graded Materials.....	50
9.1	Introduction to Metal Additive Manufacturing.....	50
9.2	Main Metal AM Process Categories.....	50
9.3	Laser-Based Metal AM Methods.....	52
9.4	Concept and Relevance of Functionally Graded Materials.....	54
9.5	Why Additive Manufacturing Is Relevant to FGMs.....	56
9.6	Relationship to Laser Metal Deposition.....	56
9.7	Industrial Relevance of FGMs.....	57
9.8	Application Drivers.....	58
9.9	Relevance to Tooling and Demonstrators.....	59
9.10	Challenges in Manufacturing FGMs.....	60
10	Module 2: Feedstock Materials and Powder Preparation.....	64
10.1	Materials.....	64
10.2	Powder Selection Criteria.....	65
10.3	Powder Blending Strategies for FGMs.....	68
10.4	Powder Characterisation Methods.....	70
10.5	Powder Handling, Storage and Safety.....	72

11	Module 3: Laser Metal Deposition Process Knowledge.....	76
11.1	LMD Process Principles.....	76
11.2	Equipment and Experimental Setup.....	77
11.3	Deposition Strategies for FGMs.....	82
11.4	Process Stability, Monitoring and Quality Control.....	84
11.5	Typical Defects and Their Causes.....	86
12	Module 4: Post-Processing by Plasma Electrolytic Polishing.....	89
12.1	Purpose of Post-Processing.....	89
12.2	Principles of Plasma Electrolytic Polishing.....	89
12.3	PeP Equipment and Test Rig.....	90
12.4	Electrolyte Selection and Process Parameters.....	91
12.5	Challenges in PeP of FGMs.....	91
12.6	Surface Integrity and Quality Assessment.....	92
13	Module 5: Characterisation and Evaluation of Manufactured Parts.....	93
13.1	Metallographic Characterisation.....	93
13.2	Microstructural and Phase Analysis.....	93
13.3	Mechanical Characterisation.....	94
13.4	Surface Roughness and Geometrical Assessment.....	94
13.5	Interpretation of Results for Process Improvement.....	95
14	Module 6: Defects, Risks and Troubleshooting.....	96
14.1	Common Defects in LMD of FGMs.....	96
14.2	Common Issues in PeP Post-Processing.....	96
14.3	Risk Factors in Process Integration.....	97
14.4	Troubleshooting Guidelines.....	97
15	Module 7: Training Delivery and Knowledge Transfer Methods.....	98
15.1	Recommended Training Formats.....	98
15.2	Suggested Structure for Technical Training Sessions.....	98
15.3	Use in Summer Schools and Internal Researcher Training.....	99
15.4	Use in Industry-Oriented Training.....	99
15.5	Training Material Types and Reusability.....	100
16	Module 8: Good Practice Derived from SEAMAC Activities.....	101
16.1	Good Practice from TECHNION.....	101
16.2	Good Practice from TUBAF.....	101
16.3	Good Practice Established at UL.....	102
16.4	Lessons Learned from Technical Exchanges and Training Events.....	102

17	Conclusions.....	103
18	Bibliography.....	104

Table of figures

<i>Figure 1: Example of a readiness profile showing gradual improvement across several readiness dimensions over time.....</i>	<i>17</i>
<i>Figure 2: The readiness profile showing improvement across several readiness dimensions from beginning till the end of the SEAMAC project.....</i>	<i>37</i>
<i>Figure 3: Structure and interconnections of the SEAMAC D3.2 Technical and Non-Technical Toolkit....</i>	<i>48</i>
<i>Figure 4: Laser powder bed fusion system used for metal AM training and development.....</i>	<i>50</i>
<i>Figure 5: Spherical metal powder particles used as AM feedstock a), powder material during laser sintering b) and final product c).....</i>	<i>51</i>
<i>Figure 6: Laser-based directed energy deposition system with powder delivery.....</i>	<i>54</i>
<i>Figure 7: Example of measured composition change across an SS316L-In718 graded deposit.....</i>	<i>58</i>
<i>Figure 8: Powder particle morphology from different atomisation routes.....</i>	<i>65</i>
<i>Figure 9: High-energy attritor concept used for mechanical alloying and intensive powder mixing.....</i>	<i>69</i>
<i>Figure 10: Prevention measures for metal and ceramic powder handling – safe packaging.....</i>	<i>72</i>
<i>Figure 11: Powder-bed machine layout showing powder handling elements around the build chamber.</i>	<i>73</i>
<i>Figure 12: The substrate serves as a heat-sink resulting in a high temperature gradient perpendicular to the melt/substrate interface. Since $k_0 = 0$ plane solidification does not exist. The high G/V resulted in directional solidification of the α-Fe dendrites.....</i>	<i>86</i>

Table of tables

<i>Table 1: AM powder quality characteristics including composition, particle size distribution, flowability, density, morphology, microstructure and thermal conductivity.....</i>	<i>66</i>
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List of Acronyms

Abbreviation / Acronym	Description
AM	Additive Manufacturing
BRL	Business Readiness Level
CAD	Computer-Aided Design
CC BY-NC-SA 4.0	Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International licence
CRL	Customer Readiness Level
DED	Directed Energy Deposition
DED-Arc/M	Arc-based Directed Energy Deposition of Metals
DED-LB/M	Laser-based Directed Energy Deposition of Metals
DMLS	Direct Metal Laser Sintering
ESD	Electrostatic Discharge
FGM	Functionally Graded Material
FGMs	Functionally Graded Materials
FRL	Funding Readiness Level
H ₂	Hydrogen
IP	Intellectual Property
IPR	Intellectual Property Rights
IPRL	Intellectual Property Readiness Level
IRL	Innovation Readiness Level
ISO/ASTM	International Organization for Standardization / ASTM International
KTH	KTH Royal Institute of Technology
KTO	Knowledge Transfer Office
KTT	Knowledge and Technology Transfer
LBM	Laser Beam Melting
LMD	Laser Metal Deposition

MVP	Minimum Viable Product
N2	Nitrogen
NABC	Need, Approach, Benefits, Competition
O2	Oxygen
P&L	Profit and Loss
P3	Particle filter class P3
PBF	Powder Bed Fusion
PBF-EB/M	Electron Beam Powder Bed Fusion of Metals
PBF-LB/M	Laser Beam Powder Bed Fusion of Metals
PeP	Plasma Electrolytic Polishing
PPE	Personal Protective Equipment
SAM	Serviceable Available Market
SDG	Sustainable Development Goal
SEAMAC	Strengthening the Excellence of Additive Manufacturing Capabilities
SEM	Scanning Electron Microscopy
SLM	Selective Laser Melting
SOM	Serviceable Obtainable Market
STL	Stereolithography file format
TAM	Total Addressable Market
TECHNION	Technion - Israel Institute of Technology
TMRL	Team Readiness Level
TRL	Technology Readiness Level
TTO	Technology Transfer Office
TUBAF	Technische Universität Bergakademie Freiberg
UL	University of Ljubljana
XRF	X-ray Fluorescence

2 Introduction

This deliverable provides the technical and non-technical training toolkit defined in the Grant Agreement for WP3, “Training as a driver of excellence”. Its purpose is to make critical knowledge on AM of FGMs and the competences needed for technology transfer, intellectual property, proposal preparation and administration usable by researchers and their support services. The two parts connect scientific and technical learning with the organisational conditions needed to develop and transfer research results.

The non-technical guide in Sections 3–7 introduces a holistic development pathway. It uses the KTH Innovation Readiness Level™ framework to help researchers assess technology, customer/user, business, intellectual property, team and funding readiness, identify gaps and prepare a focused development plan. It also explains when knowledge-transfer, legal, project and financial services or external partners can provide specialist support.

The technical toolkit begins in Section 8 and comprises eight modules in Sections 9–16. These cover the process chain from AM and FGM fundamentals through powder preparation, LMD, PeP, characterisation and troubleshooting to training delivery and good practice. The modules are designed for selection and adaptation to the learner’s background and intended application.

Read the two parts together when planning a research-to-application pathway. For an initial overview, start with Sections 3–4 and Section 8. For a specific technical task, select the relevant module from Sections 9–14; use Sections 15–16 to design and adapt training. Sections 5–6 help translate identified development gaps into activities and discussions with the appropriate support services.

The main outcome is a structured training and development reference that can support the transfer of knowledge to new researchers at UL and to industrial users. Researchers can connect a technical question to the relevant module and then use the non-technical guide to consider users, protection, collaboration and funding. Trainers can combine selected modules with supervised demonstrations and exercises. Research managers can use the mapping (Table 1) to locate the relevant toolkit contribution and complementary reporting.

The task mapping (Table 2) distinguishes D3.2’s reusable content from the detailed reporting allocated to other deliverables. It follows the task titles in the Grant Agreement. A correspondence between a module and a task identifies subject coverage; it does not establish that every planned activity or individual competence has been completed.

The toolkit draws on the knowledge exchanged through SEAMAC partner training, summer schools, staff exchanges and research activities. The Final Report, Section 1.2.3, records the on-site training at Technion on 19–23 February 2023 and at TUBAF on 19–23 June 2023, together with the three summer schools hosted by Technion, TUBAF and UL. These activities provide the training context; the present document organises reusable content rather than repeating their daily programmes.

The toolkit should be used with local supervision, equipment-specific instructions, laboratory safety rules and the applicable institutional procedures. Learning outcomes and suggested training formats are guidance for users. They do not replace qualification of a particular manufacturing route, verification of specimen results or specialist advice on legal, financial and intellectual-property matters.

Table 1: Target audiences and routes through the toolkit

Intended audience	Use of the toolkit	Recommended entry point
Researchers and postgraduate students	Understand the process chain; assess a research idea and plan its development.	Sections 3–5 and 8; Modules 1–6 (Sections 9–14).
Trainers and technical staff	Select teaching content; prepare supervised practical exercises and researcher onboarding.	Section 8; Modules 2–8 (Sections 10–16), with local procedures.
Industrial users and collaborators	Discuss process feasibility, quality risks, user needs and routes to further development.	Sections 3–6; Modules 1, 3–6 and 7 (Sections 9, 11–15).
Research managers, knowledge-transfer and administrative staff	Identify development gaps and specialist support; connect technical activity to application and resources.	Sections 3–7; task mapping below; D3.1 for institutional implementation.
Non-specialist researchers and Commission Services	Understand the output, intended reuse and boundaries of the toolkit.	Executive Summary, Section 2, Section 8 and Conclusions.

Table 2: WP3 task coverage and complementary deliverables

WP3 task (Grant Agreement)	Contribution in D3.2	Complementary reporting
3.1 On-site training on powder blends and characterisation	Modules 1, 2 and 5: AM fundamentals, powder preparation and characterisation; non-technical guidance on transfer and support.	Final Report §1.2.3: event delivery; D1.1/D2.1: research results; D3.1: administrative learning.
3.2 On-site training on improving surface integrity by PeP	Modules 4–6: PeP, evaluation and troubleshooting; Sections 3–6: application and development planning.	Final Report §1.2.3: event delivery; D1.1/D2.1: post-processing results; D3.1: support-unit development.

WP3 task (Grant Agreement)	Contribution in D3.2	Complementary reporting
3.3 Summer schools	Modules 7–8: training formats, modular reuse and lessons for delivery; both parts provide teaching content.	Final Report §1.2.3 and D4.1: programmes and participation; D3.3: continuation.
3.4 International industrial workshop	Industry-oriented training guidance in Module 7; Sections 3–6: user needs, collaboration and development routes.	D4.1: workshop and outreach reporting; D2.1: demonstrator results.
3.5 Upgrade of UL administrative units	Sections 3–7: transferable guidance on technology transfer, IPR, development planning and support networks.	D3.1: institutional changes and administrative training; D5.1/D5.2: management frameworks.

The Grant Agreement also includes proposal preparation, project administration and financial reporting within the non-technical scope of D3.2. The present guide introduces funding opportunities and project-support routes; the corresponding administrative training and institutional implementation are reported in D3.1. Users should consult their own institution's responsible services for the applicable proposal, budgeting and financial-reporting procedures. Public access to this toolkit does not imply access to internal institutional resources or support services.

Access, adaptation and FAIR-aligned reuse

The toolkit is freely accessible on the SEAMAC website (<https://www.seamac.si/deliverables/>). Conditions for adaptation, reproduction and redistribution are specified in the accompanying copyright and licensing notices. Where the intended reuse is not covered by those terms, users should obtain permission from the relevant rights holders. Third-party frameworks, figures and source materials remain subject to their respective terms.

The contents, module titles, acronyms, bibliography and references to complementary deliverables support navigation and interpretation. When adapting material for training, retain its source, module and version identification, preserve technical qualifications and distinguish teaching examples from measured project results. These practices support traceability and FAIR-aligned reuse, subject to the applicable permissions.

The toolkit is a training resource. Research-data management and sharing are addressed in D5.1, and dissemination and exploitation planning in D5.2. Its public availability does not imply that all underlying datasets or referenced training materials are publicly accessible. Claims of public access to such resources should identify their verified location and applicable access and reuse conditions.

3 From a research idea to industrial use

A research idea often begins as a promising observation, result, method, material, process, dataset, algorithm, device principle, or scientific insight. At this early stage, its value is usually expressed in research terms: novelty, explanatory power, experimental performance, publication potential, or contribution to a scientific field. Industrial use, however, asks a different set of questions. It does not only ask whether the idea is scientifically interesting, but whether it can create value in a real environment, for real users, under technical, economic, legal, organisational, and regulatory constraints. This transition can be understood as a gradual movement through several forms of maturity. A research result is a validated piece of knowledge or an experimental outcome. It may show that something is possible, that a mechanism exists, or that a certain approach performs better than alternatives under specific research conditions.

Case study: Research result

In the case of Plasma Electrolytic Polishing, the research result is the demonstrated understanding that a plasma-assisted electrochemical process can improve the surface quality of metallic components while using less hazardous electrolytes than conventional acid-based electropolishing. The value lies mainly in scientific evidence: the process can reduce roughness, improve surface characteristics, and show environmental advantages under defined experimental conditions.

A technology is more than a result. It is a defined way of doing something: a method, process, material, device, software component, or system that can be described, repeated, tested, and potentially transferred beyond the original research setting.

Case study: Technology

As a technology, PeP includes the process window, electrolyte formulation, equipment concept, operating parameters, monitoring approach, and possible material applications. This makes it possible to describe, test, compare, and improve the process beyond the original research environment.

A prototype is a tangible or functional representation of the technology. It helps the team and external stakeholders test whether the technology can work outside the purely conceptual level. A prototype may still be incomplete, fragile, expensive, or dependent on expert handling, but it makes the idea concrete enough to generate evidence.

Case study: Prototype

At prototype level, PeP becomes visible and testable through a functional system rather than only a process description. For example, a research team uses a pilot unit to polish additively manufactured titanium or stainless-steel samples and compares the results with alternative finishing methods. The prototype still requires expert operation, but it enables structured learning about performance, limitations, and next development steps.

A solution for a user goes one step further. It connects the technology to a real problem, user group, application context, and value proposition. At this stage, the question is no longer only “Does it work?” but also “For whom does it work?”, “Which problem does it solve?”, “How important is this problem?”, and “What would the user need in order to adopt it?”

Case study: Solution for a user

The research group obtained actual industrial components from companies, processed them on a prototype device, and used the treated parts as a basis for discussion with the industrial partners. This moved the conversation beyond generic samples or abstract performance claims. The companies could assess the usefulness of the new polishing approach in their own context: the quality of the treated surfaces, access to complex geometries, reduced reliance on hazardous chemicals, fit with existing processes, and the practical value compared with current polishing methods.

An industrially validated technology is a technology that has been tested in conditions that resemble or reflect the environment in which it would actually be used. It is not only technically functional; it is also sufficiently reliable, usable, compatible with existing processes, and credible for further development with industrial partners. In the KTH Technology Readiness Level logic, higher readiness involves evidence that the technology works in relevant or operational environments and, at higher levels, that the complete technology is functional, compatible with user processes, and producible at a reasonable cost.

Case study: Industrially validated technology

Industrial validation started when the feedback from processed industrial parts was translated back into the technology. The research group adapted the PeP parameters, testing logic, and final product concept according to what companies recognised as useful in their own context. This helped transform the prototype experience into a more industry-oriented device concept, with clearer attention to repeatability, usability, safety, surface quality, and integration into existing industrial workflows.

Technology Readiness Levels, or TRLs, are useful because they help describe how far a technology has progressed from early research towards application. Moving from lower to higher TRL usually means moving from scientific exploration and laboratory validation towards demonstration, prototyping, validation in relevant environments, and eventually use in real operational settings. For researchers, this can be helpful because it translates development into a more structured pathway: what has already been shown, what remains uncertain, and what kind of evidence could support the next step.

At the same time, TRL alone gives only a partial picture. A technology can be technically advanced but still difficult to transfer. It may work in a laboratory but have no clearly defined user. It may solve a problem that is scientifically interesting but not important enough for industry to invest in. It may be technically strong but difficult to protect, expensive to scale, dependent on unavailable infrastructure, or unsuitable for regulatory approval. It may also require a team, partners, or funding that are not yet in place.

In practice, this means that a research team can look at an idea through several connected lenses:

Technology: What exactly has been developed? What evidence shows that it works? In which environment has it been tested? What would be needed to demonstrate it in a more relevant or industrial setting?

User: Who experiences the problem? Who would use the solution? Who would decide about adoption? Who would pay for it? Has the problem been discussed with people outside the research team?

Market and value: Which application areas are most realistic? What alternatives already exist? Why would a company, public organisation, hospital, municipality, or other user prefer this solution? What value would it create for them?

Intellectual property and knowledge protection: What is new? What has already been published or disclosed? Who contributed to the result? Could the knowledge be protected through patents, copyright, design rights, know-how, trade secrets, data rights, or contracts?

Team and competencies: Which capabilities are already present in the research team? Which ones could be added through collaboration with KTT (knowledge and technology transfer)/TTO (technology transfer office) staff, legal experts, project officers, financial services, industry partners, mentors, incubators, or external specialists?

Funding and resources: What activities are needed for the next development step? What equipment, testing, personnel, external services, or partnerships would be required? Which funding routes could support proof-of-concept, validation, prototyping, industrial testing, or commercialisation?

Regulation and standards: Are there standards, certifications, safety requirements, clinical requirements, environmental rules, or sector-specific procedures that could influence development? When these questions are explored early, they can reduce later uncertainty.

Industrial partners: Which companies or organisations could help test, validate, adapt, scale, or apply the technology? A partner does not only represent a possible customer; in many cases, a partner can help define requirements, provide access to real environments, contribute complementary knowledge, or support later adoption.

This broader view changes the role of the researcher. The goal is to recognise which questions matter, where the main gaps are, and when it is useful to involve the right support. In a university context, this is especially important because technology transfer is rarely a linear path from publication to patent to company. It can involve invention disclosure, IPR assessment, de-risking, industry outreach, licensing, joint development, incubation, investment, spin-out creation, or research and development collaboration. The Knowledge transfer office (KTO) at University of Ljubljana (UL) similarly frames valorisation as a process that connects invention disclosure, intellectual property, problem-solution fit, product-market fit, industry outreach, licensing, de-risking, incubation, investment, and partnerships.

A technically promising idea can therefore lose momentum for reasons that are not purely technical. It may lack a clearly confirmed user need. It may be disclosed publicly before protection options have been considered. It may require validation data that no one has planned or funded. It may be too difficult for an industrial partner to integrate into existing processes. It may need regulatory evidence, a clearer value proposition, or a team with additional competencies. None of these issues necessarily means that the idea is weak. More often, they show where the next development activities can be focused.

For researchers, the key shift is to see industrial use not as a final administrative step after the research is finished, but as a gradual learning process. Each conversation with a user, each technical test in a more realistic environment, each IPR discussion, each market insight, and each partnership can help clarify what the idea could become. In this sense, moving towards industrial use is not only about raising TRL. It is about developing the idea as a whole.

For this reason, the development of a research idea benefits from a more holistic view. Technical readiness is one dimension, but it is not the only one. The KTH Innovation Readiness Level approach reflects this broader logic by looking not only at technology, but also at customer or user readiness, business readiness, intellectual property readiness, team readiness, and funding readiness. For example, Customer Readiness Levels examine whether a possible need has only been assumed, whether feedback from potential users has been collected, whether the problem has been confirmed by several customers or users, and whether early users are testing or buying the solution. Business Readiness Levels add questions about value proposition, market, competition, costs, revenues, positioning, and sustainability. Intellectual Property Readiness Levels help structure questions about possible protection, ownership, prior art, freedom to operate, and the role of IPR in creating value.

4 Self-assessment framework for the holistic development of a research idea

Before looking at each readiness dimension in more detail, it is useful to introduce the logic behind the KTH Innovation Readiness Level™ framework. The framework can help a researcher or research group look at a research-based idea as more than a technical result. It creates a structured way to explore what has already been developed, what remains uncertain, and which next activities could move the idea closer to use in an industrial, societal, or organisational context.

Attribution and use of the KTH Innovation Readiness Level™ framework

This guide draws on the KTH Innovation Readiness Level™ model, developed by KTH Innovation, as a framework for guiding idea development and assessing progress across key innovation dimensions. The model and associated resources are made available by KTH Innovation under the Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International licence (CC BY-NC-SA 4.0), which allows sharing and adaptation for non-commercial purposes with appropriate attribution, indication of changes, and distribution under the same licence. In this guide, the KTH IRL framework is used and adapted for the context of public research organisations, with particular attention to researchers, research groups, knowledge transfer professionals, technology transfer professionals, and other support services. The adaptation does not imply endorsement by KTH Innovation. More information about the model is available on the official KTH Innovation Readiness Level™ website: <https://kthinnovationreadinesslevel.com/>.

The purpose of this self-assessment is not to judge whether an idea is “good” or “bad”. It is better understood as a development map. It helps describe the current maturity of an idea and identify the gaps that need attention before the idea can be tested, validated, adopted, licensed, further developed with a partner, or transformed into a new venture. In this sense, the framework supports a shift from asking “Is this a promising research result?” to asking “What is already in place, what is still missing, and who can help us move forward?”

The KTH IRL logic is especially useful because it looks beyond technical readiness alone. A technology can be scientifically strong and still remain difficult to transfer if the user need is unclear, the intellectual property position is uncertain, the team lacks capacity for the next phase, or the development path is not connected to funding and implementation options. For that reason, each idea is reviewed through six complementary dimensions: Technology Readiness, Customer/User Readiness, Business Readiness, IPR Readiness, Team Readiness, and Funding Readiness.

Technology Readiness considers whether the technology works, which functions have already been demonstrated, and in what type of environment validation has taken place. It helps distinguish between a research result, a laboratory proof of concept, a prototype, and a technology that is ready to be tested or used in a relevant operational setting.

Customer/User Readiness shifts attention to the people, organisations, or systems that may benefit from the technology. It asks whether the problem has been understood from the perspective of potential users, customers, decision-makers, or industrial partners. This dimension helps researchers test whether the assumed need is recognised outside the research group.

Business Readiness does not only refer to startups. In the context of public research organisations, it can also mean understanding the most realistic route towards use. This may include licensing, joint development with a company, contract research, a pilot with an industrial partner, integration into a larger R&D project, public-sector or societal implementation, or a spin-out when that route is appropriate. The key question is whether there is a plausible logic for creating, delivering, and capturing value.

IPR Readiness helps clarify what knowledge, results, data, methods, software, inventions, or know-how may need to be protected or managed. It also helps identify what has already been publicly disclosed, who contributed to the result, and whether professional support from knowledge transfer, technology transfer, IPR, legal, or patent experts should be involved before publication, presentation, or partner discussions.

Team Readiness focuses on the people and capacities needed for the next development step. A research group may have strong scientific expertise, while still needing support in industrial communication, project design, regulatory issues, IPR, business development, finance, or partner management. This dimension helps make such needs visible without implying that the researcher should cover all roles alone.

Funding Readiness connects the development gaps with resources. It asks what activities are needed next, what they may cost, which partners may be relevant, and which funding routes could support the transition from research towards validation, piloting, or implementation.

Different ideas require different pathways. Some may be best suited for licensing, some for collaborative development, some for public-sector or societal implementation, some for further research funding, and some for spin-out creation. The value of the framework lies in making these options visible early enough, while there is still time to shape the development path. The self-assessment can therefore be used as a practical working tool. A researcher or research group can go through each dimension, describe the current level of maturity, identify missing evidence, and translate the gaps into concrete activities. At the same time, the framework helps recognise when it is useful to involve professional services such as knowledge transfer or technology transfer offices, legal support, project offices, financial services, incubators connected to public research organisations, industry liaison staff, or external experts.

The following section applies this logic to each readiness dimension. For every dimension, the guide introduces key self-assessment questions, typical development activities, and a short case-based illustration. The intention is to support researchers in building a more complete picture of their idea and in preparing a realistic development plan that connects technology, users, value, intellectual property, team capacity, and funding.

5 Preparation of a development plan across KTH Innovation Readiness Level™ dimensions

This section translates the KTH Innovation Readiness Level™ logic into a practical self-assessment and planning tool for researchers and research teams in public research organisations. Each dimension helps describe where the idea currently stands, what has already been developed or validated, and which gaps could be addressed next.

The readiness levels can be used as a snapshot, but they become more useful when they are followed over time. A research idea rarely progresses equally across all dimensions. Technology readiness can move faster than customer, business, IPR, team or funding readiness, or the opposite can happen. For this reason, a simple readiness profile (Figure 1) can help the team visualise progress across dimensions and identify where the next bottlenecks are likely to appear.

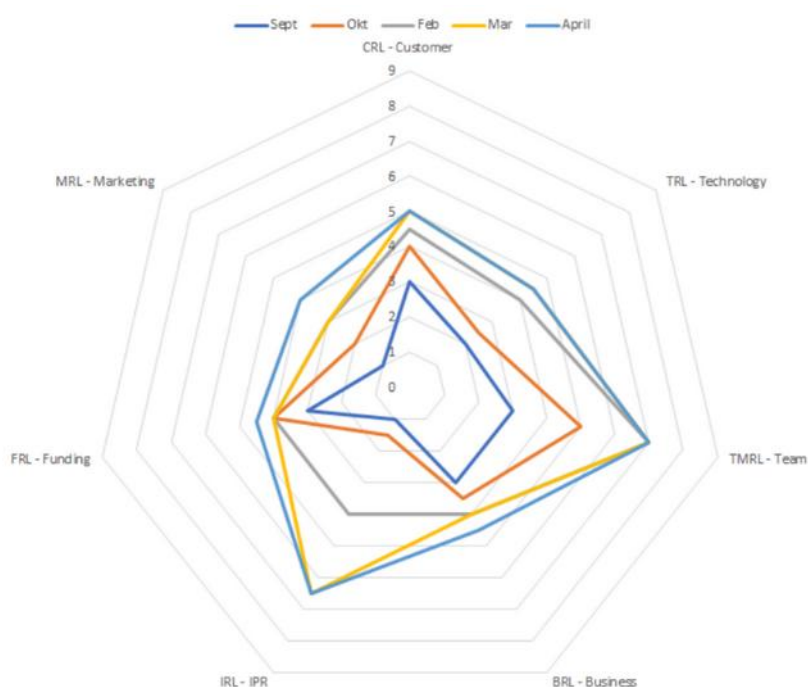


Figure 1: Example of a readiness profile showing gradual improvement across several readiness dimensions over time.

The aim is not necessarily to reach the highest level in every dimension at the same time. Rather, the profile helps the researcher ask a more useful question: which dimension is limiting the next development step? For example, a technology can be technically promising, but still lack user validation, a clear IPR position, the right team competences, or funding for the next experiment. In that case, the next activity may not be another technical test, but a customer interview, an invention disclosure, a partner discussion, or preparation of a project application.

To support this process, each readiness dimension can be translated into a simple action plan. The researcher first identifies the **start readiness level**, then defines a **planned readiness level** for a specific period, and finally lists the activities that can create the evidence needed for that progression (see a case study in the next subsections).

In the following subsections, each readiness dimension is structured in the same way:

Element	Purpose
Readiness level introduction	Explains what the dimension means and why it matters for the development of a research idea.
Case study development path	Shows how a project can move from a starting readiness level towards a planned level through concrete activities.
Readiness thermometer	Provides a quick visual orientation from lower to higher readiness levels.
Detailed readiness table	Describes the levels in more detail and helps the researcher identify the current position and next step.

This format makes progress visible without overstating it. A project can plan to reach a higher level, achieve only part of that progression, and still create valuable evidence for the next phase. The important point is to make the development path explicit: where the idea started, where the team aimed to go, which activities were performed, and what readiness level was actually supported by the evidence.

5.1 Technology readiness level

Technology readiness level (TRL) describes how far a research result has developed towards a technology that can be tested, demonstrated and eventually used in practice. It is not only a question of whether the underlying science works. TRL helps the researcher look at three connected elements: the technology itself, the environment in which it has been tested, and the type of evidence or delivery that has been achieved.

In this document, the word technology is used broadly. It can refer to a product, process, method, material, software, system, prototype or technical solution. At lower TRL levels, the technology can still be a concept, early proof-of-concept or laboratory prototype. At higher TRL levels, it becomes closer to a complete solution that is functional, compatible with user needs and possible to produce or implement at reasonable cost.

The second element is the environment. A result demonstrated in a laboratory is not the same as a result validated in a relevant environment, and this is again different from a technology demonstrated in operational conditions. This distinction is important for researchers in public research organisations, because strong laboratory evidence can be an excellent starting point, while additional steps are often useful before an industrial partner can assess whether the technology works under realistic conditions.

The third element is the delivery or type of evidence. Early stages usually involve proof-of-concept activities, testing of critical parameters and validation of basic functionality. Middle stages focus on integrated prototypes, validation in relevant environments and demonstration of performance. Later stages involve operational testing, production validation, release to manufacturing or use by first users.

For this reason, the transition between levels is often more important than the level itself. For example, moving from TRL 5 to TRL 6 usually means moving from validation of integrated components towards a representative prototype demonstrated in a relevant environment. Moving from TRL 6 to TRL 7 means that the prototype is no longer only a test

object, but is being shaped into a reliable and scalable technology that can work in operational conditions.

This also helps avoid common development traps. A research team can develop the technical solution too far before confirming user needs, invest in performance improvements before the use case is clear, or create a prototype that works for testing but is difficult to scale, maintain or integrate. TRL therefore supports a more balanced conversation: what has already been proven, what is still uncertain, and what is the next meaningful validation step.

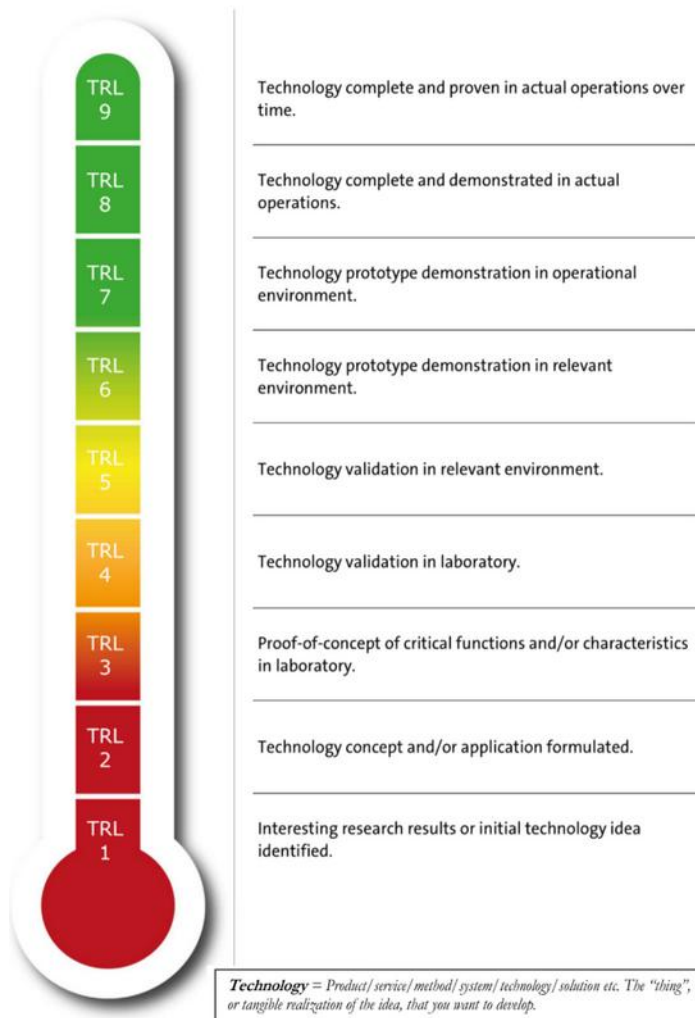
<i>Case study: SEAMAC project development path</i>		
Start	Plan	Activities performed
TRL2	TRL 6	• The technology concept was defined: deposition of a high-value steel layer onto a cast iron base, with the aim of combining a lower-cost structural material with a high-performance functional surface. [TRL 2] • Different joining and deposition routes were explored, including direct deposition and the use of intermediate layers between cast iron and maraging steel. The transition from cast iron towards maraging steel was gradually developed through experimental trials. [TRL 2 → TRL 3] • Test samples were prepared to evaluate whether the deposited material system achieved sufficient bonding and mechanical performance. [TRL 3] • Samples were sent for tensile and shear strength analysis, providing evidence on the quality of the material connection and supporting selection of the most promising deposition route. [TRL 3 → TRL 4] • Based on the test results, a prototype extrusion tool was designed and produced using the selected deposition approach. [TRL 4 → TRL 5] • The deposited tool surface was polished using plasma electrolytic polishing, connecting the material deposition route with the surface finishing process. [TRL 5] • The tool was tested in a laboratory environment to evaluate functional performance under controlled conditions. This confirmed progress towards a representative prototype, while further validation in a relevant environment remained the next step. [TRL 5] • A prototype setup for PeP trials was prepared, enabling further testing of surface finishing parameters. [TRL 5] • The deposition process was adapted for curved surfaces by developing the required kinematics and process parameters. [TRL 5 - 6]

The case study illustrates that TRL progression is not always a clean jump from one level to another. A project can plan for a higher readiness level, achieve part of that progression, and still create valuable evidence for the next development step. In this example, the project moved from a formulated technology concept towards prototype-level validation,

while the transition towards a fully relevant-environment demonstration remained a next step.

The TRL thermometer below can be used as a quick orientation tool. It helps the researcher position the technology according to three connected questions: what has been developed, where it has been tested, and what kind of evidence has been produced. The detailed table that follows provides a more structured description of each level and can support the preparation of a development plan.

Technology Readiness Level - TRL



9	- Complete technology is scalable and proven to work in actual operations by several users over time - Continuous development, improvement, optimization of technology and production is ongoing
8	- Complete technology has been proven to work in actual operations by first users - Complete technology = Complete - contains everything the user needs to use it; Functional - everything works the way it should for the user to solve their problem/need; Compatible - compatible with people, processes, goals, infrastructure, systems, etc. at the user; Producible - possible to produce at a reasonable cost - Proven to work = meet all performance requirements/specifications - Actual operations = implemented by end-users on their own in their day-to-day operations
7	- Prototype near or at the complete technology has been shown to actually work in an operational environment - Operational environment = environment that addresses all the operational requirements and specifications where the technology will be used by the end-users

	• Complete end-user requirements/specifications and/or use cases in place
6	• Representative model or prototype of the technology has been shown to actually work in a relevant environment • Representative model = a functional form of the technology, generally reduced in scale, near or at operational specification • Prototype = the technology in a form that can be used to evaluate the technical and/or manufacturing feasibility or utility of the final product • Shown to actually work (i.e. demonstration) = meet most of the important performance requirements
5	• Basic components are integrated and tested in a more realistic form in a relevant environment • Test results give evidence indicating that the technology will work (i.e. validation) • Relevant environment = lab or other controlled environment that simulates the most important and most stressing aspects of the operational environment • More defined end-user requirements/specifications and/or use cases based on feedback from users
4	• Basic components are integrated and shown to work together and produce desired results in the laboratory environment • Test results give initial evidence indicating that the technology concept will work (i.e. initial validation)
3	• Tests in the laboratory environment (analytical and/or experimental) of important parameters/features/functions show that the technology concept could work and be feasible • Laboratory environment = the environment where technology is typically developed, often not the same environment as where it will be used • Active R&D is initiated to develop the technology further • There is a first idea of end-user requirements/specifications and/or use cases
2	• A potential technology concept is defined and described. • Practical applications can be defined/researched but are speculative, and no proof or detailed analysis that the technology will work.
1	• Research results with potential benefits or useful applications identified • Vague idea of a technology to be developed

5.2 Customer readiness level

Customer readiness level (CRL) describes how far a research result or technology has developed in relation to real users, customers and other stakeholders who influence adoption. It is not only a question of whether someone might find the idea interesting. CRL helps the researcher look at three connected elements: the problem or need, the people and organisations connected to that problem, and the evidence that the proposed solution creates value for them.

In this document, the word customer is used broadly. In the context of public research organisations, the customer is not always a buyer in the narrow commercial sense. It can be an industrial partner, end user, paying customer, decision maker, procurement function, production engineer, clinician, quality manager, public-sector organisation, regulator or another actor who influences whether the solution can be adopted. For this reason, customer readiness is relevant not only for spin-out creation, but also for licensing, joint development, contract research, pilot projects, industrial collaborations and wider societal use.

The second element is the problem or need. A technology can have many possible applications, but customer readiness helps the researcher move from a broad assumption that “there is a market” towards a clearer understanding of who has the problem, why it matters, how it is currently solved, and what would make a new solution worth considering. At lower CRL levels, this understanding may be based mainly on desk research and internal assumptions. At higher levels, it is supported by direct conversations, repeated

feedback, confirmed problem importance, testing with users, customer agreements or first sales.

The third element is evidence. Early customer readiness may involve secondary market research, mapping of possible applications and a first problem hypothesis. Middle levels focus on direct feedback from possible users, industry experts or customers, clearer segmentation, identification of the user, paying customer and decision maker, and an initial value proposition. Later levels involve customer testing, confirmed benefits, first structured sales activities, customer agreements, qualifications, test sales, first users and, eventually, repeatable customer acquisition.

For this reason, the transition between CRL levels is often more important than the level itself. Moving from CRL 2 to CRL 3 usually means moving from desk research towards direct external feedback. Moving from CRL 3 to CRL 4 means that the problem or need has been confirmed by several relevant customers or users, and that the team understands who the user, payer and decision maker are. Moving from CRL 5 to CRL 6 means moving from expressed interest and initial problem-solution fit towards actual testing that confirms customer value and benefits.

A research team can develop a technically strong solution before confirming who experiences the problem, focus on an attractive application without understanding who pays for implementation, or speak mainly with technically interested people while missing the actual decision makers. Customer readiness therefore supports a more balanced conversation: who has the problem, how strong the need is, what alternatives already exist, and what evidence shows that the proposed solution creates value.

<i>Case study: SEAMAC project development path</i>		
Start	Plan	Activities performed
CRL2	CRL 6-7	• FGM manufacturing and PeP post-processing were positioned around CRL 2, since the customer need was recognised from secondary market understanding, industrial context and known challenges in AM, tooling, surface finishing and post-processing. • The Grant Agreement identified relevant industrial needs and application areas, including advanced manufacturing, tooling, surface finishing and post-processing. This supported the initial problem and customer-need hypothesis. [CRL 2] • Through exploratory research activities, the understanding of possible users, customer segments and relevant industrial problems was refined. Application-oriented discussions and project activities supported movement towards CRL 3–4. • FGM samples were produced and characterised. The results enabled more concrete discussions of possible industrial applications, since the technology could be presented through test results rather than only a concept. [CRL 3 → CRL 4] • A demonstrator extrusion die was manufactured and tested. This supported progress towards CRL 4, because the problem, possible application and customer value could be discussed using a tangible demonstrator. • PeP post-processing was applied to industrial components. Successful polishing cases confirmed practical customer value,

		while unsuccessful cases helped define technology boundaries, especially for closed geometries and materials such as high-carbon tool steels. [CRL 5 → CRL 6] The signed contract with one company for further development of PeP technology for its product indicated movement towards CRL 7, where customer agreements, product qualification or extended customer testing become relevant.
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The case study illustrates that CRL progress is not only about finding interested companies. It is also about understanding the structure of the customer environment. In this example, the project developed a clearer view of who could benefit from the technology, what problem was being addressed, which alternatives customers already use, and which adoption barriers influenced the path towards industrial uptake.

The CRL thermometer below can be used as a quick orientation tool. It helps the researcher position the idea according to three connected questions: who has the problem, how well the problem and customer context have been validated, and what evidence shows that the proposed solution creates value. The detailed table that follows provides a more structured description of each level and can support the preparation of a development plan.

Customer Readiness Level - CRL



9	- Widespread product deployment, sales to several customers in a repeatable and scalable way (including through partners when relevant) - Large and substantially growing number of active users (significant customer traction) - Company focuses on business development, customer acquisition, growth of sales, efforts to build
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	user/customer demand, etc.
8	• Market ready product/service sold to customers at/near target market price • Substantial number of active users of market ready product/service (initial customer traction) • Sales/user acquisition process implemented with dedicated people and support systems (CRM system, etc.) • Agreements in place with first partners to reach customers (when relevant)
7	• Customer agreements in place - first sales/test sales of early versions of product/service or customers/users engaged in product/service qualifications or extended testing • Small number of active users of early versions of product/service • Discussions initiated with partners to reach customers/users (when relevant)
6	• Testing of product/service by customers/users has confirmed the customer value and benefits • Updated sales pitch and value proposition based on customer/user feedback • Defined first sales/user acquisition process and initiated structured sales activities • Identified possible partners or key stakeholders relevant to reach customers/users
5	• Customers/users have expressed interest for the product/service and confirmed that it can solve customers' problems/needs (i.e. initial problem-solution fit) • Established relationships with potential target customers/users providing input • Decided which target customers/segments to focus on first • Defined first sales pitch and value proposition adapted to target customer/segment
4	• The problem/need and its importance is confirmed from multiple customers or users. Numbers are typically limited but depend on B2B/B2C and market structure (e.g. 5-10 in B2B, if market is concentrated 2-5 market leading customers, in B2C higher e.g. 10-20) • Customer segmentation with initial basic customer profiles in place • Identified who the user, paying customer, and decision maker is • A product/service hypothesis with clear positioning against customer alternatives is defined based on customer/user feedback
3	• Received feedback from primary market research, i.e. direct contacts with e.g. a few possible users/customers or persons with industry/market knowledge (experts) • A more developed understanding of possible customers and possible customer segments • The problem/need hypothesis is clear and updated after customer/user/expert feedback
2	• Some market research is performed, typically derived from secondary sources • Brief familiarity with the market, possible customers and their problems/needs, and alternatives • There is a first reasonably clear description of the problem/need hypothesis
1	• Thinking (yourself) that a possible need/problem or opportunity might exist in a market • No clear hypotheses on who customers are, what problems exist, etc. If hypotheses exist they are unclear, speculative, and there is no proof or analysis to support assumptions • Limited or non-existing knowledge of the market and customers/users

5.3 Business readiness level

Business readiness level (BRL) describes how far a research result or technology has developed towards a viable, realistic and sustainable route to use. It is not only a question of whether the technology has commercial potential. BRL helps the researcher look at three connected elements: the business concept, the market structure and value chain, and the sustainability aspects that can influence adoption and long-term value.

In this document, the word business is used broadly. In the context of public research organisations, business readiness does not only refer to creating a start-up or selling a product. It can also describe licensing, joint development with a company, contract research, service provision, a pilot with an industrial partner, integration into an existing production process, or participation in a larger development project. For this reason, BRL is relevant whenever a research result is being developed towards practical use, industrial uptake or societal implementation.

The second element is the market structure and value chain. A technology can appear promising, but its route to use depends on how the market is organised, who the relevant actors are, where the technology fits in the value chain, and which alternatives already exist. At lower BRL levels, this understanding may be based mainly on assumptions, desk research and a first description of possible target markets. At higher levels, it is supported by market feedback, clearer positioning, validated pricing assumptions, first sales, or operational business metrics.

The third element is sustainability. In BRL, sustainability is not only an external impact topic. It can become part of the value proposition and business model. Environmental benefits, social impact, safety improvements, circularity, regulatory compliance or governance aspects can all influence whether a technology is attractive to customers, partners, funders or public-sector stakeholders. At lower BRL levels, sustainability may only be recognised as a possible aspect of the idea. At higher levels, it is translated into defined metrics and integrated into the business model.

For this reason, the transition between BRL levels is often more important than the level itself. Moving from BRL 2 to BRL 3 usually means moving from a broad business concept towards a first structured description of the business model, target market and competitive landscape. Moving from BRL 4 to BRL 5 means that first calculations and market assumptions are tested through market feedback, especially assumptions about willingness to pay, pricing, value-chain position and competition. Moving from BRL 5 to BRL 6 means moving from validated assumptions towards a realistic business scenario, such as a pilot, test sale, pre-order, structured industry project or customer validation process.

A research team can assume that technical superiority automatically creates business value, describe a large market without identifying the first accessible segment, or focus on sustainability benefits without translating them into customer or partner value. Business readiness therefore supports a more balanced conversation: what value is created, who captures that value, which route to use is realistic, what evidence supports the business assumptions, and how sustainability strengthens or challenges the path towards adoption.

<i>Case study: SEAMAC project development path</i>		
Start	Plan	Activities performed
BRL 1-2	BRL 5	• FGM manufacturing and PeP post-processing were approximately at BRL 1-2. The business opportunity was recognised, especially in relation to AM post-processing, tooling, dies and moulds, but the value proposition, target market, customer segments, pricing logic and exploitation routes were still only broadly defined. • Through the project activities, the business understanding progressed towards BRL 3-4. FGM demonstrators, PeP trials and industrial case studies helped clarify possible target applications, technical boundaries, competitive positioning and the conditions under which the technologies could create business value. • PeP showed stronger progress than FGM in business readiness, reaching elements of BRL 5-6 in selected cases. Successful polishing of industrial parts, combined with failed cases caused by geometry or material limitations, helped validate in which segments and for which products the service or technology could be commercially useful and where it should not be offered.

		• The signed contract with one company for development of PeP technology for a specific product is an important indicator of movement towards BRL 6, because the business case is no longer based only on general interest but on a realistic industrial development scenario with a concrete partner and its willingness to pay for provided value. • The solution for reducing peak currents at the beginning of polishing, currently in the patent-application process, further supports business readiness by strengthening differentiation, protectable know-how and potential future exploitation. This is particularly relevant for moving from BRL 5-6 towards higher levels.
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The case study illustrates that BRL progress is not only about estimating market size or preparing a business model canvas. It is also about understanding the market structure, the value chain, the adoption barriers, the most realistic commercialisation route and the sustainability logic of the idea. In this example, the project moved from a general business concept towards a more structured view of target markets, competition, value proposition, adoption constraints and possible partner pathways.

The BRL thermometer below can be used as a quick orientation tool. It helps the researcher position the idea according to three connected questions: what business concept is being developed, how well the market and value-chain assumptions have been tested, and how sustainability can contribute to value creation and positive impact. The detailed table that follows provides a more structured description of each level and can support the preparation of a development plan.

Business Readiness Level - BRL



9	- Business model is operational and proven as business meets/exceeds expectations on profit, growth, scalability. - Actively pursuing additional target markets, internationalization strategy in place. - Expanded competitor monitoring covering new markets and future scenarios. - Operations, growth and sustainability are balanced (validated by sustainability metrics)
8	- Sales and other metrics show that business model is viable (e.g. regarding profit, growth) Future additional target markets described including international possibilities and markets. - Implemented continuous competitor monitoring. - Sustainability is integrated into the business and used as a way to create business value and positive impact
7	- Business model validated by first sales on commercial terms to several customers. - Target market and sales estimates validated by market feedback. - Market differentiators/USPs validated by market feedback and implemented in marketing and communication. - Sustainability metrics defined (incl. how to monitor and report).
6	- Business model validated by target customers in realistic business scenario (pilot, test sales, pre-order etc.). - Decided on first target market (incl. geographical focus) based on relevant market input. - Key market differentiators/USPs defined and added to pitch/presentation. - Key sustainability metrics proposed (e.g. carbon footprint, social impact, circularity).
5	- Key assumptions of business model (specifically willingness to pay and pricing) validated by market feedback. - Target market description(s) updated based on market feedback (incl. own positioning in value chain) Updated own positioning in competitive landscape based on market feedback. - Considered how sustainability could be integrated into business to achieve positive impact.

4	• First calculations of main costs and revenues (including pricing) show possible economic viability. • Well defined possible target market(s) description (TAM, SAM, SOM, value chain, geographical scope). • Suggested own positioning in competitive landscape. • SDG assessment outlining positive and negative impact of business.
3	• Draft of business model described e.g. in canvas format. • First description of possible target market(s) with estimates of market size (TAM, SAM). • Description of competition/competitive landscape e.g. in a matrix or positioning map. • First description of which SDG(s) the business could target
2	• Business concept described in structured form, e.g. value proposition (NABC). • Initial overview of markets and their potential market size. • Listed some competitors and/or alternative solutions. • Some insight into sustainability aspects of business (e.g. why and how sustainability) .
1	• Vague/unspecified description of business idea/value proposition/business model. • Little insight into the market and its potential and size. • Little insight into competition and/or alternative solutions. • None or very low awareness of how sustainability aspects could affect the business idea.

5.4 Intellectual property readiness level

Intellectual property readiness level (IPRL) describes how far a research result or technology has developed in relation to ownership, protection, access and use of knowledge. It is not only a question of whether the result can be patented. IPRL helps the researcher look at three connected elements: what is potentially protectable, who has rights or claims connected to the result, and which IPR strategy can best support the route towards use.

In this document, intellectual property is used broadly. In the context of public research organisations, IPR can include patents, copyright, software, databases, designs, trademarks, technical documentation, research data, methods, materials, prototypes, know-how, confidential information and trade secrets. Some results can be protected through formal registration or patent filing. Others create value because they are difficult to reproduce, depend on specialist expertise, or are embedded in validated processes, protocols or datasets.

The second element is ownership and disclosure. A result can appear promising, but its transfer potential depends on who contributed to it, under which employment or project conditions, whether external partners were involved, and whether any part of the result has already been publicly disclosed. Publications, conference presentations, theses, posters, project reports, websites, public databases or informal sharing with companies can all influence the possibilities for protection. At lower IPRL levels, these questions may still be unclear. At higher levels, inventors or creators are identified, ownership is clarified, agreements are reviewed, and relevant disclosures are documented.

The third element is the IPR landscape and protection strategy. A research team can have a new technical result, but similar solutions, publications, patents or commercial products may already exist. IPR readiness helps the team move from an internal assumption of novelty towards a more informed understanding of prior art, freedom-to-operate, possible blocking rights and realistic protection options. At lower IPRL levels, this may involve basic searches and a first description of the possible IPR. At higher levels, it is supported by professional analysis, formal applications, ownership agreements, freedom-to-operate assessment and an IPR strategy aligned with the intended transfer route.

For this reason, the transition between IPRL levels is often more important than the level itself. Moving from IPRL 1 to IPRL 2 usually means moving from a general idea that some IPR might exist towards mapping possible forms of IPR, relevant contributors, ownership questions and applicable institutional or contractual rules. Moving from IPRL 2 to IPRL 3 means preparing a sufficiently detailed description of the result and starting to evaluate protection possibilities through searches of publications, patents, products or state-of-the-art solutions. Moving from IPRL 3 to IPRL 4 means that protection possibilities are assessed more systematically, preferably with professional support, and that priorities for protection begin to emerge. Moving from IPRL 4 to IPRL 5 means that a first formal application or registration may be filed, basic agreements are put in place, and a draft IPR strategy starts to support the development route.

A research team can publish or present too early, assume that a patent is the only valuable form of protection, overlook contributors or partner rights, or approach a company before clarifying what can be shared and what should remain confidential. IPR readiness therefore supports a more balanced conversation: what is new, what has already been disclosed, who has rights connected to the result, which external IPR may affect the path forward, and which protection or knowledge.

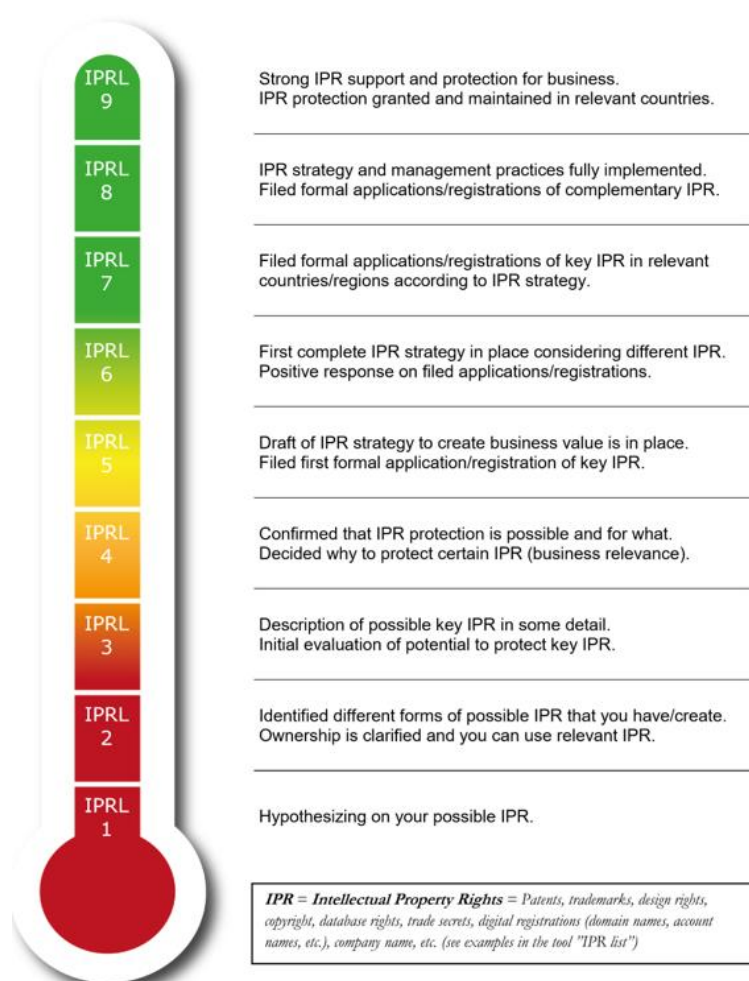
<i>Case study: SEAMAC project development path</i>		
Start	Plan	Activities performed
IPRL 1-2	IPRL 4	• FGM manufacturing and PeP post-processing were approximately at IPRL 1-2. The technologies had clear potential for generating protectable know-how, but the specific intellectual property elements, ownership routes and protection priorities were still only broadly identified. • During the project, the activities progressed towards IPRL 2-3, as the deposition of FGM samples, material characterisation, PeP trials and demonstrator testing created more concrete technical knowledge that could be documented, assessed and compared against the state of the art. • FGM-related work mainly strengthened know-how around powder blends, deposition strategies, material transitions, demonstrator manufacturing and testing. This supports progress towards IPRL 3, but does not yet indicate a formal protection route unless a specific inventive step is identified and assessed. • PeP progressed further in IPR terms because industrial trials revealed practical process limitations and led to a technical solution for reducing peak currents at the beginning of polishing. This moved the activity from general know-how towards a more clearly defined protectable result. • The peak-current reduction solution, currently in the patent-application process. The German patent application was filled on 10th of September 2026, This corresponds to a stage where key IP has been analysed and a first formal protection route is being prepared and filed, hence reaching IPRL 5.

The case study illustrates that IPRL progress is not only about deciding whether to file a patent. It is also about understanding what is new, what has already been disclosed, who contributed to the result, which prior art or third-party rights exist, and which protection or

knowledge-management route best supports the path towards use. In this example, the project moved from a general assumption that the technology might contain protectable intellectual property towards a more structured understanding of the patent landscape, freedom-to-operate considerations, possible protection limits and alternative routes such as know-how, process expertise or trade secrets.

The IPRL thermometer below can be used as a quick orientation tool. It helps the researcher position the idea according to three connected questions: what potential IPR exists, how clearly ownership and disclosure have been addressed, and how well the protection strategy supports the intended route to use. The detailed table that follows provides a more structured description of each level and can support the preparation of a development plan.

Intellectual Property Readiness Level – IPRL



9	• IPR strategy is proven to support and create value for business • Key and complementary IPR is granted and maintained in several countries relevant for business - Agreements in place to access all necessary external IPR
8	• IPR strategy is fully implemented. IPR is proactively used to support/protect business, IPR related agreements are professionally managed, process for securing new IPR in place • Key IPR is granted in first country/region with relevant scope for business - Filed complementary or additional IPR application(s)/registration(s)
7	• Entered into national/regional phase (US, EU, JP etc.) with key IPR application/registration • More complete assessment of freedom-to-operate and clear understanding of dependency

	on/restriction by other IPR
6	• Complete IPR strategy elaborated (validated by professional) that supports business strategy • Identified possible complementary/additional IPR to protect • Initial assessment of freedom-to-operate with the purpose to understand the IPR landscape in the field (who is active, what key IPR) and if you could be dependent on/stopped by other IPR • Positive response on applications from authorities, and analysis of response performed • If no positive response: analysis performed together with professional with good prospects
5	• Draft IPR strategy in place - first analysis and plan (preferably by professional) on how different IPR can be used to protect and be of value for the business. (see e.g. tool KTH IPR Strategy) • First complete formal application/registration of key IPR filed in cooperation with professional • Basic agreements in place to ascertain control of key IPR (e.g. assignments, ownership, etc.)
4	• Confirmed possibilities for protection of key IPR through searches/analysis by a professional • Analysed (ideally with professional) the key IPR and what the priorities should be for what to protect to create value for the business/project • Possibly filed first IPR application/registration in some less elaborate form, e.g. own filing of trademark, “provisional” patent application (i.e. not professionally drafted), etc.
3	• Considered what forms of IPR are key/most important and could/should be protected • Sufficiently detailed description of possible IPR to evaluate possibility for protection • Evaluation of protection possibilities via e.g. own searches of publications, state-of-the art solutions etc. in the field • Possibly initial searches or analysis by professional of relevant prior art or conflicting IPR
2	• Mapped different forms of IPR that exist or could come up during development (see IPR list) - Specific ideas for IPR exist, but are not well described and defined. • Agreements related to IP are identified and ownership is clarified. Inventors/creators are clarified. Knowledge of applicable IP policies, potential restrictions in contracts, etc.
1	• Hypothesizing that results or ideas might contain some possible form of IPR • Some ideas on possible IPR may exist, but are speculative • No description and documentation of the possible IPR • Limited knowledge or unclarity regarding relevant legal aspects (ownership, use-rights etc.) - Limited knowledge of uniqueness and the technical field, state-of-the art, publications etc.

5.5 Team readiness level

Team readiness level (TMRL) describes how far the people around a research result or technology are prepared to take the idea into the next development phase. It is not only a question of whether the research team is scientifically strong. TMRL helps the researcher look at three connected elements: the competencies needed for the next step, the roles and responsibilities of the people involved, and the wider support network that can help the idea move towards use.

In this document, the word **team** is used broadly. In the context of public research organisations, the team does not only refer to researchers or to a future start-up founding team. It can include researchers, technical staff, KTT professionals, IPR experts, project office, financial service, legal service, external specialists, mentors, industrial partners, users, regulatory experts, incubators or other ecosystem actors. The relevant team can therefore change over time, depending on whether the next step is technical validation, customer discovery, IPR protection, pilot testing, licensing, joint development, spin-out creation or project funding.

The second element is competence and capacity. A research group can have strong scientific and technical expertise, but the next development phase often requires additional capabilities. These can include industrial communication, IPR, project management, financial planning, regulatory understanding, business development, market engagement, quality systems, production scale-up or partner management. At lower TMRL levels, these

needs may still be unclear. At higher levels, the team has identified the competence gaps, involved relevant support services, clarified roles and created a realistic plan for adding missing capacity.

The third element is alignment. Team readiness is not only about having enough people involved. It also depends on whether the people have a shared understanding of the goal, the development route, their responsibilities, their level of commitment and the decision-making process. At early levels, there may be one motivated researcher or a small group with limited capacity. Middle levels involve a clearer champion, identified gaps, initial role discussions and a plan to involve additional competencies. Later levels involve a well-functioning team with clear roles, shared goals, continuous learning and support structures.

For this reason, the transition between TMRL levels is often more important than the level itself. Moving from TMRL 1 to TMRL 2 usually means moving from an individual idea towards a first understanding of which additional people or competencies could help verify and develop the idea. Moving from TMRL 2 to TMRL 3 means that competence and capacity gaps are identified, and that a first plan exists for finding the most important missing competencies. Moving from TMRL 3 to TMRL 4 means that the idea has a clearer development direction, at least one committed champion, several relevant competencies in place, and an initiated plan to involve additional support. Moving from TMRL 4 to TMRL 5 means that roles, commitment, knowledge sharing and team alignment become more structured.

A research team can try to solve all development questions alone, involve KTT or legal support too late, underestimate the need for industrial communication, or start discussions with companies before internal roles and ownership questions are clear. Team readiness therefore supports a more balanced conversation: who is already involved, which competencies are missing, which support services can help, who can act as the development champion, and how the team can be organised for the next realistic step.

Before moving to the case-study example, it is useful to emphasise that team readiness is not a judgement of whether a research group is capable or not. It is a way to identify which competencies and support structures are useful for the next development step. In public research organisations, a strong development team is often built gradually around the idea. The relevant question is therefore not only “who is in the team today?”, but also “who should be involved next so that the idea can progress in a realistic and supported way?”.

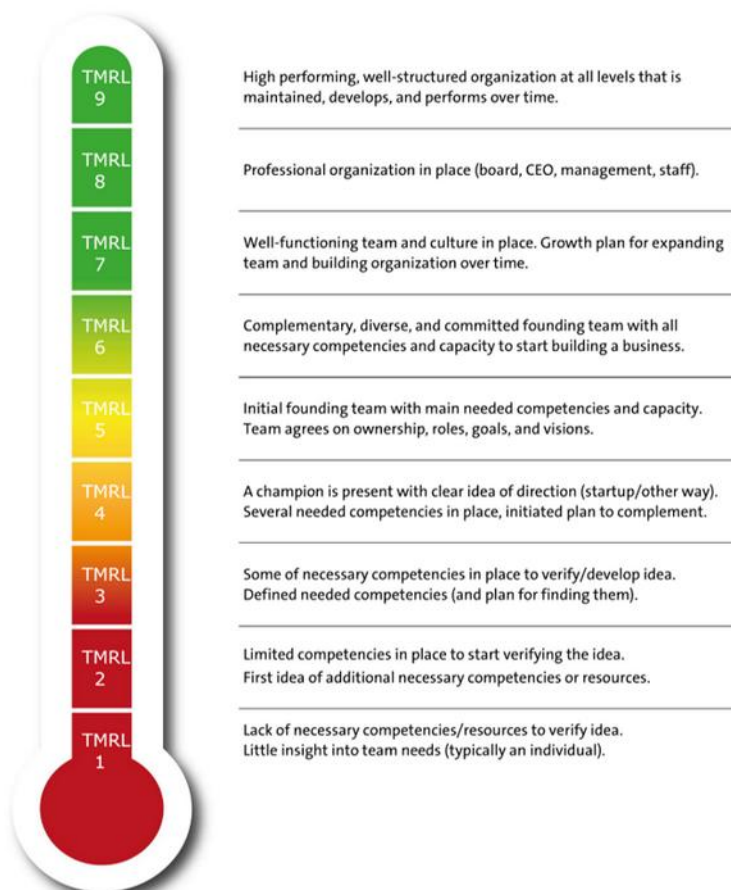
<i>Case study: SEAMAC project development path</i>		
Start	Plan	Activities performed
TMRL 3-4	TMRL 6	• FGM and PeP activities were approximately at TMRL 3-4. UL had relevant expertise in additive manufacturing and direct energy deposition, but important competence gaps remained in FGM material behaviour, advanced characterisation and PeP post-processing. These gaps were explicitly addressed through cooperation with TECHNION and TUBAF. • The project structure already supported progress towards TMRL 4, because a clear consortium, steering committee, WP leaders, external advisory board and wider UL support capacity were defined. This meant that the team had champions, several required competencies and a plan for adding missing expertise.

		• During the project, the team progressed towards TMRL 5, as researchers, PhD candidates and administrative staff worked together through training, staff exchanges, expert visits, summer schools, industrial workshops and joint experimental activities on FGM and PeP. • The installation of the PeP machine in Slovenia, the execution of industrial polishing cases, the FGM demonstrator work, and the involvement of UL, TUBAF and TECHNION experts show that the team developed practical capability, not only theoretical knowledge. This supports movement from a planned team structure towards an operational team with shared technical experience. • In selected PeP activities, the team can be interpreted as approaching TMRL 6, because the necessary near-term competencies became available: process expertise, machine operation, industrial interaction, problem-solving capacity and IPR-related support for the peak-current reduction solution. However, this maturity is stronger for PeP than for FGM.
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The case study illustrates that TMRL progress is not only about forming a larger team. It is also about recognising which competencies are needed at a specific development stage, which support services can reduce risk, and which external actors can help the project move closer to practical use. In this example, the project moved from a primarily research-driven activity towards a more structured development setting, where technical expertise was connected with IPR, project planning, industrial communication, regulatory considerations and potential partner involvement.

The TMRL thermometer below can be used as a quick orientation tool. It helps the researcher position the idea according to three connected questions: which competencies are already present, which roles and responsibilities are clear, and which additional people or organisations could support the next development phase. The detailed table that follows provides a more structured description of each level and can support the preparation of a development plan.

Team Readiness Level – TMRL



9	- The organization is high performing and well-functioning (cooperation, social environment, etc.) - All levels of the organization actively engaged in continuous learning and development - Organizational culture, structure, processes etc. are continuously improved and developed - Incentives/rewards are aligned to motivate the whole organization to reach goals and perform well - The management team is maintained, developed and performs over time
8	- There is a clear leadership and management team with relevant professional experience - Competent and diverse board, and relevant advisors in place and professionally used - HR policies/processes/responsible in place to assure good HR practices and team diversity - Necessary recruitments according to longer term plan are ongoing to ascertain relevant competencies, capacity, and diversity in the organization - All levels of the organization are properly trained and motivated
7	- Well-functioning team with clear roles - Goals, vision, purpose, and culture are clearly articulated and documented to support team and organizational development - Plan in place for how to build necessary organization and grow the team over longer term (~2 yrs) - Processes/systems and plan for continuous learning and staff development implemented - Board and advisors operational and supporting business and organizational development
6	- Complementary and diverse founding team in place, capable of starting to build a business - All key competencies and capacity necessary for the near term are present, incl. a clear CEO - Committed team where everyone feels responsibility and accountability - Started recruitment of advisors and/or board members, keeping in mind board diversity - Awareness of risks to team performance (conflicts, burn-out/mental health, politics, etc.)
5	- An initial founding team working together and all spending significant time. The founding team jointly having main needed competencies and capacity to start building this startup - Aligned team with clarified roles, shared goals and visions, and clear commitment (e.g. time spent) - The team has agreed on their respective shares (signed agreement). Ownership is balanced and in-

	- centivizing, and reflects historical and future commitment and contribution - Activities to get additional competencies and capacity in progress, keeping in mind team diversity - Initial systems/processes/tools in place to share knowledge and information within the team
4	- Team (or individual) has a clear idea of how to take the idea to market (startup, IP deal, etc.) - At least one champion (driver and committed to take the idea forward) is present - Several, but not all, necessary competencies are present, typically multiple individuals - A plan is in place and initiated to find necessary additional competencies and capacity (described e.g. in a requirement profile), keeping in mind team diversity - The team has started discussions on roles, commitment, ownership, etc. going forward
3	- One or several individuals that possess some, but not all, of necessary competencies and capacity to start verifying the idea - Needs and gaps in competencies, capacity, and team diversity are identified - Initial plan is defined for how to find needed prioritized competencies (near-term, <1 year)
2	- Limited competencies and/or capacity present - typically 1-2 persons - First idea of which additional persons/competencies that could be needed to verify/develop idea - First idea of overall goal for the project
1	- Typically an individual lacking necessary competencies in key areas such as tech, business etc. - Little insight into needed/necessary competencies and other needed resources (e.g. partners, service providers etc.) to verify and develop the idea

5.6 Funding Readiness Level

Funding readiness level (FRL) describes how far a research result or technology has developed in relation to the resources needed for the next development phase. It is not only a question of whether funding is available. FRL helps the researcher look at three connected elements: what activities need to be financed, which type of funding fits the next step, and how well the project is prepared for a funding application, investor discussion, industry contribution or internal support decision.

In this document, funding is used broadly. In the context of public research organisations, funding can include internal proof-of-concept funding, public grants, collaborative research projects, industry co-funding, contract research, innovation funds, philanthropic or mission-oriented funding, licensing-related income, spin-out investment, or other financial resources. The most suitable source depends on whether the next step is research validation, technical development, prototype building, user testing, pilot implementation, regulatory preparation, commercialisation or scale-up.

The second element is the development plan. A funding need becomes clearer when the team has described what should happen next, how long it could take, which people and partners are involved, which equipment or services are needed, and what the main milestones are. At lower FRL levels, this understanding may still be broad and approximate. At higher levels, the activities, costs, risks, milestones and expected results are described in a structured development or project plan.

The third element is funding-source fit. Different funding sources support different types of progress. A scientific grant may support further research, while proof-of-concept funding may support validation, prototyping or early market engagement. An industry partner may support a pilot or joint development activity, while investment funding is more relevant when there is a clear commercial route and a team capable of executing it. Funding readiness helps the researcher connect the development need with the right type of financial support, rather than preparing the same project description for every possible source.

For this reason, the transition between FRL levels is often more important than the level itself. Moving from FRL 1 to FRL 2 usually means moving from limited insight into costs towards a first understanding of the activities and resources needed for initial validation. Moving from FRL 2 to FRL 3 means that a draft development plan, approximate cost structure and first funding options are described. Moving from FRL 3 to FRL 4 means that the plan becomes more concrete, usually with a 6–12 month perspective, a cost budget, key risks, milestones and relevant funding sources for the next phase. Moving from FRL 4 to FRL 5 means that funding needs are outlined over time, a possible funding roadmap is defined, and the funding pitch or application has been tested with a relevant audience.

A research team can underestimate the resources needed for validation, prepare a proposal before the development activities are clear, apply for a funding source that does not match the maturity of the idea, or describe technical work packages without linking them to milestones, risks, partners and expected results. Funding readiness therefore supports a more balanced conversation: what needs to be financed, why this is the right next step, which funding source fits the phase, what evidence supports the application, and which project, financial or KTT support can strengthen the plan.

The funding readiness is not only about finding money. It is about translating the development needs of the idea into a realistic plan that can be understood by funders, project officers, industrial partners or internal decision makers. In public research organisations, this often means connecting technical development, TRL progress, partner involvement, time planning, cost planning and expected results into one coherent funding logic.

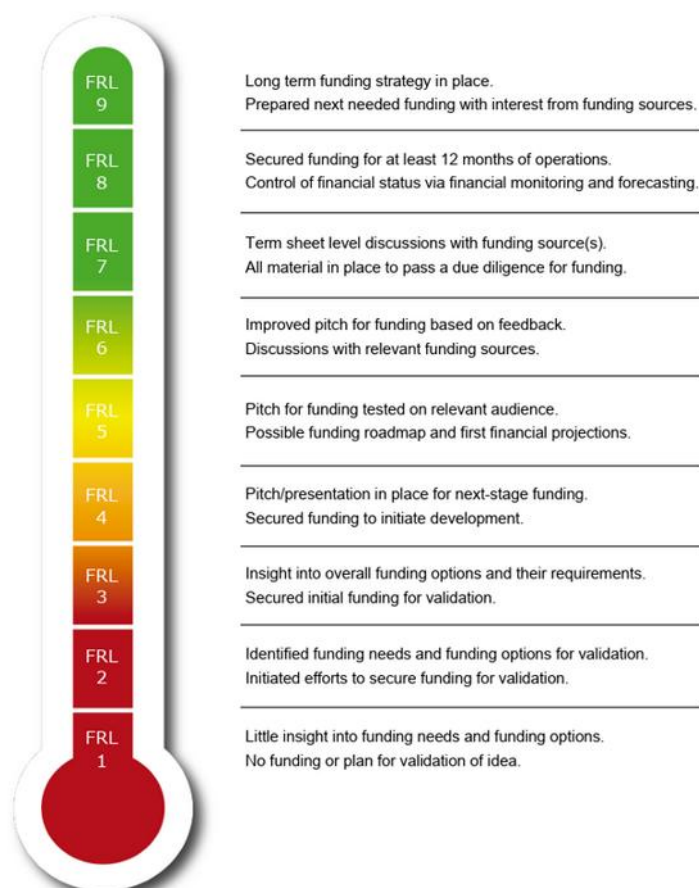
<i>Case study: SEAMAC project development path</i>		
Start	Plan	Activities performed
FRL 3-4	FRL 5	• At the beginning of SEAMAC, the FGM and PeP activities were approximately at FRL 3-4. The research direction, consortium and initial funding framework were defined through the SEAMAC grant, but the long-term funding needs beyond the project were still exploratory. • During the project, the activities progressed passed FRL 5, because the available funding enabled concrete implementation: FGM deposition and characterisation, demonstrator manufacturing, PeP machine installation in Slovenia, staff training and industrial trial activities. • PeP showed stronger progress than FGM in funding readiness, because industrial polishing cases and the contract with one company created a first route towards externally supported continuation. This indicates movement from grant-based research funding towards a more application-driven funding logic. • The peak-current reduction solution and patent-application process further strengthen the funding position, since protectable know-how can make future proposals, industrial contracts and exploitation routes more convincing. • Several follow-up project proposals were submitted to continue FGM and PeP activities. This indicates progress towards a clearer funding roadmap and identification of suitable funding sources. Two of them have been selected for funding, namely DigiGreenMM

		(GA 101341271) and MicroMan4Health (GA 101312169), both involving AM and PeP technologies, and both grant agreements have been signed, contractually securing support for the activities covered by these projects. This supports an assessment of FRL 7 , with progression towards FRL 8 upon receipt of funding, expected by the end of 2026, provided that it covers at least approximately 12 months of relevant activities and is supported by appropriate financial monitoring and an updated funding roadmap.
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The case study illustrates that FRL progress is not only about identifying possible grants or estimating a budget. It is also about understanding which development activities need support, how these activities contribute to readiness progress, which partners or services are involved, and what evidence is needed to justify the next funding step. In this example, the project moved from a general understanding that further development required resources towards a more structured view of activities, costs, timeline, risks, milestones, partners and suitable funding routes.

The FRL thermometer below can be used as a quick orientation tool. It helps the researcher position the idea according to three connected questions: what needs to be financed, how clearly the development plan and cost logic are described, and how well the funding source fits the next development phase. The detailed table that follows provides a more structured description of each level and can support the preparation of a development plan.

Funding Readiness Level – FRL



9	- Defined next needed funding reflecting scale-up plans, company performance and financial status/forecast. - Long term funding strategy in place covering e.g. scale-up of operations. - Identified and established interest from suitable next step funding sources for longer runway. - Pitch/presentation, business plan and all necessary supporting material is continuously updated.
8	- Financial monitoring and accounting system enables control of financial status and forecast of funding needs. - Updated funding roadmap based on forecasts and business progress. - Secured funding for at least ca 12 months runway (funding received) or predictable recurring revenue. - Presentation/pitch for funding is developed to include complete business plan
7	- Basic accounting in place shows financial status. Different scenarios of funding needs outlined. - Funding roadmap includes more details on target sources over time and backup alternatives/scenarios. - Concrete discussions (term sheet level) with one or several funding sources that are clearly interested. - Presentation/pitch for funding also includes compiled necessary supporting material to pass due diligence.
6	- Funding needs clarified with more detailed financial projections (incl. cash-flow) - Funding roadmap updated based on feedback and to extend over time (e.g. seed, A-round etc). - Discussions initiated with relevant funding sources (typically investors) on ask (how much, for what, valuation) Improved pitch/presentation for funding based on feedback from relevant audience.
5	- Funding needs over time outlined with initial financial projections (P&L, budget) - Defined possible funding roadmap with desirable funding sources/investors and impact on cap table. - Possibly secured additional funding for next step(s) of development plan but still requiring more for next stage - Pitch for funding tested on relevant audience (e.g. pitched to investor, submitted funding application)
4	- Defined development/project plan (e.g. 6-12 months) with cost budget, key risks, value driving milestones etc. - Identified relevant funding sources for next stages of development/project plan. - Secured sufficient funding to initiate at least first step(s) of the development/project plan. - Pitch/presentation for funding (oral and written) such as investor pitch deck or funding application
3	- Draft of costs and activities in a development/project plan (e.g. 6-12 months). Insight into overall funding needs - Understanding of overall funding options e.g. sources and types (own, soft, equity, loans) and their requirements Secured sufficient funding to initiate validation, typically soft funding (grants). - A first presentation for funding incl. description of key aspects relevant for funding e.g. market potential
2	- Insight into costs and relevant activities for initial validation (e.g. 1-6 months) - Identified funding sources for initial validation - Initiated efforts to secure funding - A description that can be used for seeking initial funding (incl. business concept e.g. NABC)
1	- Little insight into costs and relevant activities for validation of idea. Little insight into overall funding needs. - Little insight into different funding options. - No funding available or secured. - Initial description of idea but lacking aspects relevant for funding e.g. business concept, market potential

The readiness profile in Fig.2 illustrates the development of the FGM and PeP case study across several KTH Innovation Readiness Level dimensions during the SEAMAC project. At the beginning of the project, the activities were mainly positioned at early readiness levels, with promising technical concepts, limited customer validation, an emerging business rationale, and only partly established exploitation routes. By the end of the project, clear progress can be observed in several dimensions. Customer readiness increased through demonstrator-based discussions, industrial PeP trials and the identification of suitable and

unsuitable applications. Business readiness improved through a clearer understanding of potential markets, industrial value and technical limitations. Intellectual property readiness advanced particularly through the PeP-related solution for reducing peak currents, which is in the patent-application process. Team readiness increased through the establishment of an operational consortium involving UL, TUBAF and TECHNION, supported by staff exchanges, PhD work, training events and joint experiments. Funding readiness also improved through the preparation of follow-up proposals and the first company contract, although long-term continuation funding has not yet been secured.

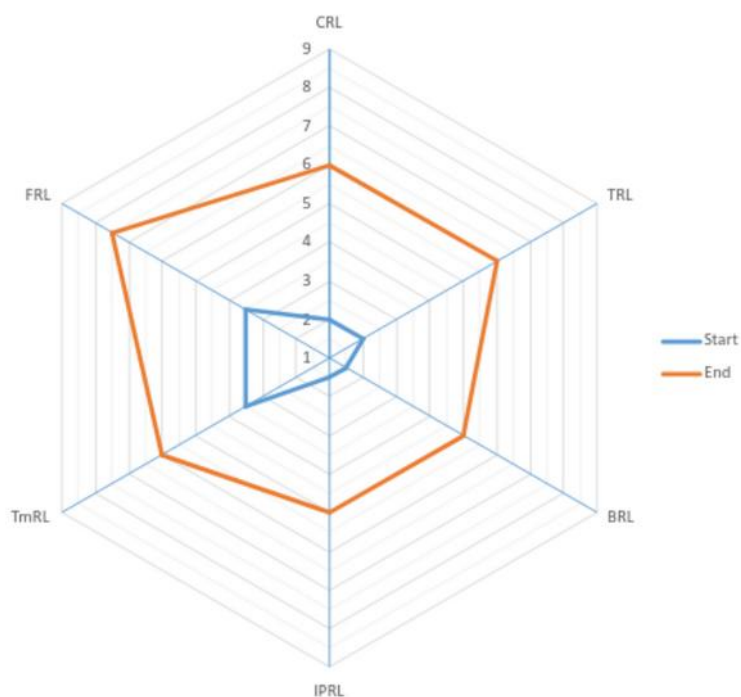


Figure 2: The readiness profile showing improvement across several readiness dimensions from beginning till the end of the SEAMAC project.

5.7 Toolbox - Innovation methods and techniques to progress

The readiness levels help the researcher describe where the idea currently stands. The toolbox helps the researcher decide how to move forward. It includes practical methods, templates and techniques that can support progress from one readiness level to the next. These tools are not fixed steps and do not belong to only one readiness dimension. The same method can often support several dimensions at the same time.

For example, the NABC method can help describe the need, the approach, the benefits and the competition. It can therefore support customer readiness, business readiness, funding readiness and even the communication of technology readiness. A roadmap can help structure technical development, but it can also show when customer feedback, IPR support, team development or funding will be needed. A budget template can support funding readiness, but it can also clarify whether the proposed business route is realistic.

The toolbox is therefore best understood as a set of practical aids that researchers can use when a readiness assessment reveals a gap. The purpose is not to complete every tool, but

to select the tool that helps answer the most important question at the current stage: What needs to be clarified, tested, documented or planned next?

Typical toolbox methods include:

- NABC – helps structure the idea around the Need, Approach, Benefits and Competition. Useful for early communication, customer discussions, business concept development and funding pitches.
- Technology roadmap – helps describe the next technical development steps, expected milestones, validation activities, dependencies and longer-term development direction.
- MVP or prototype definition – helps clarify what should be tested first and what level of functionality is enough to learn from users, partners or technical validation.
- Customer interviews and customer discovery – help move from assumptions towards direct feedback from potential users, customers, decision makers, industry experts or other stakeholders.
- Customer personas and customer tiers – help distinguish between different types of users, paying customers, decision makers, early adopters and strategic partners.
- TAM, SAM, SOM – helps structure the market view by separating the total market, the realistically reachable market and the first obtainable segment.
- Value chain mapping – helps identify where the technology fits, who creates value, who captures value, and which partners or intermediaries influence adoption.
- Competitive landscape map and comparison matrix – help compare the proposed solution with existing alternatives, competing technologies, incumbent processes or substitute solutions.
- Lean Canvas or Business Model Canvas – helps describe the business logic, assumptions, customer segments, value proposition, channels, resources, partners, costs and revenue logic.
- Riskiest Assumption Test (RAT) – helps identify the assumption that could most strongly affect the project and design a small test to validate or challenge it.
- Profit & Loss (P&L) or budget template – helps estimate costs, revenues, development resources, service costs, equipment needs or project funding requirements.
- Sustainable development goals (SDG) and impact tools – help reflect on environmental, social and governance aspects, and translate sustainability into value, impact indicators or funding arguments.
- IPR checklist and types of IP/IPR overview – help identify whether the result may include patents, copyright, software, data, design, know-how, confidential information or trade secrets.
- Novelty search and patent disclosure templates – help prepare the information needed for an initial IPR discussion with KTT/IPR professionals or patent experts.
- Competence map over time – helps identify which competencies are already present and which may be useful in the next phase, such as IPR, regulation, project management, finance or business development.
- Team Canvas – helps clarify roles, goals, expectations, responsibilities, collaboration principles and possible gaps in the team or support network.
- Funding roadmap – helps connect development activities with possible funding sources, timelines, project calls, partner contributions or investment needs.
- Pitch templates – help prepare a concise explanation of the idea for funders, partners, internal decision makers, KTT services or industrial stakeholders.

- Grant application or project planning templates – help translate the development plan into work packages, milestones, deliverables, indicators, partner roles and budget logic.

Researchers can use the toolbox after completing the self-assessment. If the assessment shows that the main gap is technical validation, a technology roadmap or MVP definition may be useful. If the gap is customer understanding, customer interviews, personas or value-chain mapping may be more helpful. If the gap is IPR, novelty search and patent disclosure templates can support the discussion with KTT/IPR services. If the gap is funding, a funding roadmap, budget template or pitch template can help structure the next step.

Different toolbox methods require different levels of experience, time, data and support. Some can be used independently by a researcher or research team, for example a first NABC description, a simple roadmap or a basic competence map. Others benefit from professional support, especially when they involve IPR, legal questions, market validation, financial planning, grant preparation, regulatory issues, investment readiness or structured partner engagement. In these cases, researchers can use the toolbox as a starting point for a more focused discussion with the Knowledge Transfer Office, project office, financial or legal services, incubators, mentors, patent attorneys, external experts or industrial partners. The aim is not that the researcher becomes a specialist in every method, but that they can recognise which tool is useful, what kind of input it requires, and when additional expertise can improve the next development step.

The toolbox therefore connects the readiness assessment with practical action. It helps the researcher move from “we know this is missing” to “this is the method we can use to clarify, test or plan the next step.”

6 From individual initiative to the right support network

Developing a research-based idea towards application is rarely a linear process and rarely the responsibility of one person alone. In the early stages, the researcher or research team is usually best placed to describe the scientific result, explain the technical principle, identify possible applications and reflect on why the idea could matter. At the same time, progress towards use often raises questions that go beyond the technical field: intellectual property, ownership of results, user validation, collaboration with companies, funding, regulation, contracts, business models and team capacity.

The aim is to help researchers recognise when a question can be explored independently and when it is useful to involve people with complementary expertise. In this sense, professional services and external partners are not an administrative step at the end of the process, but potential collaborators in shaping a more realistic development path.

What researchers can usually start developing independently

Many important development activities can be led by researchers or research teams themselves. In many cases, researchers are also the best placed to explain the scientific and technical substance of the idea, recognise possible applications, understand the limits of the current evidence, and communicate why the result could be relevant beyond the research environment. For some researchers, these activities are not only a necessary step in the transfer process, but also an opportunity to further develop their own talent for communication, application-oriented thinking, collaboration and innovation leadership.

At an early stage, a researcher or research team can prepare a clear explanation of the technology or research result for audiences outside the immediate scientific field. This can include describing what the result does, which problem or need it could address, what has already been demonstrated, where the current uncertainties are, and what kind of evidence would strengthen the case for further development. Such an explanation does not need to be a marketing document. It can serve as a working description that helps different people understand the idea and contribute to its development.

Researchers can also explore possible applications and user groups. This may include identifying sectors where the result could be relevant, considering who could benefit from it, distinguishing between users, customers and decision-makers, and reflecting on how the result compares with existing alternatives. At this stage, the aim is often to make assumptions explicit, not to prove market demand conclusively.

Another useful researcher-led activity is the preparation of an initial overview of potential partners or stakeholders. These may include industrial companies, public-sector organisations, clinical partners, NGOs, infrastructure providers, standardisation bodies, or other research groups. Researchers can also outline a first development logic: what has already been achieved, what could be tested next, which resources may be needed, and which questions remain open.

The key point is not that the researcher should do everything alone. Rather, these activities help the researcher remain an active driver of the idea while making better use of the surrounding support ecosystem. Where KTT, IPR, legal, project, financial, incubator, industrial or other professional support is available, it can be involved at the moment when

it adds value: for example, when the idea moves towards external communication, protection, formal collaboration, funding, pilot testing, licensing, spin-out creation or investment readiness.

In this way, the researcher's own initiative and the support ecosystem are not alternatives. They work best when they reinforce each other: the researcher brings deep knowledge, motivation and credibility, while support services and external partners contribute complementary expertise, networks, structure and experience with the path towards use.

When KTT or IPR support becomes useful

KTT and IPR support becomes especially valuable when a research result may contain something new, useful and potentially patentable. In these situations, the key principle is simple: check the protection opportunity before public disclosure. In practice, this often means patent first, publish later — or, more precisely, assess whether a patent application or another form of protection should be prepared before the result is published, presented or shared externally.

This is not about delaying scientific communication unnecessarily. The aim is to avoid losing an opportunity that may only exist before public disclosure. A journal article, conference presentation, poster, thesis defence, public pitch, website description, open repository upload or unprotected discussion with an external company can affect the possibility of later patent protection. Early contact with KTT or IPR support helps the researcher coordinate publication and protection, so that scientific dissemination and future use of the result can both be preserved where possible.

In many public research organisations, this type of support is available through a Knowledge Transfer Office, Technology Transfer Office, IPR office, legal office, innovation office or another unit responsible for research valorisation and collaboration with external partners. Where such support is not available internally, researchers can seek initial guidance from relevant national intellectual property offices, patent information centres, legal advisers or patent attorneys in their country. The researcher does not need to assess these questions alone; the support ecosystem exists to help clarify options early enough for them to remain open.

KTT or IPR support can help assess whether the result is potentially novel, whether a patent or another form of protection could be relevant, and whether additional steps are useful before external communication. This may include an invention disclosure, a first prior art search, clarification of ownership, assessment of contributors, or preparation of a broader protection strategy.

Support can also be valuable when the result includes know-how, software, data, methods, designs, materials, prototypes or other intellectual assets that may not always be best protected through patents. In some cases, publication is the right path. In others, a patent application, trade secret approach, software licence, copyright, design protection or contractual arrangement may be more appropriate.

The practical message for researchers is therefore not to choose between publication and protection, but to create the option to do both in the right order. When there is a reasonable possibility that a result could be patentable or otherwise valuable for future use, early contact with the appropriate KTT, IPR or legal support structure can help preserve future options while still allowing scientific dissemination to proceed.

When legal support becomes useful

Legal support becomes valuable when collaboration starts to require formal agreements. This can include non-disclosure agreements, memoranda of understanding, research collaboration agreements, consortium agreements, licence agreements, material transfer agreements, data-sharing arrangements or spin-out related documents.

The role of legal colleagues is not only to prepare documents, but also to help shape a clear and balanced relationship between the researcher and their counterpart in another organisation. This is especially important when both sides are interested in building a longer-term collaboration, not just completing a single transaction. A well-prepared agreement can clarify expectations, protect the interests of both parties, and create a basis for trust, continuity and mutual benefit.

Researchers do not need to prepare these agreements themselves, but it is helpful if they recognise when a conversation is moving into legally relevant territory. This usually happens when external partners exchange confidential information, discuss rights to future results, request access to existing knowledge, contribute resources, or explore possible commercial use of research outcomes.

Legal support can also help clarify ownership, use rights, responsibilities, liability, publication rights, confidentiality, licensing terms and the relationship between academic and commercial objectives. In this way, legal support can make collaboration easier rather than more difficult: it helps ensure that the relationship is transparent, fair and robust enough to support future joint work.

When project and financial support becomes useful

Project and financial support becomes valuable when the next development step requires structured resources. This may include a grant application, proof-of-concept funding, a pilot project, equipment purchase, subcontracting, hiring, travel, testing, certification or collaboration with external partners.

For researchers, this support is useful both before and after funding is secured. In the pre-grant phase, project and financial colleagues can help shape the idea into a realistic project structure: activities, work packages, milestones, deliverables, indicators, budget logic, partner roles, risks and timeline. In the post-grant phase, they can support implementation, reporting, procurement, cost eligibility, documentation and communication with the funder.

At the same time, it is valuable for researchers to develop a basic understanding of project and financial logic. They do not need to become project officers or financial specialists, but familiarity with concepts such as eligible costs, budget categories, prices with and without VAT, staff costs, subcontracting, equipment costs, co-financing, reporting requirements and audit documentation can make collaboration much easier. This knowledge also helps researchers design development activities that are financially realistic from the beginning.

In this sense, project and financial support is not only administrative assistance. It is part of building a broader development environment around the idea. By involving the right colleagues early, the researcher can connect scientific goals with available funding instruments, realistic budgets and feasible implementation plans. This increases the chance that the idea is not only funded, but also successfully carried out after the grant is approved.

This support becomes especially important when the idea moves from a small exploratory activity to a structured development project. At that point, the quality of the project structure can strongly influence whether the idea receives support, whether the project can be implemented smoothly, and whether later collaboration with partners, funders or users can continue without avoidable administrative or financial difficulties.

When other researchers and interdisciplinary collaborators become useful

Some ideas benefit from additional scientific, technical or contextual perspectives before they can move forward. A technology may connect with expertise in materials, design, software, regulation, clinical practice, manufacturing, environmental impact, social sciences, humanities, user behaviour or another application field. In such cases, involving other researchers can strengthen both the idea and its development pathway.

Interdisciplinary collaboration can help test assumptions, identify new applications, understand user contexts, address ethical or societal questions, and connect the technology with real-world systems. This is particularly relevant when the research result does not fit neatly within one discipline, or when implementation depends on organisational, behavioural, regulatory, environmental or social factors.

Researchers can build this kind of network gradually. Within their own public research organisation, useful contacts may be found by following internal news, research highlights, project announcements, newsletters, seminar programmes, doctoral schools, competence centres, research infrastructure updates or innovation-related events. Events that bring together active and application-oriented researchers — such as researchers' nights, interdisciplinary workshops, summer schools, challenge-based programmes, industry days or internal networking events — can be especially useful for discovering complementary expertise.

Potential collaborators can also be identified through scientific publications, conference programmes, project databases, professional associations, thematic networks and contacts from previous research or industry projects. In some cases, the most relevant collaborator may be in another public research organisation, a clinical environment, a technical institute, a social science or humanities department, or an international research network.

The important point is that interdisciplinary collaboration does not need to start as a large formal project. It can begin with a conversation: asking whether someone sees the same problem from another perspective, whether the idea has relevance in their field, or whether a missing competence could be added to the next development step. Over time, such connections can help the researcher build a stronger environment around the idea and make the path towards use more realistic.

When an incubator or accelerator becomes useful

An incubator or accelerator can be useful when the idea begins to show entrepreneurial potential. This does not necessarily mean that a spin-out company has already been selected as the preferred exploitation path. At this stage, incubators and accelerators can help researchers explore whether a venture route is realistic, what kind of team would be needed, how the value proposition could be tested, how early customers or users could be approached, and what type of business model might fit the opportunity.

Incubators and accelerators can also provide mentoring, entrepreneurial training, access to networks, pitch development, support for proof-of-concept activities, and connections to investors or experienced founders. This support is particularly relevant when the development path requires a dedicated team, rapid iteration, market testing, or preparation for possible company creation.

When investors, business angels or venture capital funds become relevant

Investors usually become relevant at a later stage, when the idea has developed beyond a scientific result and can be presented as a credible opportunity. This normally requires a defined problem, identifiable target users or customers, a plausible development and exploitation plan, initial team logic, and a clear funding need. For research-based technologies, this often means that the main technical and market risks have at least been identified, and that there is a credible route towards validation, licensing, spin-out creation, or scale-up.

Business angels, venture capital funds and other private investors can provide financing, networks and strategic guidance. However, they also assess risk, ownership, scalability, team capacity and potential return. For this reason, researchers are usually better prepared for investor conversations after first working with KTT, incubators, project support services, or experienced mentors.

Investor contact becomes particularly relevant when a spin-out path is being seriously explored, when proof-of-concept results indicate commercial potential, when early customer interest is visible, or when public funding alone is not sufficient for the next development phase.

A practical rule of thumb

A simple way to decide when to involve support is to look at the type of risk or commitment that appears in the next step. When the next step is mainly about understanding the technology, describing possible applications or forming first assumptions, the researcher can usually begin independently. When the next step involves public disclosure, ownership, external partners, contracts, funding, regulatory obligations, company creation or investment, it is useful to involve the relevant support services early.

The researcher remains the intellectual owner and scientific driver of the idea. The role of support services and external partners is to help transform the idea into a more complete development pathway: technically credible, legally secure, financially realistic, user-informed and better prepared for collaboration with industry or other users.

7 Reflections on Innovation Readiness

Developing a research-based idea towards application is not a separate activity that begins only after the research has ended. It is a gradual learning process in which a result, method, technology or prototype becomes clearer through testing, feedback, reflection and collaboration. Scientific and technical quality remain the foundation of this process. At the same time, the path towards use often depends on additional dimensions: understanding potential users, clarifying the value of the solution, considering intellectual property, building the right support network, identifying suitable partners and connecting development activities with realistic funding options.

This guide has presented a practical way for researchers and research teams in public research organisations to look at their ideas more holistically. The aim is not to place additional administrative expectations on researchers or to suggest that they need to become specialists in law, finance, business development, project management or commercialisation. Rather, the aim is to support a more confident and informed way of working: recognising which questions are relevant, which gaps may influence the next step, which activities can reduce uncertainty, and when complementary expertise can be helpful.

The KTH Innovation Readiness Level™ logic is useful in this context because it helps make the development path visible. Instead of looking only at technical maturity, it encourages the researcher to consider technology, users, business logic, intellectual property, team capacity and funding as connected dimensions of one development process. Progress does not need to be equal across all dimensions. In some cases, the next bottleneck may be technical validation. In others, it may be user feedback, IPR clarification, partner engagement, team capacity or funding readiness. The value of the framework lies in helping the team identify which dimension is most relevant for the next meaningful step.

The practical use of the guide begins when self-assessment is translated into action. A readiness level is not the final result of the exercise. It is a starting point for asking what kind of evidence, conversation, test, analysis or decision could help the idea move forward. The toolbox supports this transition by connecting identified gaps with methods that can be used to explore, test or plan the next step. A researcher may start with a clearer technology description, a customer interview, a value proposition, a novelty search, a competence map, a funding roadmap or a project planning template. Some of these activities can be carried out independently, while others benefit from the involvement of knowledge transfer, legal, project, financial, incubation or external expert support.

Support services, interdisciplinary collaborators and external partners are therefore not only relevant at the end of the process. They can become part of the development path whenever their input helps clarify risks, protect knowledge, shape the next experiment, connect with users, prepare a project, or identify a realistic route towards application. The researcher remains the holder of the core scientific and technical understanding, while the wider support network helps build a more complete pathway around the idea.

There is also no single route from research to use. Depending on the nature of the result, the most appropriate pathway may involve licensing, joint development with a company, contract research, a pilot project, public-sector or societal implementation, further research and development funding, incubation or spin-out creation. The purpose of early reflection is not to force the idea into one predefined route, but to make the possible routes more

visible and to prepare the next step in a way that is proportionate to the maturity of the idea.

In practice, the guide can be used as a development companion. A researcher or research team can select one idea, describe its current position across the readiness dimensions, identify the most important gaps, choose a small number of concrete activities, and involve the right people early enough to make the next step more realistic. In this way, the development of non-technical competencies becomes part of the research-to-application journey: not as a replacement for scientific excellence, but as a way to help strong research results find clearer, better supported and more meaningful paths towards use.

8 Introduction to Technical Part of the Toolkit

The SEAMAC Technical Toolkit is an editable training resource for additive manufacturing of functionally graded materials within the SEAMAC project. It connects project knowledge on powder preparation, laser metal deposition, plasma electrolytic polishing, characterisation and training delivery so that researchers, trainers and industry-facing users can reuse the material in a structured way.

Purpose of the Technical Toolkit

The purpose of the toolkit is to support technical knowledge transfer on metal additive manufacturing of functionally graded materials. It provides a common reference for the process chain addressed: powder and feedstock preparation, laser metal deposition, post-processing by plasma electrolytic polishing, characterisation of manufactured parts, defect interpretation and practical training delivery.

The toolkit is intended to help users move from separate training materials toward an integrated view of the manufacturing route. In this context, the value of the document is not only in explaining individual technologies, but also in showing how decisions in one step affect later steps. Powder selection influences feeding and melt-pool behaviour; deposition strategy influences defects and residual stress; post-processing and characterisation determine how the final part is assessed. The technical scope follows the training activities. It covers additive manufacturing fundamentals, functionally graded materials, powder preparation, laser metal deposition, plasma electrolytic polishing, characterisation, defects, troubleshooting and knowledge-transfer methods. The emphasis is on training and researcher onboarding rather than on reporting every experimental result in detail.

The toolkit is not a replacement for laboratory procedures, machine manuals, safety data sheets or formal risk assessments. It should be used together with local laboratory rules, equipment-specific instructions and current project documentation.

Target Users

The primary target users are researchers, doctoral candidates, postdoctoral researchers, trainers and technical staff involved in SEAMAC-related additive manufacturing activities. The content is also relevant for summer school participants, new researchers joining the field and industry participants who need a structured overview of the process chain.

Different users can approach the toolkit at different depths. New learners may begin with the introductory modules and use later modules as guided reading. Researchers and technical staff can use the toolkit as a checklist for planning experiments, documenting process chains and interpreting results. Trainers can reuse the modules as a basis for lectures, practical demonstrations, workshops and train-the-trainer activities.

Industry-oriented users should use the toolkit as a structured introduction to capabilities, risks and evaluation criteria. The document is written to connect technical choices with application relevance, but it does not replace application-specific feasibility testing.

Objectives Relevant to the Technical Toolkit

The technical focus combines powder laser metal deposition, new powder blends, plasma electrolytic polishing and functionally graded materials. These topics form a connected

process chain rather than isolated training subjects. For the toolkit, the most relevant objective is the transfer and consolidation of knowledge so that UL can strengthen its research profile, train new researchers and support industry-oriented activity in metal additive manufacturing. The toolkit therefore gives attention to both technical content and the way that content can be taught, reused and adapted.

The technical modules reflect the main competence areas of the project: powder and material preparation, LMD process development, FGM fabrication strategy, PeP post-processing, part characterisation and interpretation of results. These areas support the wider goal of building sustainable additive manufacturing capability beyond a single project event.

How to Use Technical Toolkit

The technical toolkit can be read sequentially, but it is primarily designed as a modular reference. Users new to the topic should start with the fundamentals of additive manufacturing and functionally graded materials, then continue through feedstock preparation, laser metal deposition, post-processing and characterisation. Users with existing AM experience may go directly to the modules that support their current task.

For training events, the modules can be combined with demonstrations, sample preparation, measurement exercises and group interpretation of results. This structure reflects the summer school model used in SEAMAC, where lectures, laboratory work, company visits and discussion sessions are combined.

For researcher onboarding, the toolkit should be used together with local supervision, laboratory safety training and access to equipment-specific procedures.

Technical Competence Framework

The SEAMAC technical competence framework describes the knowledge and skills that users should develop when working with metal additive manufacturing of functionally graded materials. It is intended as a practical training guide, not as a formal certification scheme.

Core Competence Areas

The first competence area is understanding the metal additive manufacturing process chain. Users should be able to explain how feedstock, design, process parameters, post-processing and characterisation interact, and why functionally graded materials require attention to composition, microstructure and property variation.

The second area is feedstock and powder preparation. Users should understand powder selection, particle size and morphology, powder handling, powder safety, blending strategies and documentation of powder batches. For FGM work, users should also understand why powder ratios, segregation risk and feeder behaviour matter.

The third area is laser metal deposition. Users should understand the basic operating principle of LMD, the role of laser power, travel speed, powder feed, shielding gas, melt-pool stability, dilution and deposition strategy. They should be able to connect process settings with likely effects on track geometry, defects and gradient quality.

The fourth area is post-processing by plasma electrolytic polishing. Users should understand why post-processing is needed for AM parts, how PeP is positioned in the

SEAMAC process chain, and how electrolyte selection, process parameters, part geometry, safety and surface measurement influence the result.

The fifth area is characterisation and interpretation. Users should be able to relate metallography, microstructural analysis, phase analysis, mechanical testing, surface roughness and geometrical measurements to the quality of manufactured parts. They should also be able to distinguish between measurement results, interpretation and process-improvement decisions.

The sixth area is training reuse and documentation. Users should be able to record process chains clearly, preserve reusable training outputs, adapt material for different audiences and update the toolkit as new SEAMAC results become available.

Expected Learning Outcomes

After working with the toolkit, a new user should be able to describe the SEAMAC process chain from powder preparation to final evaluation, identify the purpose of each main module and explain the relationship between AM, FGMs, LMD, PeP and characterisation.

A technically trained user should be able to plan a basic training or onboarding sequence using the modules, identify which information must be recorded during powder preparation and deposition, recognize common risks in powder handling and processing, and select appropriate characterisation methods for a given training objective.

A research user should be able to connect process parameters and material choices with likely defects, post-processing needs and measurement results. The user should also be able to communicate uncertainty clearly, avoid unsupported conclusions and propose follow-up work based on observed evidence.

A trainer should be able to adapt the material for lectures, demonstrations, practical exercises, summer schools, staff exchanges and industry-oriented workshops while preserving the technical logic of the process chain.

Competence Levels for Different User Groups

Introductory users need a broad overview, shared vocabulary and awareness of safety and documentation requirements. They should focus first on the AM process chain, basic FGM concepts, the purpose of each technology and the main quality risks.

Research users need enough depth to plan experiments, document parameters, handle powder and samples correctly, interpret characterisation results and communicate limitations. They should be able to move between modules and understand how an upstream choice may affect downstream results.

Technical staff and laboratory users need practical competence in preparation, handling, equipment operation, measurement routines, safety controls and repeatable documentation. They should work with local procedures and equipment-specific instructions in addition to this toolkit.

Trainers and supervisors need the ability to select content for a target audience, combine theory with demonstrations, guide result interpretation and preserve reusable outputs. They should also be able to update the toolkit without changing its modular structure.

Industry-oriented users need a process-chain understanding that supports discussion of feasibility, quality risks, inspection needs and application relevance. They do not need the

same depth as laboratory operators, but they should understand which technical questions must be answered before an AM or FGM route can be considered mature for an application.

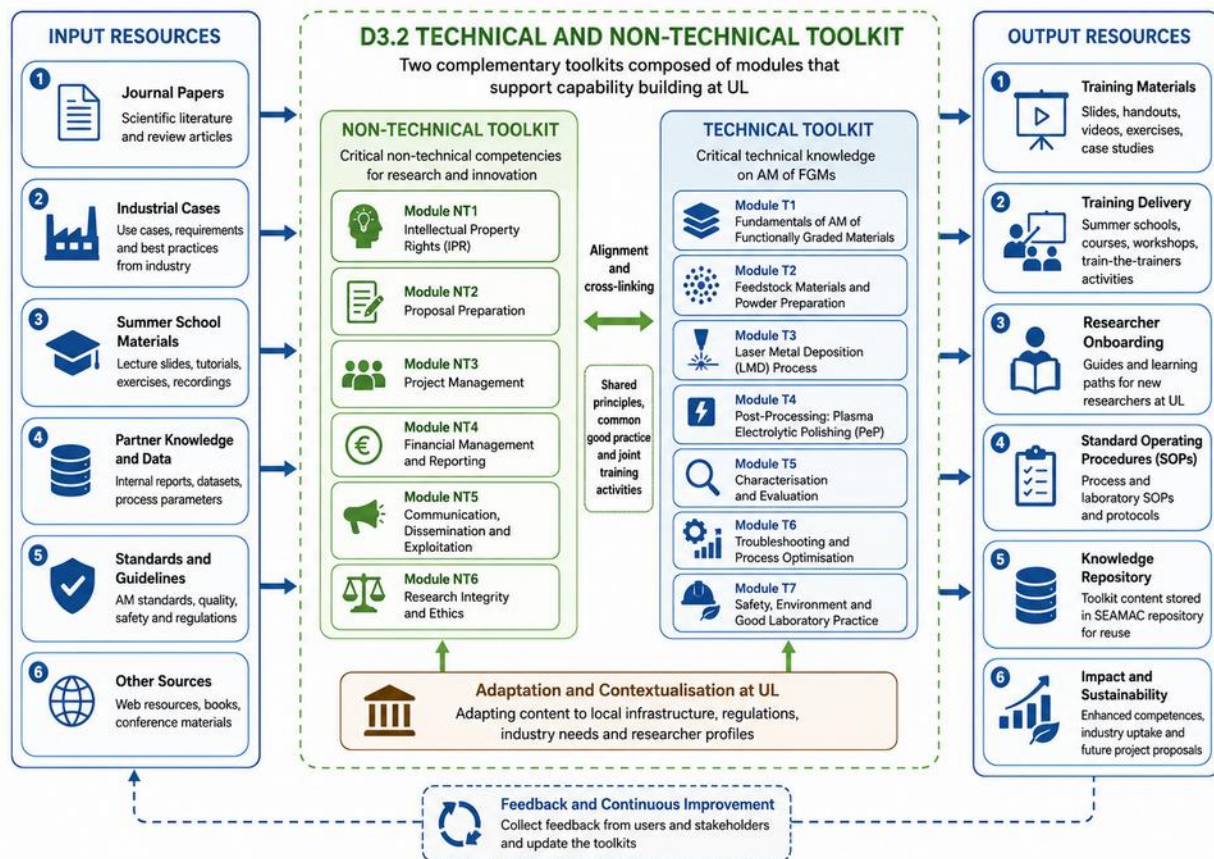


Figure 3: Structure and interconnections of the SEAMAC D3.2 Technical and Non-Technical Toolkit

9 Module 1: Fundamentals of AM of Functionally Graded Materials

This chapter introduces metal additive manufacturing (metal AM) as the technical foundation for later SEAMAC training topics, especially functionally graded materials (FGMs), laser metal deposition (LMD), post-processing and quality assessment.

It is intended as an entry point for graduate students, researchers and industry trainees who need a common vocabulary before working with process parameters, materials and experimental results.

9.1 Introduction to Metal Additive Manufacturing

Definition of Metal Additive Manufacturing

Additive manufacturing (AM), often called 3D printing, creates three-dimensional objects from digital model data by joining material successively rather than removing it. In the training sources and supporting literature, AM is described as a layer-by-layer or track-wise process in which material is added and consolidated until the part is complete.

For metal AM, the feedstock is metallic powder, wire or another metal form, and the deposited material is consolidated into a solid component using an energy source such as a laser, electron beam or electric arc.

Key features of metal AM include:

- production from 3D CAD data;
- layer-wise or track-wise material addition;
- local melting or solid-state bonding, depending on the process;
- reduced dependence on product-specific moulds, dies or tools;
- ability to manufacture geometries that are difficult or impossible with conventional subtractive routes, such as lattice structures, internal channels and freeform features.

Digital Process Chain

Most metal AM workflows begin with a digital model and then pass through build preparation before manufacturing. A simplified process chain is:

1. Define the part geometry in CAD.
2. Check that the model is printable and watertight.
3. Convert or export the geometry to a suitable build format, commonly including STL-based workflows.
4. Orient the part and prepare support structures if required.
5. Slice the geometry into layers or toolpaths.
6. Select material, machine and process parameters.
7. Manufacture the part.
8. Remove powder or supports, post-process and inspect the result.

The design training material emphasises that AM should be considered from the start of the design process, rather than using AM only to reproduce shapes originally intended for conventional manufacturing.

9.2 Main Metal AM Process Categories

Metal AM includes several process families. The most relevant categories for this toolkit are powder bed fusion and directed energy deposition, because they connect directly to metal powders, laser processing and the SEAMAC focus on graded materials. Binder jetting is also relevant as a metal AM route, but its consolidation sequence differs from fusion-based methods.

Powder Bed Fusion

Powder bed fusion (PBF) uses a focused thermal energy source to selectively fuse regions of a powder layer. New powder layers are spread over the build platform and fused successively until the component is complete. In metal AM literature, laser powder bed fusion may also appear under older or commercial names such as selective laser melting (SLM), direct metal laser sintering (DMLS) or laser beam melting (LBM); this toolkit uses the more general PBF-LB/M terminology where appropriate.

Important metal PBF variants include:

- **PBF-LB/M:** laser beam powder bed fusion of metals, including industrial systems such as laser-based machines used for stainless steels, titanium alloys, nickel alloys and other engineering metals.
- **PBF-EB/M:** electron beam powder bed fusion of metals, typically operating under vacuum and used for selected reactive or high-performance materials.

PBF is commonly associated with high geometrical precision and the ability to produce complex shapes, including fine lattice structures. It also requires careful powder handling, support strategy, thermal management and post-processing. Process-inherent surface roughness, partially fused powder and staircase effects can be especially important for thin struts, internal channels and other surfaces that are difficult to access after printing.



Figure 4: Laser powder bed fusion system used for metal AM training and development.

Directed Energy Deposition

Directed energy deposition (DED) feeds material into a melt pool generated by a focused energy source. The feedstock may be powder or wire, and the deposition head or workpiece motion creates tracks and layers. Compared with PBF, DED is typically less focused on very fine feature resolution and more suited to material addition, repair, coating and composition control over larger tracks.

Relevant DED variants include:

- **DED-LB/M:** laser-based directed energy deposition of metals;
- **DED-Arc/M:** arc-based directed energy deposition of metals;
- related laser powder deposition welding processes.

DED is particularly relevant for SEAMAC because it can support local material delivery and controlled changes in composition, which are central ideas in functionally graded material manufacturing.

Binder Jetting and Other Metal Routes

Binder jetting can also be used for metal parts. In this route, a binder selectively joins powder particles and the part is later cured, debound and sintered to improve density and mechanical integrity. This differs from laser or electron beam fusion because the dense metal part is not produced directly during printing.

Other AM process categories, such as material extrusion, vat photopolymerisation and material jetting, are important in the wider AM field but are less central to the metal FGM focus of this module.

9.3 Laser-Based Metal AM Methods

Laser-based metal AM processes use a laser as the local heat source. Two process concepts are especially important:

- **Laser powder bed fusion:** the laser scans across a powder bed and selectively melts each layer.
- **Laser metal deposition:** powder or wire is delivered into a laser-generated melt pool and deposited as tracks.

Both methods require control of:

- laser power;
- scan or travel speed;
- layer thickness or track height;
- hatch spacing or track overlap;
- powder flow rate or wire feed rate;
- shielding gas and atmosphere;
- substrate condition and heat accumulation.

These parameters affect melt pool stability, residual stress, distortion, surface condition, microstructure and defect formation. In fusion-based processes, surface condition is not only cosmetic: it can influence dimensional accuracy, fatigue behaviour, fluid flow in channels, corrosion response and the feasibility of later post-processing. Later toolkit modules address these relationships in more process-specific detail.

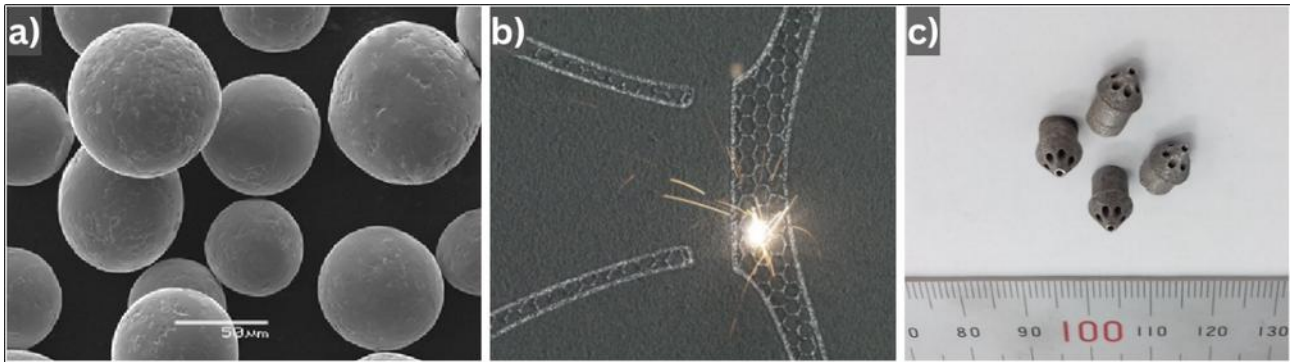


Figure 5: Spherical metal powder particles used as AM feedstock a), powder material during laser sintering b) and final product c).

Metal Powders and Feedstock

Metal powder quality is a critical input for many AM processes. Training sources from Technion identify a broad range of AM materials, including Ti-6Al-4V, stainless steel 316L, 17-4PH, Scalmalloy, Nitinol, maraging steel, Inconel 718, high entropy alloys and other alloys under development.

Relevant powder characteristics include:

- particle size distribution;
- particle shape and sphericity;
- flowability;
- oxygen, nitrogen and hydrogen content;
- chemical composition;
- reuse history and contamination risk.

Figure 5 shows spherical metal powder particles used as AM feedstock, powder material during laser sintering and a final product made from the processed material.

For FGM manufacturing, feedstock control becomes even more important because the target part may require a controlled transition between materials rather than a single uniform alloy.

Relevance to SEAMAC and Functionally Graded Materials

Functionally graded materials are designed with spatially varying composition, microstructure or properties. Metal AM is relevant to FGMs because it can place material locally and build parts from digital instructions.

In the SEAMAC context, metal AM provides a route to:

- combine design freedom with material gradation;
- manufacture research demonstrators for graded metal systems;
- study how process parameters influence microstructure and defects;
- connect powder preparation, deposition, simulation, post-processing and characterisation in one training workflow.

LMD is especially important because powder-fed deposition can, in principle, vary the material feed during the build. This makes it a natural transition point from general metal AM toward SEAMAC-specific FGM process knowledge.

Advantages and Limitations

Metal AM offers several advantages for technical and industrial applications:

- complex geometries and internal features;
- lightweight and lattice structures;
- component consolidation;
- rapid iteration from CAD to part;
- reduced need for product-specific tooling;
- potential for repair, coating and local material addition in DED processes.

However, metal AM also has practical limitations:

- process qualification is demanding;
- material properties depend strongly on parameters and thermal history;
- residual stress and distortion can occur;
- supports and post-processing are often required;
- powder handling introduces safety and quality requirements;
- surface finish and dimensional accuracy may need secondary operations;
- defects such as porosity, lack of fusion or cracking must be controlled.

These limitations are not secondary details. They are part of the manufacturing route and must be considered during design, build preparation, post-processing and inspection. Complex AM geometries can make this more demanding because some surfaces are hard to reach with conventional mechanical finishing tools.

Industrial Relevance

The training sources identify aerospace, automotive, medical, tooling and spare-part applications as important AM use cases. Metal AM is particularly relevant where one or more of the following apply:

- high-value components;
- low production volume;
- complex geometry;
- weight reduction;
- functional integration;
- rapid development of new materials or designs;
- repair or modification of expensive components.

For industry-oriented SEAMAC training, the key message is that metal AM should be treated as a complete manufacturing chain. Successful implementation depends on the interaction between design, feedstock, machine capability, process parameters, post-processing and quality control.

9.4 Concept and Relevance of Functionally Graded Materials

This chapter introduces functionally graded materials (FGMs) as a core concept of the process chain. It builds on the general metal additive manufacturing background from Chapter 4.1 and prepares the reader for later modules on powder preparation, laser metal deposition, post-processing and characterisation.

The aim is to establish a shared vocabulary for describing material gradients before moving into process-specific detail.

Definition of Functionally Graded Materials

Functionally graded materials are materials or components whose composition, microstructure or properties vary with position. Instead of treating a part as one uniform material, an FGM is designed so that different regions provide different functions.

In the training material, FGMs are introduced as a way to replace abrupt transitions between dissimilar materials with an intermediate layer or gradual transition. This is important because sharp changes in material properties can create local stress concentrations, cracking risk or unwanted metallurgical phases.

Typical properties that may be graded include:

- hardness;
- wear resistance;
- corrosion resistance;
- thermal conductivity;
- thermal expansion;
- toughness;
- stiffness;
- porosity or density.

The important idea is not simply that two materials are present. The important idea is that the transition between material states is deliberately controlled.

Homogeneous, Multi-Material and Graded Parts

The distinction between homogeneous, multi-material and graded parts is useful for later process planning.

Material concept	Description	Typical transition
Homogeneous material	One main material throughout the part	No intentional material transition
Multi-material part	Two or more materials placed in different regions	Often a sharp interface
Functionally graded material	Composition, structure or properties vary with position	Controlled gradual or stepwise transition

A multi-material part may contain a direct interface between material A and material B. In an FGM, the transition may pass through intermediate compositions or structures. This can reduce thermo-mechanical mismatch and improve compatibility between regions, provided the gradient is designed and manufactured correctly.

Types of Gradients

FGMs can be classified by the type of variation introduced into the component.

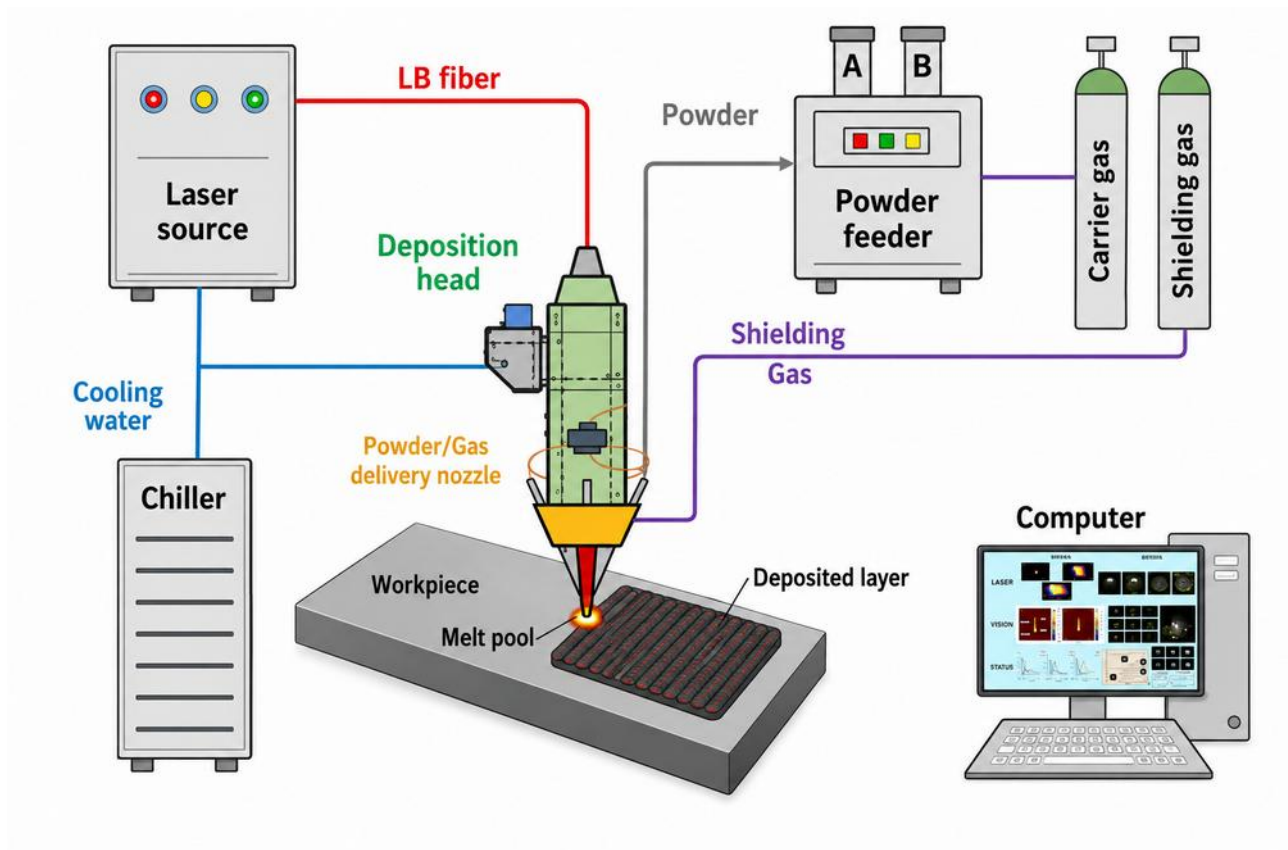


Figure 6: Laser-based directed energy deposition system with powder delivery.

Compositional Gradients

A compositional gradient changes the local chemical composition of the material. In metal additive manufacturing, this may be achieved by changing the powder mixture or wire feed ratio during deposition.

In the SEAMAC context, compositional grading is central because powder-fed LMD can vary material feed during the build. This enables a transition, for example, from one steel or alloy system toward another.

Microstructural Gradients

A microstructural gradient changes the local grain structure, phase distribution or solidification structure without necessarily changing the nominal alloy composition. These gradients may result from changes in thermal history, cooling rate, reheating or local process parameters.

Microstructural gradients are important because mechanical properties are often controlled not only by composition, but also by grain size, phases, defects and residual stress.

Property Gradients

A property gradient describes the intended engineering effect, such as a transition from a tough core to a hard surface, or from a heat-conductive region to a wear-resistant region.

Property gradients are usually the design goal. Compositional and microstructural gradients are the manufacturing routes used to achieve them.

Geometric or Cellular Gradients

In some AM applications, the gradient may be produced by changing geometry rather than material composition. Examples include changes in porosity, lattice cell size or local density. Powder bed fusion is often associated with this type of geometrical or porosity-based grading.

For SEAMAC, the main emphasis is on material and composition gradients produced by LMD, but geometric gradients remain part of the wider FGM vocabulary.

9.5 Why Additive Manufacturing Is Relevant to FGMs

Additive manufacturing is relevant to FGMs because the part is built locally. Material is added in layers or tracks, and this creates opportunities to control geometry, composition and thermal history as the part is produced.

Compared with conventional routes, metal AM can support:

- local material placement;
- controlled changes in feedstock composition;
- fabrication of complex geometry;
- integration of material gradation into the digital process chain;
- research-scale testing of gradient strategies.

Not all AM processes are equally suited to all FGM types. Powder bed fusion can support geometric or porosity gradients, while directed energy deposition is especially relevant for compositional gradients because material can be delivered into a melt pool during deposition.

9.6 Relationship to Laser Metal Deposition

Laser metal deposition is particularly important for SEAMAC because it can feed powder into a laser-generated melt pool. If two or more powders are supplied in controlled ratios, the local composition of the deposit can be adjusted during the build.

In a simplified LMD-based FGM workflow:

1. Select the base material and target material.
2. Define the desired gradient function.
3. Prepare powder blends or controlled powder feed ratios.
4. Select deposition strategy and process parameters.
5. Deposit tracks and layers according to the gradient plan.
6. Characterise geometry, microstructure, defects and local properties.
7. Adapt process parameters and post-processing based on results.

This makes LMD a natural bridge between material design and manufacturing. It also makes process control demanding, because the melt pool, powder flow, dilution and cooling conditions all influence the final gradient.

Smooth Transitions Can Be Useful

FGMs are useful when different regions of a component must perform different functions, but a sharp interface would be problematic.

A gradual transition may help to:

- reduce abrupt changes in thermal expansion;
- reduce local thermo-mechanical stresses;

- avoid weak interfaces between dissimilar materials;
- tune hardness, toughness or wear resistance by position;
- combine a low-cost base material with a higher-performance surface or functional region.

These benefits are not automatic. The gradient must be compatible with the material system and the manufacturing process. Poorly designed gradients can still lead to cracking, porosity, brittle phase formation or unstable deposition.

Relevance to SEAMAC

SEAMAC focuses on the development of a process chain for AM of FGMs, including powder preparation, LMD, post-processing and characterisation. The project context highlights cast iron and maraging steel as an important material direction for demonstrator development, with attention to powder blends, LMD process parameters, PeP post-processing and final part properties.

Within the toolkit, FGMs connect several technical areas:

- powder selection and blending;
- process parameter development;
- deposition strategy;
- thermomechanical behaviour;
- post-processing response;
- metallurgical and mechanical characterisation;
- industrial demonstrator development.

For learners, the key message is that an FGM is not just a material combination. It is a designed transition that must be considered across the complete manufacturing chain.

9.7 Industrial Relevance of FGMs

This chapter explains why functionally graded materials are relevant to industry and why they are important in the SEAMAC training context. The focus is on practical drivers rather than detailed application case studies.

FGMs are most relevant when a component must satisfy different requirements in different locations and when a single homogeneous material is not the best solution.

Why Industry Is Interested in FGMs

Industrial components often experience non-uniform loading, temperature, wear, corrosion or contact conditions. A surface may need high hardness, while the interior needs toughness. A tool may require local thermal conductivity but also strength and dimensional stability. A repaired part may need compatibility between the original base material and the added material.

FGMs offer a way to design material response by location. In principle, this allows the component to use expensive or high-performance material only where it is needed, while retaining a lower-cost or easier-to-manufacture material elsewhere.

For industry-oriented training, the main value of FGMs is the combination of:

- local functionality;
- reduced abrupt material mismatch;
- potential material efficiency;

- integration with digital AM process planning;
- opportunities for repair, coating and hybrid manufacturing.

9.8 Application Drivers

Thermal Gradients

Many engineering parts operate with strong temperature differences. These conditions can create thermal stress, distortion or fatigue. A graded material can be designed so that thermal conductivity, thermal expansion or high-temperature capability changes across the component.

This is relevant to tooling, energy systems, aerospace components and other applications where temperature gradients influence performance.

Wear and Corrosion Resistance

Some parts fail first at the surface because of wear, corrosion or contact fatigue. A graded design may place a wear-resistant or corrosion-resistant material near the surface while keeping a tougher or lower-cost material beneath it.

This is particularly relevant for tools, moulds, dies and repaired surfaces where only selected regions require enhanced surface performance.

Lightweight and Structural Efficiency

FGMs can also support lightweight design when grading is achieved through density, porosity or cellular structure. In these cases the gradient may not be primarily chemical; it may be geometric or structural.

This type of grading can help tune stiffness, energy absorption or local mechanical response.

Biomedical Compatibility

Biomedical components may require combinations of strength, stiffness, surface response and compatibility with surrounding tissue. Graded porosity, surface condition or composition can be relevant where mechanical or biological requirements vary across the implant.

This topic is broader than the SEAMAC demonstrator focus, but it is useful for understanding why FGMs are considered across multiple industrial sectors.

Repair, Coating and Transition Zones

Directed energy deposition and LMD are relevant to repair and local material addition. A graded transition can be useful when adding material to an existing component because it may reduce mismatch between the substrate and the added layer.

In this context, the FGM is not necessarily the whole part. It may be a local transition zone, coating system or repaired region.

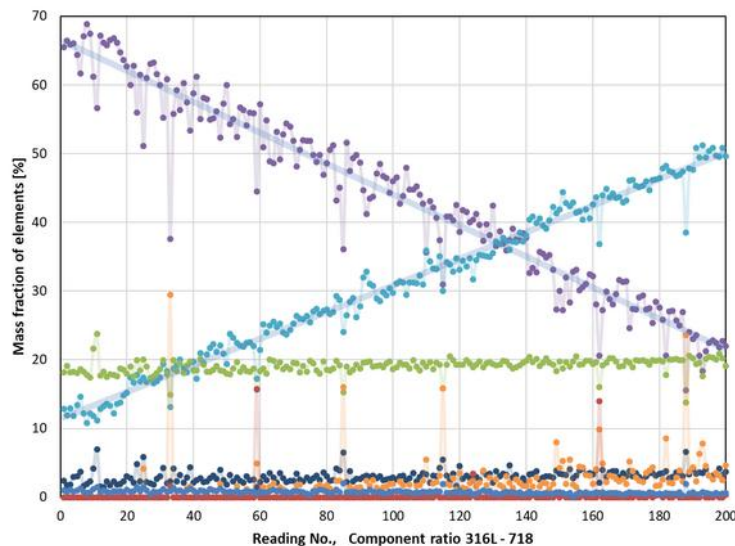


Figure 7: Example of measured composition change across an SS316L-In718 graded deposit.

9.9 Relevance to Tooling and Demonstrators

The SEAMAC project context identifies tooling as an important industrial direction, especially because toolmaking is a strong Slovenian industrial domain. Large dies and moulds can be cost-intensive if made entirely from high-performance materials. A graded approach may allow a cost-effective base material to be combined with a higher-performance functional region.

For example, a component concept may require:

- a base material that provides bulk shape and structural support;
- a transition region that reduces mismatch;
- a functional surface region with higher hardness, wear resistance or thermal performance.

The process chain links powder blends, LMD, PeP and characterisation. This is important because an industrially relevant FGM is not only a material design; it must also be manufacturable, post-processable and inspectable.

AM is Compatible with Industrial FGM Development

Additive manufacturing can build parts from digital instructions, and LMD can deliver material into a local melt pool. This makes AM useful for developing graded parts because the process can be adapted by position.

Potential AM-related advantages include:

- local material addition;
- reduced need for product-specific tooling;
- ability to test different gradient strategies;
- use of powder-feed control for composition changes;
- integration with monitoring, simulation and data-driven optimisation.

However, these advantages only become industrially useful when the full process chain is controlled. A promising gradient design is not enough if the part cannot be produced repeatably or inspected reliably.

Practical Adoption Considerations

For industrial use, FGMs must satisfy normal manufacturing requirements as well as material-gradient requirements.

Important adoption considerations include:

- **Qualification:** The process must produce repeatable properties and acceptable defect levels.
- **Inspection:** Local composition, geometry, defects and surface state must be measurable.
- **Traceability:** Powder batches, blend ratios, process parameters and post-processing history must be documented.
- **Cost:** The added complexity must be justified by performance, repair value or material savings.
- **Production volume:** FGMs may be most attractive for high-value, low-volume or specialised components.
- **Post-processing:** Surface finishing, heat treatment or PeP may be needed before functional use.
- **Design capability:** Engineers need tools and training to define gradients that are meaningful and manufacturable.

Balanced View of Industrial Readiness

FGMs offer strong potential, but they should not be presented as a simple drop-in replacement for conventional materials. Industrial use requires confidence in process stability, material compatibility, inspection methods and long-term performance.

For this reason, SEAMAC treats FGMs as part of a complete manufacturing chain. The industrial relevance lies not only in the final part concept, but also in the ability to train researchers and engineers to connect material design, AM process knowledge, post-processing and quality assessment.

9.10 Challenges in Manufacturing FGMs

This chapter introduces the main challenges involved in manufacturing functionally graded materials by metal additive manufacturing. It is written as a bridge from the introductory FGM concept toward later modules on powders, LMD, post-processing, characterisation and troubleshooting.

The central message is that FGM manufacturing is a process-chain problem. The final gradient depends on feedstock preparation, deposition strategy, process parameters, thermal history, material compatibility, post-processing and inspection.

Overview of Manufacturing Challenges

FGMs are more demanding than single-material AM parts because the material state changes across the component. A process that works for one alloy may not work for a

mixture or transition region. A parameter set that produces stable deposition at one composition may produce porosity, cracking or unwanted phases at another.

Key challenge areas include:

- defining the target gradient;
- preparing and controlling powder blends;
- maintaining stable deposition;
- managing dilution and melt pool behaviour;
- controlling thermal history and residual stress;
- avoiding cracking, porosity and detrimental phases;
- post-processing surfaces with varying composition;
- verifying local properties and defects.

Feedstock and Powder Handling

For powder-fed LMD, the powder is not only a consumable. It is part of the material design. Particle size, morphology, flowability, composition and blending quality all affect the stability of powder delivery and the resulting deposit.

In the SEAMAC project context, powder blends are central to the transition between selected materials. This introduces several practical questions:

- Are the powders compatible in particle size and flow behaviour?
- Can the blend ratio be controlled reliably?
- Does the powder feed system deliver each material consistently?
- Are oxygen, nitrogen, hydrogen or contamination levels acceptable?
- Does powder reuse change the blend behaviour?

These questions are treated in more detail in Module 2.

Composition Control and Gradient Design

An FGM requires a defined transition from one material state to another. This transition may be linear, progressive, regressive, stepwise or locally adapted. The selected gradient function must be meaningful for both design and manufacturing.

Key fabrication strategy variables for LMD-based FGM production.

Strategy variable	Typical options
Deposition path	unidirectional, bidirectional, segmented
Interlayer dwell or cooling time	no dwell, dwell until a defined temperature is reached
Material gradient function	linear, progressive, regressive
Material gradient orientation	transverse, longitudinal

Important design variables include:

- deposition path;
- dwell time or cooling time between layers;
- gradient function;
- gradient orientation;

- layer height and track overlap;
- powder feed ratio;
- total build geometry.

A gradient that looks simple in a diagram can be difficult to realise in the part because the melt pool mixes incoming powder with previously deposited material. The resulting composition may differ from the nominal powder feed ratio due to dilution, remelting and local thermal history.

Process Stability and Melt Pool Control

In LMD, material is added into a laser-generated melt pool. Stable deposition requires a balance between laser power, travel speed, powder mass flow, spot size, shielding gas and heat accumulation.

For FGMs, this balance changes as the composition changes. Different materials may have different melting behaviour, absorptivity, viscosity, thermal conductivity and solidification behaviour. As a result, the process window may shift across the gradient.

Typical process stability concerns include:

- irregular track geometry;
- lack of fusion;
- excessive dilution;
- balling or unstable bead formation;
- overheating and distortion;
- inconsistent layer height;
- local changes in porosity or cracking tendency.

These issues are addressed in more detail in Module 3.

Material Compatibility

Material compatibility is one of the most important FGM challenges. The purpose of the gradient is often to reduce mismatch between two materials, but the intermediate compositions must also be viable.

Compatibility concerns include:

- **Dilution:** mixing between the substrate, previous layer and new powder changes the local composition.
- **Cracking risk:** thermal stresses and brittle microstructures can cause cracking during cooling.
- **Phase formation:** intermediate compositions may form unwanted phases or hard brittle regions.
- **Thermal expansion mismatch:** different materials expand and contract differently during heating and cooling.
- **Melting and solidification behaviour:** different alloys may require different energy input and cooling control.

The SEAMAC context highlights cast iron and maraging steel as a relevant material direction. This is challenging because carbon content, weldability, heat-affected zones and cracking behaviour must be considered when developing a graded transition.

Defects and Residual Stress

Defects in FGM manufacturing may be similar to defects in other metal AM processes, but the causes can be more complex because both geometry and composition vary.

Important defect types include:

- porosity;
- lack of fusion;
- cracks;
- distortion;
- excessive roughness;
- local hardness variation;
- undesirable microstructural zones;
- residual stress accumulation.

The SEAMAC kickoff material links LMD parameters and FGM fabrication strategy to geometry, dilution, microstructure, residual stress, cracks, corrosion susceptibility and wear resistance. This reinforces that FGM quality cannot be evaluated by geometry alone.

Monitoring, Simulation and Quality Assurance

Because FGM production involves changing material conditions, monitoring and simulation are especially useful. Process data can support understanding of how parameter changes, cooling conditions and gradient design affect the final part.

Relevant quality assurance topics include:

- monitoring of process stability;
- documentation of powder ratios and process parameters;
- thermomechanical simulation;
- measurement of local composition;
- metallographic analysis;
- hardness and mechanical testing;
- surface roughness and geometric inspection;
- feedback from post-processing results into LMD strategy.

These topics connect directly to Modules 3 and 5.

Post-Processing Challenges

FGM parts often require post-processing, but post-processing can be more difficult when composition varies across the surface. A polishing electrolyte, heat treatment or mechanical finishing method may affect different material regions differently.

For PeP, multi-material and FGM-like parts introduce questions such as:

- whether one electrolyte is suitable for all regions;
- whether different materials are removed at different rates;
- whether graphite, oxides or local phases influence surface response;
- whether several post-processing steps are needed;
- how to maintain geometry while improving surface quality.

Detailed PeP theory belongs to Module 4. At this stage, the important point is that FGM manufacturing does not end after deposition. Post-processing must be planned as part of the process chain.

Characterisation Challenges

FGMs require characterisation methods that can resolve local variation. A single average material property may hide important differences across the gradient.

Useful characterisation questions include:

- Does the measured composition follow the intended gradient?
- Are there cracks or pores in specific transition regions?
- How do hardness and microstructure change across the part?
- Are residual stresses concentrated near specific material transitions?
- Does post-processing affect all material regions acceptably?
- Does the final part meet the intended functional requirements?

The answer may require combining microscopy, chemical analysis, roughness measurement, hardness testing, mechanical testing and non-destructive inspection.

10 Module 2: Feedstock Materials and Powder Preparation

10.1 Materials

Feedstock selection is the starting point for the SEAMAC process chain because the intended functionally graded material is created by controlling which powders enter the laser metal deposition process, how they mix, and how they respond during melting, solidification and post-processing.

In the SEAMAC work plan, the main material direction is a graded transition from cast iron toward maraging tool steel. This material pair is relevant to tooling and mould applications, where a cost-effective cast-iron base may be combined with a higher-performance surface or functional region.

Material Direction

The project scope identifies the following material concept:

- a cast-iron or iron-based starting region;
- a series of modified steel powder blends;
- a transition toward maraging tool steel;
- LMD deposition of individual powders and mixed powder ratios;
- post-processing by plasma electrolytic polishing where suitable;
- metallurgical, mechanical and surface characterisation of the resulting demonstrators.

The gradient is not treated as a simple two-material joint. It is planned as a controlled chemical and microstructural transition in which the powder ratios, deposition strategy and cooling conditions influence the final properties.

Cast Iron as Base Material

Cast iron is important in SEAMAC because it is widely used in tooling, mould and die applications. It can provide a practical base material for industrially relevant demonstrators, especially where the full component does not need to be made from a more expensive high-performance alloy.

For LMD-based grading, cast iron also introduces metallurgical challenges. The carbon content and carbon equivalent are important because they influence weldability, cracking tendency and the risk of brittle phase formation during rapid thermal cycling.

Maraging Tool Steel as Functional Material

Maraging steels are high-strength steels whose properties are developed through alloy design and heat treatment rather than high carbon content. In the SEAMAC concept, maraging tool steel represents the higher-performance material to be deposited progressively over the cast-iron base.

The training value of this material combination is that it requires learners to consider:

- chemical compatibility between feedstocks;
- carbon equivalent and cracking risk;
- powder flow and feed stability;

- dilution with the substrate or previous layer;
- microstructural evolution across the gradient;
- downstream response to post-processing and characterisation.

Broader AM Powder Materials

The SEAMAC training sources also refer to common AM materials such as Ti-6Al-4V, stainless steels, 17-4PH, Scalmalloy, nickel alloys, Nitinol, maraging steels and high-entropy alloy systems. These examples are useful for teaching because they show that powder-based AM is not limited to one alloy family.

However, the module focus remains the SEAMAC feedstock problem: preparing powder blends for a cast-iron to maraging-steel FGM and understanding which powder characteristics must be controlled before process development can be meaningful.

Feedstock Forms

Metal AM can use several feedstock forms, including powder, wire and rod. For this module, powder is the central feedstock because powder-fed LMD can vary material supply during deposition and can therefore support compositionally graded structures.

Powder feedstock may be obtained by:

- direct purchase from qualified powder suppliers;
- atomisation of wire or rod feedstock;
- small-batch atomisation for experimental alloy development;
- blending of existing powders to reach target intermediate compositions.

In SEAMAC, the source route matters because it affects particle shape, particle size distribution, chemistry, oxygen content and batch-to-batch consistency.

This section defines the material basis for the following module parts. Powder selection, blending, characterisation and handling are not separate administrative steps. They determine whether LMD process parameters can be developed reproducibly and whether the intended material gradient can be evaluated reliably.

10.2 Powder Selection Criteria

Powder selection for metal AM is a technical decision that links material chemistry, powder production route, flow behaviour, process stability and safety. For SEAMAC, selection must also support controlled blending between cast iron and maraging steel.

Main Selection Criteria

Important powder selection criteria include:

- chemical composition and allowed impurity levels;
- particle size distribution;
- particle shape and sphericity;
- surface condition and oxide content;
- internal porosity;
- flowability and apparent density;
- satellites, agglomerates and fines;

- moisture sensitivity;
- reuse history;
- compatibility with the intended LMD feeder and nozzle system.

The training material identifies highly spherical particles, fine surfaces, few satellites, low internal porosity, narrow size distribution and high purity as desirable powder characteristics for AM.

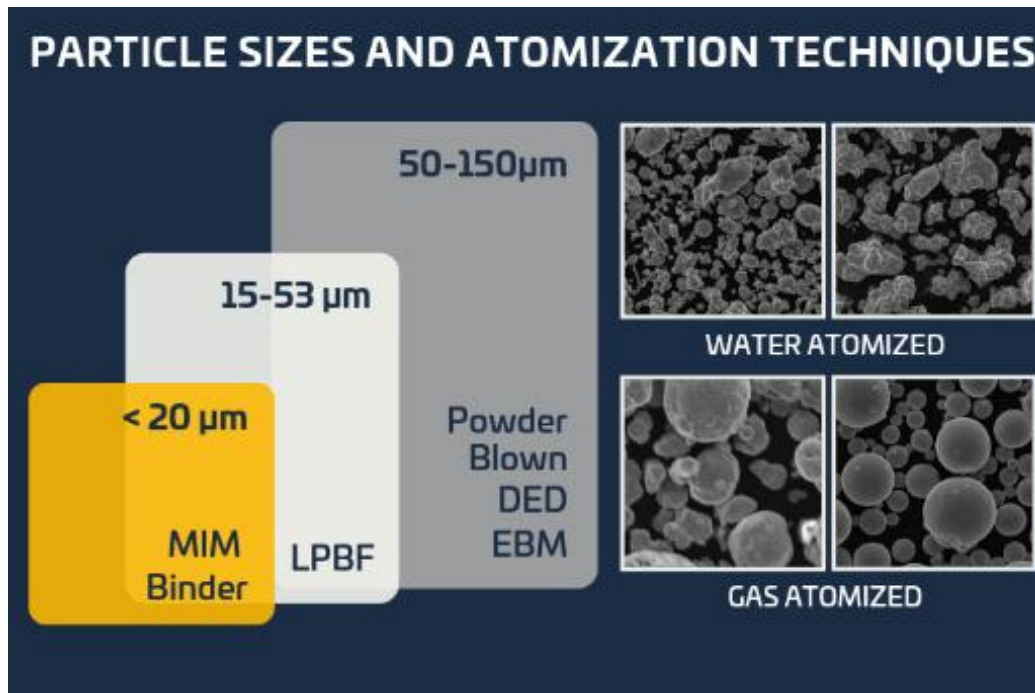


Figure 8: Powder particle morphology from different atomisation routes.

Particle Size Distribution

Particle size distribution affects both powder delivery and melting behaviour. Very fine particles can increase dust risk, oxidation sensitivity and agglomeration. Very coarse particles may feed less consistently and may require more energy or residence time to melt completely.

For the SEAMAC LMD work, the grant agreement identifies a relevant particle-size range of 40-150 micrometres. This range should be treated as a process-specific starting point, not a universal rule for all AM processes. Powder bed fusion typically uses different powder-size windows than LMD because the recoating and layer formation requirements are different.

Particle Shape and Flowability

Spherical or near-spherical powders generally support better flowability and packing than irregular powders. This is why gas atomisation, plasma atomisation and electrode-based atomisation routes are commonly discussed for AM feedstock.

Irregular powders may still be useful in some powder-metallurgy contexts, but they can create problems in AM when consistent feeding, spreading or metering is required. In LMD, poor flow can affect powder mass flow rate, powder stream geometry, catchment efficiency and local composition.

Table 3 summarizes powder quality characteristics, their effects on AM processing and common detection methods.

Table 3: AM powder quality characteristics including composition, particle size distribution, flowability, density, morphology, microstructure and thermal conductivity.

Characteristics	Effects on AM	Common detection methods
Chemical composition	Differences in chemical composition will influence the final part properties. Compliance with existing material standards pertaining to different industrial applications is necessary.	Inductively coupled plasma, optical emission spectroscopy, X-ray fluorescence
Particle Size Distribution	The minimum layer thickness that can be built in Additive Manufacturing is a function of powder particle size. The range of PSD influences the energy requirement and the packing bed density.	Laser diffraction and sieve analysis
Flowability	Influences the homogeneous distribution of powder in the powder bed. Flowability will be poor for powder batches containing a large proportion of smaller particles less than 6 micrometres (0.0002 in).	Hall flowmeter, Carney flowmeter, powder rheometry
Density	Effective packing of powder is required to ensure minimum porosity in the final part. Packing density has a significant effect on the thermal conductivity of the powder bed.	Hall flowmeter, Carney flowmeter, Scott volumeter and gas pycnometer
Powder morphology	Influences homogeneous distribution of powder and the packing density. Powders with spherical shapes that spread easily in the powder bed are required for AM.	Scanning Electron Microscopy (SEM)
Microstructure	Important to understand the grain morphology of the powder and to correlate it with microstructural characteristics of the final part.	Optical microscopy or SEM
Thermal conductivity	An important thermo-physical property of the metal powder, which affects the consolidation behaviour of powder.	Guarded hot plate method

Chemistry and Impurities

Powder chemistry must match the intended alloy or blend composition. For SEAMAC, chemical composition is especially important because the target is a controlled transition rather than a single alloy.

Key chemical checks include:

- alloying element concentrations;
- carbon level and calculated carbon equivalent for iron-based blends;
- oxygen, nitrogen and hydrogen residual gases;
- contamination from handling, sieving, containers or previous powder batches;
- changes caused by reuse or exposure to humidity and air.

Oxygen is particularly important for reactive metals such as titanium alloys, and gas content is also relevant to iron-based powders because it can influence porosity, inclusions and process repeatability.

Powder Production Route

The powder production route influences particle morphology and chemistry. The powder training source identifies several relevant routes:

- water atomisation;
- gas atomisation;
- plasma-assisted atomisation;
- electrode induction gas atomisation;
- ultrasonic atomisation for small-batch production;
- mechanical comminution;
- mechanical alloying.

For AM, atomisation routes that produce spherical particles with controlled chemistry are usually preferred. Mechanical alloying can be useful for experimental or composite powder systems, but it may change particle shape, introduce contamination from milling media, and require careful characterisation before AM use.

Practical Selection Questions

Before powder is accepted for SEAMAC experiments, the following questions should be answered:

Question	Why it matters
Is the chemistry compatible with the target blend?	Defines the intended material gradient.
Is the particle-size range suitable for LMD?	Affects feeding and melting behaviour.
Is the powder sufficiently spherical and free-flowing?	Supports stable powder delivery.
Are residual gases and oxides controlled?	Reduces contamination and defect risk.
Has the powder been reused or exposed to air?	Indicates possible ageing, oxidation or contamination.
Is safety documentation available?	Required for handling, storage and risk assessment.

10.3 Powder Blending Strategies for FGMs

Powder blending is the feedstock step that turns the FGM concept into a practical deposition plan. In SEAMAC, the central task is to define powder mixtures that move from cast iron toward maraging steel while limiting cracking risk and preserving process stability.

Why Blending Is Needed

An abrupt transition between dissimilar metals can create high local stress, incompatible microstructures or brittle phases. A graded blend introduces intermediate compositions so that the material transition can be studied and adjusted.

For LMD, blending can be implemented in two main ways:

- **pre-blended powders**, where each intermediate composition is prepared before deposition;
- **dynamic feeder mixing**, where two or more powders are metered separately and mixed by changing feeder ratios during deposition.

Both approaches can be used for training and research. Pre-blended powders are easier to document batch by batch, while dynamic feeder mixing gives more flexibility during deposition if the equipment can meter powders reliably.

Gradient Strategy

The SEAMAC project text identifies powder material ratios between cast iron and maraging steel from 100/0 to 0/100. The gradient function may be:

- linear;
- progressive;
- regressive;
- discrete stepwise;
- compared against a direct material transition.

The selected function should be recorded with the powder batch, deposition path and process parameters. Without this traceability, it is difficult to connect local composition to microstructure, hardness, cracking, residual stress or polishing response.

Pre-Blended Intermediate Powders

Pre-blending prepares a set of intermediate powder compositions before printing. A simple experimental series could include:

Blend ID	Cast iron powder	Maraging steel powder	Purpose
B0	1	0	Base reference
B1	0.75	0.25	Early transition
B2	0.5	0.5	Mid-transition
B3	0.25	0.75	Late transition
B4	0	1	Functional material reference

The exact ratios should be chosen according to the scientific question and machine capability. Finer composition steps may improve understanding of phase formation, but they also increase experimental effort and powder handling complexity.

Dynamic Powder Feed Control

Dynamic mixing uses separate powder hoppers or feeders and changes their mass flow rates during deposition. This approach is closely aligned with powder-fed DED and LMD because the local deposit composition can be adjusted through feed ratio control.

Journal literature on direct laser metal deposition of FGMs supports this concept: metallic gradients can be produced by adjusting the amount of each powder entering the melt pool. This is useful context for SEAMAC, but the actual validated ratios, feeder response and gradient quality must be established experimentally for the cast-iron to maraging-steel system.

Mechanical Alloying and Composite Additions

The powder training source describes mechanical alloying as repeated deformation, welding and breaking of particles under high-energy milling. This can produce fine and homogeneous powder structures, including metal-metal or metal-ceramic mixtures.

In this process, particles are repeatedly plastically deformed, cold welded and fractured during many high-energy impacts. The final powder structure is therefore the result of a statistical sequence of successful impact events. Local adiabatic heating can occur during impact, which may increase diffusion between contacting particles.

Mechanical alloying is commonly carried out in an attritor, where a rotating impeller agitates balls and powder together. Milling media may include stainless steel, tool steel or ceramics such as alumina, WC-Co or zirconia, depending on the required contamination control and powder system.

As additional concept is the use of nano grain-refinement agents in a metal matrix composite approach. The grant agreement notes that a spray dryer may be used to mix nano grain refinement additions with micro metal powders.

This strategy requires careful control because nano-scale additions can:

- agglomerate if mixing is insufficient;
- alter flowability;
- increase dust and inhalation risk;
- change melt pool behaviour;
- complicate chemical analysis.

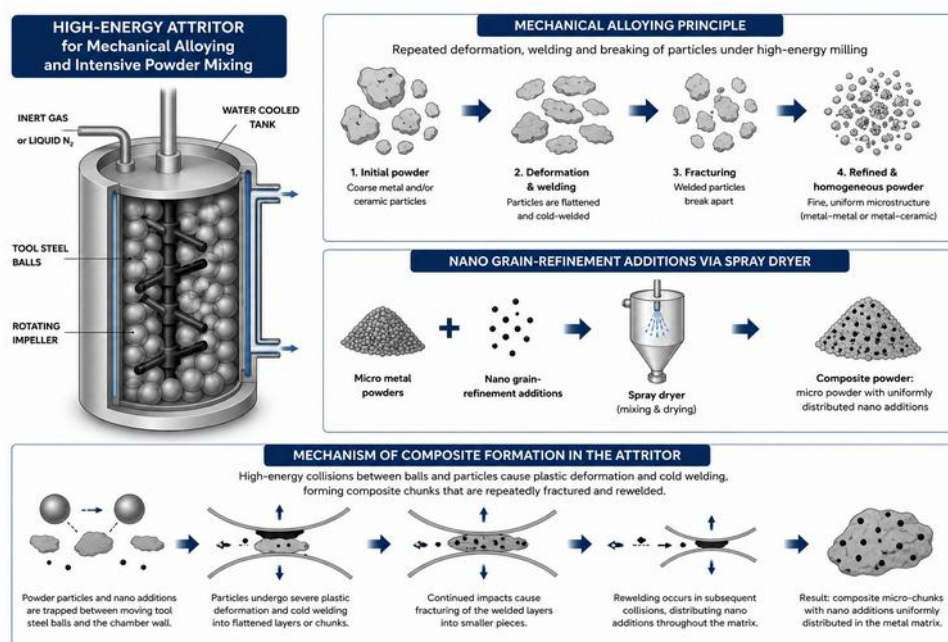


Figure 9: High-energy attritor concept used for mechanical alloying and intensive powder mixing.

Blending Controls

For each blend, record:

- powder supplier or production route;
- batch identifiers;
- nominal blend ratio by mass or volume;
- blending method and duration;

- sieving or deagglomeration steps;
- storage container and atmosphere;
- measured particle-size distribution after blending;
- measured chemistry and residual gas content;
- observations of segregation, agglomeration or flow changes.

Segregation is a practical risk when powders differ strongly in particle size, density or morphology. A blend that is chemically correct at preparation may still feed inconsistently if it separates during handling, vibration or hopper flow.

10.4 Powder Characterisation Methods

Powder characterisation verifies whether a feedstock is suitable for the intended AM process and whether a powder blend matches the planned gradient. For SEAMAC, characterisation must support both process development and later interpretation of deposited material properties.

Characterisation Objectives

Powder characterisation should answer four practical questions:

- Does the powder have the required particle-size distribution and morphology?
- Does the chemistry match the intended alloy or blend composition?
- Are oxygen, nitrogen, hydrogen and other contamination risks controlled?
- Is the powder likely to feed reproducibly during LMD?

The answers should be recorded before deposition so that changes in process stability or part quality can be traced back to feedstock properties.

Size and Shape Measurement

The SEAMAC grant agreement identifies Camsizer measurement for powder shape and distribution. Image-based particle analysis is useful because it can report both size distribution and shape descriptors such as aspect ratio or sphericity.

Relevant powder morphology features include:

- particle size distribution;
- sphericity;
- aspect ratio;
- satellites;
- agglomerates;
- broken or irregular particles;
- fines content;
- large outlier particles.

These features influence flowability, packing, powder stream behaviour and melting response.

Chemical Composition

X-ray fluorescence analysis is identified in the project sources as a method for chemical composition measurement. For SEAMAC blends, chemical analysis is needed not only for the end-member powders but also for intermediate mixtures.

For iron-based gradients, the calculated carbon equivalent should be tracked because it is associated with weldability and cracking tendency. Composition data should therefore be

linked to the blend ratio and to later LMD observations such as cracking, dilution and microstructure.

Residual Gas Measurement

The project plan identifies LECO analysis for hydrogen, nitrogen and oxygen residual gases. These gases are relevant because they can influence porosity, oxide formation, embrittlement or process reproducibility.

Residual gas analysis is especially important when:

- powders have been stored for a long time;
- powders have been exposed to humid air;
- recycled powders are used;
- fine particles or high surface-area powders are present;
- reactive or oxygen-sensitive alloy systems are processed.

Flowability and Handling Tests

Flowability should be checked in a way that reflects the intended process. A powder that spreads well in a powder-bed system is not automatically suitable for a specific LMD feeder, and a powder that flows in a simple funnel test may still segregate in a vibrating hopper.

Useful practical checks include:

- apparent and tapped density;
- Hall or Carney flow where applicable;
- feeder mass-flow calibration;
- repeatability of mass flow over time;
- visual inspection of hopper flow;
- checking whether blended powders segregate after vibration or transport.

Each powder or blend should have a short record:

Field	Recommended content
Powder or blend ID	Unique internal identifier
Material	Alloy or blend ratio
Source	Supplier, atomisation route or in-house preparation
Size distribution	Measured range and key distribution values
Morphology	Sphericity, satellites, irregular particles, agglomerates
Chemistry	XRF or other composition result
Residual gases	H ₂ , N ₂ and O ₂ where measured
Flow behaviour	Flow test or feeder calibration result
Storage state	Container, atmosphere, date opened
Reuse history	Fresh, sieved, recycled or mixed

Link to Part Characterisation

Powder characterisation does not replace part characterisation. It provides the input record needed to interpret later results. If a deposited layer shows porosity, cracking, high

roughness or unexpected phases, the powder record helps determine whether the likely cause is feedstock quality, blend design, LMD parameters or post-processing.

10.5 Powder Handling, Storage and Safety

Metal powder handling is both a quality issue and a safety issue. The same fine particles that enable powder-based AM can create inhalation, contamination, fire, explosion and housekeeping risks if they are not controlled.

Main Hazards

The powder safety training source identifies several AM hazards:

- flammable materials;
- materials harmful to health;
- fine dust particles;
- inert gas atmospheres;
- invisible laser radiation;
- hot surfaces;
- electric shock;
- moving parts and crushing hazards;
- heavy components and sharp edges.

This section focuses on powder-specific risks, but powder handling must always be integrated with the full machine and laboratory safety procedure.

Basic Handling Rules

Powder handling should be performed only by trained personnel using the relevant operating instructions, safety data sheets and parameter sheets.

Basic requirements include:

- wear the specified protective equipment;
- avoid creating airborne dust;
- keep powder containers closed when not in use;
- avoid eating, drinking or smoking in powder handling areas;
- clean deposits using suitable equipment;
- separate clean powder, used powder and waste powder;
- document powder transfer, sieving and reuse;
- follow local procedures for reactive or combustible powders.

Personal Protective Equipment

The training source identifies typical PPE for powder handling and AM machine operation:

- disposable nitrile protective gloves;
- safety glasses with side protection;
- closed protective clothing;
- closed ESD safety shoes;
- P3 filter mask or appropriate respiratory protection;
- heat-resistant gloves where hot machine components may be present;
- flame-retardant protective clothing or hood where required by the local risk assessment.



Figure 10: Prevention measures for metal and ceramic powder handling - safe packaging.

PPE must match the specific powder and process. For example, titanium, aluminium and fine reactive powders may require stricter fire and explosion controls than less reactive powders.

Storage and Waste

Powders should be stored cool and dry in closed original or approved containers. Storage records should identify the material, batch, opening date, reuse state and any known exposure to air or moisture.

Waste powder should be stored in closed, non-flammable containers and handled according to the applicable safety data sheet and institutional waste procedure. Used powder should not be returned to fresh-powder stock unless the local procedure explicitly allows it and the powder has been sieved, documented and accepted for reuse.

Machine-Related Powder Handling

Powder-based AM machines include powder loading, powder deposition, powder removal, sieving and recycling steps. Each step can expose the operator to powder or disturb settled dust.

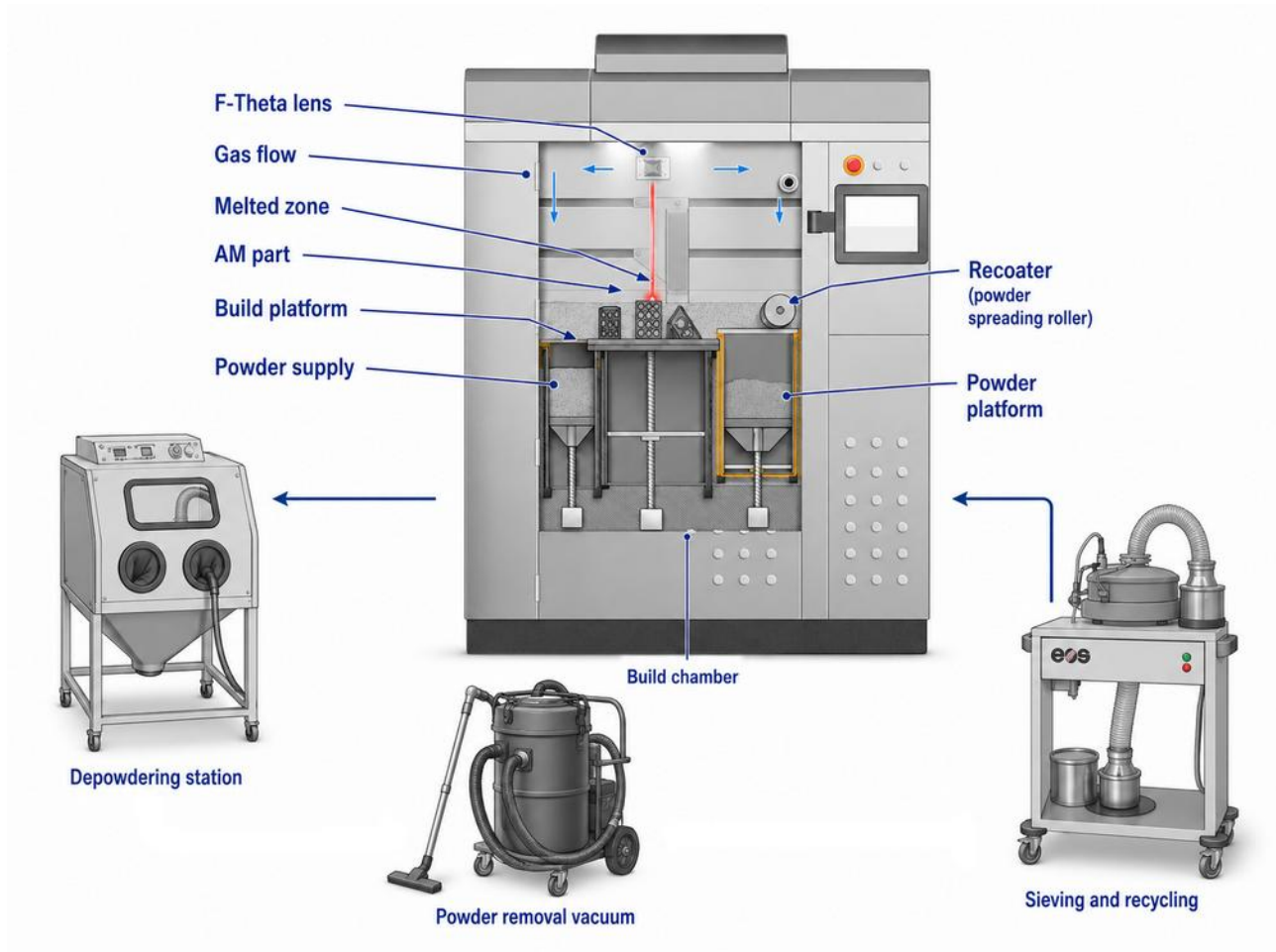


Figure 11: Powder-bed machine layout showing powder handling elements around the build chamber.

For training and laboratory work, powder handling should include:

- preparation of the build plate or substrate;
- controlled powder loading;
- verification of inert gas or ventilation conditions;
- safe part and powder removal after processing;
- sieving or separation of used powder where applicable;
- cleaning with approved vacuum, wet separator or other suitable equipment;
- prevention of cross-contamination between materials.

Quality Risks During Handling

Poor handling can damage powder quality even when no immediate safety incident occurs. Common quality risks include:

- moisture uptake;
- oxidation;
- contamination from tools or containers;
- mixing of different materials;
- loss of fines during sieving or transfer;
- segregation of powder blends;
- accidental reuse of unknown powder.

For SEAMAC FGM work, cross-contamination and segregation are especially important because local composition is part of the experiment. Handling records should therefore be treated as part of the technical dataset, not only as safety paperwork.

Emergency and Exposure Response

The training source gives basic response guidance for skin contact: wash with soap and water. Eye contact, inhalation, ingestion, fire or powder spill events must follow the local safety data sheet and laboratory emergency procedure.

For training purposes, the key rule is simple: do not improvise powder incident response. Use the documented procedure for the specific material and facility.

11 Module 3: Laser Metal Deposition Process Knowledge

11.1 LMD Process Principles

Laser metal deposition (LMD) is the central additive manufacturing process in the SEAMAC technical process chain. It belongs to the directed energy deposition family of metal AM processes, where a focused energy source creates a local melt pool and feedstock is delivered into that melt pool during machine motion.

In the SEAMAC context, LMD is important because it can combine material addition, local metallurgical bonding and composition control in one process. This makes it suitable for manufacturing functionally graded material (FGM) demonstrators, especially when the powder feed can be changed from one material ratio to another during deposition.

Basic Operating Principle

In powder-fed LMD, a laser beam locally melts the surface of a substrate or previously deposited layer. Metallic powder is carried by a gas stream through a nozzle and enters the melt pool. The powder particles melt partly or fully, mix with the molten substrate or previous layer, and solidify to form a track.

A typical LMD sequence is:

1. Prepare and fix the substrate.
2. Define the toolpath and deposition strategy.
3. Deliver shielding and carrier gas.
4. Focus the laser on the workpiece surface.
5. Feed powder into the laser-generated melt pool.
6. Move the laser head or workpiece along the programmed path.
7. Solidify the deposited track.
8. Offset tracks and layers to build the required geometry.

The process is track-wise and layer-wise. A single track forms a bead or clad. Adjacent tracks overlap to form a layer, and multiple layers form a wall, coating, repair volume or near-net-shape component.

Relationship to Directed Energy Deposition

Directed energy deposition is a broader AM category that includes processes using laser, electron beam or arc energy sources, and powder or wire feedstock. LMD is a laser-based DED process. In terminology aligned with ISO/ASTM usage, it may also be described as DED-LB/M when the deposited material is metallic.

Compared with powder bed fusion, LMD usually has:

- larger melt pools and tracks;
- lower geometrical resolution;
- higher deposition rates for many applications;
- easier integration with repair, coating and hybrid manufacturing;
- greater suitability for changing feedstock composition during deposition.

These characteristics make LMD particularly relevant for graded structures, but they also mean that process control, dilution and geometry accuracy require careful attention.

Melt Pool and Solidification

The melt pool is the active zone where energy input, powder delivery, substrate melting and material mixing occur. Its size and lifetime depend on laser power, beam diameter, travel speed, powder flow rate, material properties and heat accumulation in the workpiece.

The thermal cycle in LMD includes rapid heating, melting, solidification, and reheating by later tracks or layers. This affects:

- microstructure and grain size;
- dilution between the deposit and substrate;
- residual stress;
- distortion;
- cracking tendency;
- pore formation;
- surface roughness and track geometry.

The process simulation sources used in SEAMAC training emphasise that laser power and scan speed influence melt depth, melt temperature and time above melting. Higher power or lower travel speed generally increases heat input, while higher travel speed reduces interaction time. The useful process window is therefore a balance between sufficient fusion and excessive thermal loading.

Dilution and Material Mixing

Dilution is the mixing of newly delivered material with material remelted from the substrate or previous layer. Some dilution is required for metallurgical bonding, but excessive or uncontrolled dilution can shift the intended composition of a graded material.

For FGMs, dilution has two consequences:

- the actual local composition may differ from the nominal powder feed ratio;
- the transition between layers may be smoother or less precise than the programmed gradient.

This is not only a geometric issue. In dissimilar material systems, the local composition determines phase formation, hardness, residual stress and cracking risk. SEAMAC therefore treats LMD process knowledge and powder blend design as linked topics rather than separate tasks.

Relevance to SEAMAC

The SEAMAC project focuses on manufacturing graded structures that transition from cast iron or iron-based material toward maraging tool steel. The process must account for powder preparation, LMD parameter selection, deposition strategy, post-processing and characterisation.

For this material direction, the main LMD learning points are:

- how laser energy and powder flow create stable deposited tracks;
- how feedstock properties affect delivery and melting;
- how process parameters influence geometry, dilution and microstructure;
- how deposition strategy changes heat accumulation;
- how cracks, porosity and lack of bonding can be avoided or reduced;

- how LMD output constrains later plasma electrolytic polishing and characterisation.

11.2 Equipment and Experimental Setup

An LMD setup combines a laser source, beam delivery optics, powder delivery, motion control, shielding gas and process monitoring. The equipment must deliver energy and material to the same location with sufficient repeatability to form stable tracks and layers.

For SEAMAC, the experimental setup is not only a production tool. It is also a training and research platform for understanding how powder blends, beam configuration, process parameters and deposition strategy interact during FGM manufacturing.

Main Equipment Elements

The main hardware elements of a powder-fed LMD system are:

- **laser source**, which supplies the process energy;
- **beam delivery optics**, which shape and focus the laser beam;
- **deposition head or nozzle**, which aligns powder delivery with the melt pool;
- **powder feeders**, which meter one or more powders;
- **carrier gas supply**, which transports powder to the nozzle;
- **shielding gas supply**, which limits oxidation and stabilises the process environment;
- **motion system**, such as a CNC machine, robot or gantry;
- **workholding system**, which fixes the substrate and controls accessibility;
- **control system**, which synchronises laser power, powder flow and motion;
- **monitoring equipment**, where available, for observing the process or recording signals.

The exact configuration can vary between laboratories, but the functional requirement is consistent: laser energy, powder and motion must be coordinated at the melt pool. The LMD schematic introduced earlier in Figure 3 shows the main relationship between laser source, deposition head, powder feeder, gases, workpiece and melt pool.

Laser and Beam Delivery

The laser determines the available power, beam quality and interaction with the workpiece. The beam diameter and intensity distribution influence melt pool size, penetration depth and thermal gradient. In SEAMAC sources, the laser beam power, intensity distribution and travel speed are treated as key process inputs.

An annular laser beam LMD head developed at UL is noted in the project source material. This type of head enables axial powder feeding and adjustment of laser beam intensity distribution. For training purposes, this is useful because it highlights that the beam is not only an on/off heat source; its spatial energy distribution can affect clad geometry, process stability and heat input.

Powder Feeding System

Powder delivery is critical for both conventional LMD and FGM deposition. A single-powder system can build a uniform material. A multi-powder or multi-hopper system can vary the feed ratio between materials, enabling graded compositions.

Important powder feeding considerations include:

- calibration of feeder mass flow rate;

- response time when changing feeder settings;
- powder flow stability;
- compatibility between powder size, morphology and feeder design;
- carrier gas flow rate;
- risk of segregation in powder blends;
- residual powder capture and cleaning between materials.

For SEAMAC, the relevant powder size range identified in the project material is 40-150 micrometres for LMD. This range connects the powder preparation work in Module 2 to the process behaviour discussed in Module 3.

Nozzle and Powder-Laser Alignment

The nozzle must deliver powder into the region where the laser creates the melt pool. Poor alignment can lead to low powder catchment efficiency, asymmetric tracks, unmelted particles, excessive spatter or unstable deposition.

Training checks for nozzle setup should include:

- powder stream focus relative to the laser focus;
- stand-off distance between nozzle and workpiece;
- coaxial or lateral powder delivery configuration;
- powder flow symmetry;
- shielding gas coverage;
- collision risk along the planned toolpath.

In FGM experiments, nozzle and feeder behaviour must also be checked after material changes because different powders may not flow identically through the same setup.

Motion System and Workholding

The motion system defines the deposition path. Depending on the equipment, motion may be provided by moving the laser head, moving the workpiece, or combining both. Path accuracy, speed stability and repeatable layer height are essential for building multi-layer structures.

Workholding must keep the substrate stable while allowing access for the deposition head and shielding gas. For LMD on cast iron or tool-related substrates, fixturing should also account for heat accumulation, distortion and the possibility of preheating or controlled cooling if required by the experimental plan.

Experimental Setup Documentation

Each LMD experiment should record enough information for later interpretation. A practical setup record should include:

Item	What to Record
Machine	LMD system, laser type, nozzle type and motion platform
Optics	beam diameter, focal position and beam configuration
Powders	material, batch, size range and blend ratio
Feeder setup	feeder calibration, hopper assignment and gas flow
Substrate	material, geometry, surface preparation and preheat condition
Path	track length, overlap, layer plan and deposition direction
Environment	shielding gas type, flow rate and relevant enclosure

	conditions
Monitoring	sensors used, acquisition settings and observations

Without this documentation, it is difficult to relate defects or microstructural changes to the actual process conditions.

Key Process Parameters

LMD process parameters determine how much energy and material enter the melt pool and how the deposited track solidifies. In SEAMAC, parameter understanding is needed because the process must handle both individual powders and powder mixtures across a cast-iron to maraging-steel material transition.

The most important parameters should not be treated independently. Laser power, travel speed, powder mass flow, beam diameter, layer height and track overlap interact through heat input, melt pool size, dilution and cooling rate.

Main Parameter Groups

The core LMD parameters are:

- laser power;
- beam diameter or spot size;
- beam intensity distribution;
- travel or feed speed;
- powder mass flow rate;
- carrier gas flow rate;
- shielding gas flow rate;
- nozzle stand-off distance;
- layer height or z-increment;
- hatch spacing or track overlap;
- deposition direction and path sequence;
- substrate temperature or preheating condition.

For FGM deposition, additional variables are needed:

- powder blend ratio;
- number of feeder channels;
- feeder response time;
- gradient function;
- composition step size;
- layer or track location where the feed ratio changes.

Laser Power and Energy Input

Laser power controls the available energy for melting the substrate and powder. Too little energy can cause lack of fusion, poor bonding or unmelted powder. Too much energy can increase dilution, enlarge the heat-affected zone, increase residual stress or promote keyhole-related porosity in some conditions.

The training source on process simulation shows that increasing laser power increases melt temperature and time above melting. This can improve dissolution of particles but also changes melt depth and local composition. In a graded material, this means the same power setting may not be equally suitable for all blend ratios.

Travel Speed

Travel speed controls interaction time between the laser and the workpiece. At constant power, slower motion generally increases heat input per unit length, while faster motion reduces the time available for melting and mixing.

Travel speed influences:

- bead width and height;
- melt pool length and depth;
- dilution;
- cooling rate;
- microstructure;
- track continuity;
- residual stress and distortion.

Very high travel speed may cause discontinuous tracks or insufficient melting. Very low travel speed may overheat the workpiece, increase dilution or produce excessive build-up.

Powder Mass Flow

Powder mass flow determines how much material is delivered to the melt pool. If powder flow is too low, the track may be shallow or discontinuous. If powder flow is too high relative to laser energy, particles may remain unmelted, the melt pool may become unstable, and powder catchment efficiency may decrease.

In a multi-powder FGM experiment, the total powder mass flow and the individual feeder contributions both matter. For example, a nominal 50/50 composition only has meaning if both feeders are calibrated and the actual delivered mass flow is stable during deposition.

Track Geometry and Overlap

Single-track experiments are useful for defining an initial process window. Track width, height, penetration depth and dilution provide quick feedback on whether the selected parameters are reasonable.

For layers and walls, the overlap between adjacent tracks affects:

- layer flatness;
- remelting of neighbouring tracks;
- porosity between tracks;
- surface roughness;
- heat accumulation;
- dimensional accuracy.

A stable single track does not automatically guarantee a stable multi-track or multi-layer build. Heat accumulation changes as the part grows, so parameters may need to be validated at the intended build scale.

Parameter Window Development

A practical LMD parameter development sequence is:

1. Check powder flow and nozzle alignment without laser exposure.
2. Deposit single tracks on the target substrate.

3. Measure track width, height, penetration and dilution.
4. Inspect for pores, cracks, lack of bonding and unmelted particles.
5. Build overlapping tracks to form a layer.
6. Build multi-layer walls or blocks.
7. Repeat for selected powder blend ratios.
8. Use microscopy and hardness measurements to evaluate the material response.

In SEAMAC, this sequence should be applied to individual powders and selected mixtures before attempting the full gradient. The project source explicitly identifies laser beam power, powder mass flow, feed rate and density distribution as parameters to investigate for deposited single and multiple layers.

Practical Parameter Record

For each deposited sample, record:

Parameter	Unit or Description
Laser power	W
Beam diameter	mm
Travel speed	mm/min or mm/s
Powder mass flow	g/min per feeder
Carrier gas flow	L/min
Shielding gas flow	L/min
Stand-off distance	mm
Track overlap	% or mm
Layer height	mm
Substrate condition	material, preparation and temperature
Blend ratio	nominal and measured if available
Observed stability	qualitative notes and monitoring signals

This record should be linked to the powder batch record from Module 2 and the characterisation results from later modules.

11.3 Deposition Strategies for FGMs

Functionally graded materials require more than depositing one material after another. The deposition strategy must define how composition changes spatially, how the laser path manages heat input, and how the process avoids abrupt microstructural or mechanical discontinuities.

In SEAMAC, the main material direction is a transition from cast iron or iron-based material toward maraging tool steel. This transition is challenging because weldability, carbon equivalent, phase formation and cracking risk must be considered together with track geometry and surface condition.

Gradient Function

The gradient function defines how the material ratio changes through the build. The SEAMAC project source identifies several functions for investigation:

- linear;
- progressive;
- regressive;
- discrete stepwise;

- direct transition for comparison.

A linear gradient changes composition at a constant rate. A progressive or regressive gradient changes slowly in one region and faster in another. A discrete gradient uses a finite set of material ratios, such as 100/0, 75/25, 50/50, 25/75 and 0/100. The selected function should reflect the scientific question, machine capability and expected metallurgical risk. The main strategy variables are summarised earlier in table above.

Layer-Wise and Track-Wise Transitions

Composition can be changed between layers, between tracks or within a continuous track if the feeder system supports dynamic control. Each approach has trade-offs.

Strategy	Advantages	Risks
Layer-wise steps	easier to document and characterise	interfaces may remain compositionally abrupt
Track-wise changes	supports lateral gradients	path planning and heat history become more complex
Continuous feeder change	closer to smooth FGM concept	feeder response and actual composition may lag the command
Pre-blended powders	simple feeder control	more powder batches and handling steps

For early SEAMAC training samples, discrete layer-wise or wall-based gradients are useful because they are easier to inspect. More complex deposition paths can be added once powder behaviour and process windows are understood.

Deposition Direction and Path Planning

The grant material describes previous UL work comparing bidirectional continuous deposition and unidirectional continuous deposition for a stainless steel to Inconel 718 gradient. Visible differences in geometry, porosity and cracking were observed between strategies. This is an important training point: the same nominal powder gradient and parameter set can produce different results if the path changes heat accumulation and remelting.

Deposition strategy should therefore define:

- travel direction for each track;
- whether the path is bidirectional or unidirectional;
- start and stop locations;
- dwell time between tracks or layers;
- interlayer cooling time;
- build orientation;
- overlap and offset pattern;
- whether central, edge-first or alternating paths are used.

For wall builds, bidirectional and unidirectional strategies may create different thermal histories. For blocks or surfaces, hatch rotation and track sequencing can influence residual stress and geometry.

Cooling and Heat Accumulation

Heat accumulation changes the process as the build height increases. A parameter set that works on a cold substrate may create excessive heat input after several layers. Conversely, too much cooling can increase thermal gradients and cracking risk.

Cooling strategy may include:

- controlled interlayer delay;
- substrate preheating;
- active or passive cooling;
- monitoring interpass temperature;
- adapting power or travel speed by layer;
- limiting build height per sequence.

For cast iron to maraging steel transitions, cooling strategy is especially important because carbon-rich regions and hard phases can increase cracking susceptibility.

Dilution-Aware Gradient Planning

The intended powder ratio is not identical to the final local composition. Dilution from the substrate and previous layers changes the chemistry of the solidified material. This can be useful if gradual mixing is desired, but it can also blur the planned gradient.

A dilution-aware plan should:

- expect remelting of the previous layer;
- measure actual composition where possible;
- avoid interpreting nominal powder feed ratio as final composition without verification;
- compare cross-sections against the planned gradient;
- adjust powder ratios or layer sequence if the transition is too sharp or too diffuse.

This is a key reason why LMD, simulation and characterisation must be connected in the SEAMAC toolkit.

The measured SS316L-In718 example shown earlier in Figure 7 illustrates why chemical verification is needed: the final composition trend should be checked against the intended powder-feed or layer sequence rather than assumed from nominal settings alone.

Suggested Demonstrator Sequence

A practical training sequence for FGM deposition is:

1. Deposit reference tracks of each individual powder.
2. Deposit selected blend ratios on the same substrate.
3. Build small walls for each ratio to observe multi-layer behaviour.
4. Build a discrete gradient wall using a limited number of ratios.
5. Compare bidirectional and unidirectional deposition.
6. Section the samples and measure geometry, dilution, microstructure and hardness.
7. Use the results to refine powder ratios, path strategy and cooling approach.

This sequence keeps the experiment manageable while still exposing the main variables that control FGM quality.

11.4 Process Stability, Monitoring and Quality Control

Process stability in LMD means that the laser, powder stream, melt pool and motion system remain coordinated throughout deposition. A stable process produces continuous tracks with predictable geometry, acceptable dilution and no obvious defects. An unstable process

may show spatter, inconsistent bead shape, lack of fusion, pores, cracks or unmelted particles.

For SEAMAC, stability is especially important because the process must remain controlled while the material composition changes. Each powder ratio can behave like a different alloy with different melting behaviour, absorptivity, thermal conductivity and flow characteristics.

Stability Indicators

Useful indicators of LMD stability include:

- consistent melt pool size and brightness;
- steady powder stream;
- regular track width and height;
- absence of excessive spatter;
- absence of discontinuities or balling;
- repeatable layer height;
- stable sound and plume behaviour;
- no visible oxidation or soot-like deposits;
- no sudden change in powder catchment.

These observations should be recorded during experiments. Even qualitative notes are useful when linked to sample numbers, parameter sets and later microscopy.

Monitoring Methods

Monitoring can range from simple operator observation to instrumented process measurement. Possible approaches include:

- visible camera imaging;
- high-speed imaging;
- infrared or thermal imaging;
- pyrometry;
- melt pool imaging;
- acoustic or vibration sensing;
- laser power and machine signal logging;
- powder feeder signal logging;
- shielding gas flow logging;
- layer geometry measurement after deposition.

The FGM literature reviewed for the toolkit identifies in-situ and real-time monitoring as an important development area for additive manufacturing. For training, the immediate goal is not full closed-loop control, but disciplined observation and data capture.

Quality Control During Parameter Development

Quality control should begin with simple checks before complex builds are attempted. A practical sequence is:

1. Confirm powder batch, sieve condition and feeder calibration.
2. Verify nozzle alignment and powder flow.
3. Deposit single tracks and inspect geometry.
4. Section selected tracks to measure dilution and bonding.
5. Deposit multi-track layers and inspect overlap regions.
6. Deposit multi-layer walls or blocks.

7. Record process observations and link them to microscopy and hardness results. This sequence reduces the risk of discovering fundamental powder or parameter problems only after a full FGM demonstrator has been built.

Data to Capture

A useful LMD quality record should include:

Data Type	Examples
Input data	powder batch, blend ratio, substrate, parameter set
Machine data	laser power, speed, feeder commands, gas flows
Observations	melt pool stability, spatter, colour, powder stream behaviour
Geometry	bead width, bead height, layer height, wall straightness
Metallurgy	dilution, porosity, cracks, phase indications, microstructure
Properties	hardness, roughness, residual stress or mechanical test results

For SEAMAC, these records should also support feedback into post-processing. LMD surface condition and geometry influence how later plasma electrolytic polishing behaves.

Feedback and Parameter Adjustment

When instability is observed, parameter changes should be made systematically. Changing many variables at once makes interpretation difficult.

Typical adjustments include:

- increasing laser power if fusion is insufficient;
- reducing powder flow if unmelted particles appear;
- reducing travel speed if tracks are discontinuous;
- increasing travel speed or reducing power if dilution or heat input is excessive;
- changing overlap if pores appear between tracks;
- adding interlayer cooling if heat accumulation is excessive;
- changing feeder calibration if composition or track size drifts.

For FGM samples, the same adjustment may not work across all blend ratios. A composition-dependent parameter map may be needed.

Quality Control Checkpoints

Recommended checkpoints for Module 3 training samples are:

- **before deposition:** powder documentation, substrate preparation, feeder calibration and nozzle alignment;
- **during deposition:** process observation, monitoring signal capture and abnormal event notes;
- **after deposition:** visual inspection, dimensional measurement and surface condition;
- **after sectioning:** dilution, bonding, porosity, cracks and microstructure;

- **after property testing:** hardness, roughness and selected mechanical or residual stress results.

These checkpoints prepare the learner for the later characterisation and troubleshooting modules.

11.5 Typical Defects and Their Causes

LMD defects can originate from powder quality, parameter selection, equipment setup, material incompatibility, deposition strategy or heat accumulation. For FGMs, defect risk increases because the material properties change through the build and each composition can respond differently to the same process settings.

This section introduces the main defect types that learners should recognise before moving to detailed troubleshooting and characterisation.

Lack of Fusion and Poor Bonding

Lack of fusion occurs when the substrate, previous layer or adjacent track is not melted sufficiently to create a continuous metallurgical bond. It may appear as unbonded interfaces, gaps between tracks or weak interlayer regions.

Common causes include:

- insufficient laser power;
- excessive travel speed;
- too large a stand-off distance or poor focusing;
- insufficient track overlap;
- oxide or contamination on the substrate;
- powder flow that absorbs energy without fully melting;
- inadequate remelting of the previous layer.

In FGM builds, lack of fusion may occur only at selected blend ratios if the powder mixture changes absorptivity or melting behaviour.

Porosity

Porosity can appear as gas pores, lack-of-fusion pores or pores associated with unstable melt pool behaviour. It reduces effective cross-section and can act as a crack initiation site.

Potential causes include:

- gas entrapment in the melt pool;
- moisture or contamination in powder;
- excessive turbulence or keyhole-like behaviour;
- unstable powder delivery;
- insufficient shielding;
- pores inherited from previous layers;
- inappropriate overlap or layer height.

The SEAMAC grant material notes porosity as an issue in previous buffer-layer and LMD-related work, and the process simulation sources connect melt pool behaviour with gas porosity risks in laser-based AM.

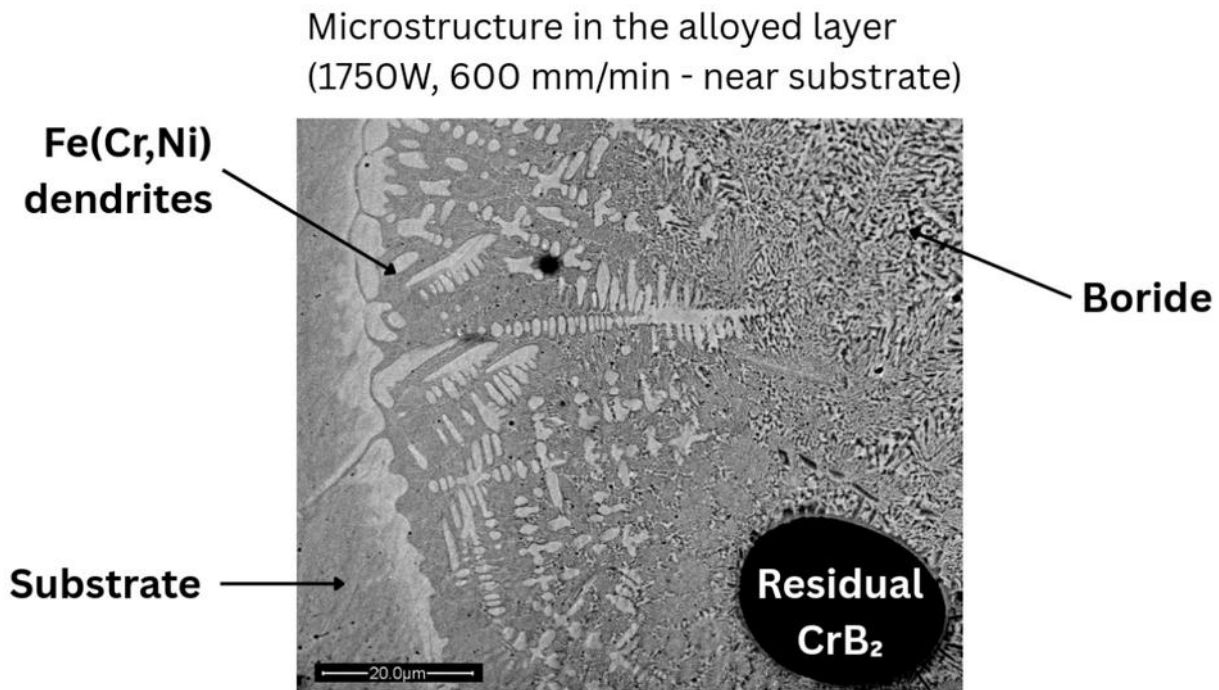


Figure 12: The substrate serves as a heat-sink resulting in a high temperature gradient perpendicular to the melt/substrate interface. Since $k_0 = 0$ plane solidification does not exist. The high G/V resulted in directional solidification of the α -Fe dendrites.

Cracking

Cracking is a critical risk when depositing crack-sensitive metals or dissimilar material combinations. Cast iron is especially challenging because high carbon content can promote hard phases and cracking during cooling.

Cracking can be driven by:

- high residual stress;
- steep thermal gradients;
- brittle phase formation;
- abrupt composition changes;
- excessive hardening in the heat-affected zone;
- poor compatibility between substrate and deposit;
- insufficient preheating or uncontrolled cooling.

The SEAMAC material direction from cast iron toward maraging steel therefore requires careful control of powder blend design, gradient function, heat input and cooling strategy.

Unmelted Powder and Inclusions

Unmelted powder inclusions occur when particles enter the deposit without fully melting or dissolving. They may result from insufficient energy, excessive powder flow, poor powder-laser alignment or powder constituents with different melting behaviour.

In multi-material gradients, this defect can appear if one powder needs more heat input than another. Literature on additive grading notes that a single parameter set may be unsuitable across a full composition gradient because each intermediate composition behaves differently.

Excessive Dilution

Dilution is necessary for bonding, but excessive dilution changes the intended local composition. In an FGM, this can move the actual gradient away from the planned gradient.

Excessive dilution may be caused by:

- high laser power;
- low travel speed;
- small beam diameter with high energy density;
- repeated remelting;
- excessive overlap;
- heat accumulation in multi-layer builds.

The result may be a broader transition zone than expected, unexpected phases or local hardness changes.

Geometry and Surface Defects

LMD parts often require post-processing because track-wise and layer-wise deposition creates surface waviness and roughness. Geometry defects can include:

- excessive bead height;
- underfilled regions;
- waviness;
- layer height drift;
- wall leaning;
- edge build-up;
- rough sidewalls;
- partially attached powder.

These features matter for SEAMAC because later PeP post-processing depends on the initial surface morphology and local material composition.

Defect Prevention Checklist

Before building an FGM demonstrator, check:

- powder batches are dry, documented and within the intended size range;
- feeder calibration is verified for each powder;
- laser focus and nozzle alignment are checked;
- single-track tests show stable bonding and geometry;
- selected blend ratios have been tested before full-gradient deposition;
- heat accumulation is managed by path planning or interlayer delay;
- substrate preparation is consistent;
- shielding gas coverage is adequate;
- monitoring and sample identification are ready.

Defects should not be interpreted only from visual appearance. Cross-section microscopy, chemical analysis, hardness mapping and surface measurement are needed to connect process cause to final material condition.

12 Module 4: Post-Processing by Plasma Electrolytic Polishing

12.1 Purpose of Post-Processing

Additively manufactured metal parts rarely leave the machine in a condition that is ready for final use. In the AM process chain, laser metal deposition (LMD) creates the graded material, but post-processing is needed to improve surface quality, dimensional condition and functional reliability.

Post-processing is especially important for LMD because the process produces overlapping tracks and layers. The resulting surface can show waviness, partially attached particles, local oxide, rough sidewalls and transitions between differently remelted regions. These features influence later measurement, fatigue behaviour, corrosion response and the ability to use the demonstrator in an industrially relevant environment.

In SEAMAC, post-processing is not treated as a cosmetic final step. It is part of the technical process chain:

- powder selection and blending define the material system;
- LMD creates the graded deposit;
- post-processing modifies the as-built surface and near-surface condition;
- characterisation checks whether the process chain produced the intended geometry, surface and material response.

Plasma electrolytic polishing (PeP) is central in this context because it can process complex metallic surfaces without relying only on mechanical tool access. This makes it relevant for AM parts, where curved surfaces, internal transitions and locally varying surface orientations are common.

For functionally graded materials, post-processing must be evaluated carefully. A surface may include regions with different alloy composition, microstructure, hardness, oxide behaviour or electrochemical response. A parameter set that works on one part of the gradient may be unsuitable for another. This is why SEAMAC treats PeP as an integrated research and training topic rather than as a fixed finishing recipe.

The training objective is that users understand why post-processing is needed, which surface features it can improve, and which risks must be checked before transferring a PeP process from a uniform alloy to an LMD-produced FGM.

12.2 Principles of Plasma Electrolytic Polishing

Plasma electrolytic polishing is an electrochemical surface finishing process for electrically conductive workpieces. The workpiece is placed in an electrolyte and connected to a power supply. At suitable voltage and electrolyte conditions, a gas-vapour envelope forms around the surface and plasma-assisted processes occur in this near-surface region.

The process combines several effects:

- electrolytic dissolution of metal from the surface;
- local plasma activity in the gas-vapour envelope;
- heat generation and transport through the electrolyte;
- chemical interaction between electrolyte and workpiece material;

- preferential smoothing of microscopic peaks when the process window is suitable.

The TUBAF training material emphasises that PeP is highly dynamic. Current, electrolyte temperature, electrolyte conductivity, workpiece geometry, local surface area and electrolyte flow all influence the process. The current response is therefore not only an electrical signal; it is also a practical indicator of how the surface and electrolyte are behaving during polishing.

Compared with purely mechanical finishing, PeP can act on surfaces that are difficult to reach with a tool. Compared with conventional electropolishing, PeP operates in a higher-voltage regime where the gas-vapour envelope and plasma effects are part of the process mechanism.

The main technical idea for training purposes is that PeP does not remove material uniformly in all situations. Material removal depends on:

- local current density;
- electrolyte chemistry and conductivity;
- temperature and flow;
- workpiece orientation and movement;
- initial roughness and real surface area;
- alloy composition and oxide behaviour.

For AM and FGM parts, this means that the initial LMD surface topology matters. Peaks, valleys, partially attached particles and local composition changes can all affect the polishing result. Successful PeP therefore requires both process control and post-process measurement.

12.3 PeP Equipment and Test Rig

A PeP setup requires a controlled electrical, chemical and thermal environment. The exact machine design can vary, but the main functional elements are consistent across laboratory and training systems.

Typical equipment elements include:

- a power supply suitable for the PeP voltage and current range;
- an electrolyte tank or local electrolyte delivery system;
- electrical connection to the workpiece;
- a counter-electrode or cathodic contact arrangement;
- temperature measurement and cooling or heating control;
- electrolyte circulation, filtration or directed flow where needed;
- fixtures for workpiece positioning, orientation and safe handling;
- safety systems for high voltage, hot electrolyte and chemical exposure.

The SEAMAC grant material identifies a PeP test rig as part of the project development path at UL, supported by TUBAF expertise. The planned capability includes immersion-based PeP for whole-part processing and electrolyte jet-based PeP for more selective surface processing.

In training, the test rig should be introduced as a process system rather than only as a machine. Learners should connect the physical components to the process variables they control:

- power supply settings control voltage and influence current response;

- electrolyte composition and temperature influence conductivity and material removal;
- flow and movement influence local polishing uniformity;
- fixtures influence contact quality, orientation and reproducibility;
- measurement devices provide feedback for parameter adjustment.

For LMD-produced FGMs, test-rig planning must also consider sample traceability. The sample should be labelled so that its material gradient direction, deposition history and intended measurement locations remain clear before and after PeP.

12.4 Electrolyte Selection and Process Parameters

Electrolyte selection is one of the most important decisions in PeP. The electrolyte must support surface smoothing and material removal for the workpiece material without causing uncontrolled etching, unstable process behaviour or unacceptable surface damage.

The TUBAF training sources emphasise that electrolyte chemistry, conductivity, temperature and lifetime influence PeP results. A suitable electrolyte for one alloy may not work for another alloy. This is a central issue for SEAMAC, because FGM surfaces may expose more than one material response along the same part.

Important process parameters include:

- applied voltage;
- current and current density;
- electrolyte composition and pH;
- electrolyte conductivity;
- electrolyte temperature;
- electrolyte flow and movement relative to the surface;
- processing time;
- workpiece orientation and exposed surface area;
- pre-cleaning and post-cleaning procedure.

Parameter selection should begin with small, documented trials. The initial objective is not only to obtain a shiny surface, but to identify a stable processing window. A useful window should produce measurable roughness reduction while avoiding excessive material removal, edge rounding, pitting, matte etching or local attack.

For FGM demonstrators, parameter selection should include checks at different positions along the gradient. If the surface composition changes from one alloy system toward another, a single electrolyte and voltage setting may polish one region more strongly than another. In some cases, multi-step processing or different electrolyte strategies may be needed.

All PeP trials should record the initial surface state, material, electrolyte, temperature, voltage, current response, time, sample orientation and post-processing treatment. These records are needed for comparison with surface and metallographic characterisation.

12.5 Challenges in PeP of FGMs

PeP of functionally graded materials is more complex than PeP of a uniform alloy. The surface may include gradual or stepwise changes in chemical composition, microstructure, hardness, oxide formation and electrochemical behaviour. These changes can alter local current density and material removal.

Key challenges include:

- different polishing rates along the material gradient;
- local pitting or etching if one composition is more sensitive to the electrolyte;
- non-uniform gloss or colour after processing;
- preferential attack of specific phases or microstructural regions;
- edge rounding or loss of dimensional accuracy in small features;
- difficulty separating PeP effects from the original LMD surface topology.

Initial surface state is especially important. LMD surfaces can include ridges, valleys, spatter, partially melted powder and heat-affected regions. PeP may smooth microscopic peaks, but it cannot be assumed to correct every macroscopic geometry error. The process must therefore be linked to the actual as-built topology.

Multi-material PeP also raises practical questions about process sequence. A single electrolyte may be acceptable if all exposed materials respond similarly. If not, the process may require modified electrolyte chemistry, shorter processing time, multiple steps, masking, local jet processing or a different pre-finishing strategy.

The training goal is to prevent learners from treating PeP as a universal finishing operation. For SEAMAC FGMs, every PeP trial should be linked to composition mapping, surface measurement and visual inspection at multiple positions along the graded region.

12.6 Surface Integrity and Quality Assessment

Surface integrity after PeP must be assessed with more than visual appearance. Gloss and colour can indicate whether a surface has changed, but they do not fully describe roughness, material removal, local attack, dimensional change or near-surface condition.

Relevant assessment methods include:

- visual inspection before and after polishing;
- optical microscopy for local surface features;
- confocal or optical profilometry for surface topography;
- tactile roughness measurement where the geometry allows it;
- mass or dimensional change for material removal estimation;
- cross-section microscopy when near-surface effects must be checked;
- chemical or phase analysis if selective attack is suspected.

For AM parts, surface assessment should distinguish between macroscopic geometry and surface texture. PeP can reduce roughness, but the measured result depends on the selected filter length, measurement direction and region of interest. LMD tracks can be directional, so measurement orientation should be recorded.

For FGMs, the measurement plan should cover several material regions. At minimum, the initial material, intermediate gradient and final material region should be checked when accessible. This helps identify whether PeP acted uniformly or whether one composition was polished more strongly.

A practical PeP quality record should include:

- sample identification and material state;
- LMD process context or link to the build record;
- pre-PeP surface condition;
- PeP parameters and current response;
- post-PeP cleaning procedure;

- surface roughness or topography values;
- visual or microscopic observations;
- interpretation of whether the polishing result supports the intended use.

13 Module 5: Characterisation and Evaluation of Manufactured Parts

13.1 Metallographic Characterisation

Metallographic characterisation prepares and examines cross-sections so that the internal condition of the manufactured part can be assessed. In SEAMAC, it connects powder preparation, LMD deposition, PeP post-processing and final quality evaluation.

For LMD-produced FGMs, metallography should show whether the deposit is continuous and whether layers and tracks are bonded. It should also reveal whether the graded region contains cracks, pores, unmelted particles or unexpected interfaces.

A typical metallographic workflow includes:

- select the sampling location and record the gradient direction;
- section the sample without damaging the region of interest;
- mount the specimen if needed;
- grind and polish through suitable steps;
- etch when phase or grain contrast is needed;
- examine with optical or electron microscopy;
- document magnification, position and orientation.

Sampling strategy is critical. A single cross-section may not represent the full demonstrator. For an FGM, at least one section should capture the intended material transition. Additional sections may be needed near start and stop regions, changes in deposition strategy, or locations with visible surface defects.

Metallographic results should be interpreted together with process records. Pores, lack of fusion, cracks and dilution patterns cannot be fully understood without knowing the LMD parameters, powder ratio, track overlap, heat accumulation and substrate condition.

13.2 Microstructural and Phase Analysis

Microstructural and phase analysis explains how the process history shaped the material. In laser-based AM, rapid heating and cooling can produce fine microstructures, non-equilibrium phases, segregation, residual stress and local variation across tracks and layers.

For SEAMAC FGMs, analysis should consider both spatial position and material composition. The microstructure may change because the powder blend changes, because heat input changes, or because the local composition affects solidification. A correct interpretation therefore needs both process knowledge and composition awareness.

Relevant methods include:

- optical microscopy for general microstructure and defect overview;
- scanning electron microscopy for higher-resolution morphology and phase contrast;
- energy-dispersive X-ray spectroscopy for local composition trends;
- X-ray diffraction for phase identification;
- electron backscatter diffraction where crystallographic texture or grain orientation is important;
- hardness mapping as a practical indicator of local microstructural change.

Phase analysis is especially relevant when dissimilar materials are combined. Intermediate compositions can form phases that are not present in either base material. These phases may affect cracking tendency, hardness, corrosion behaviour or PeP response.

The interpretation should avoid treating each measurement as isolated. Composition maps, micrographs and hardness profiles should be aligned with the build direction, gradient direction and intended powder-feed strategy. This makes the data useful for improving LMD parameters and post-processing choices.

13.3 Mechanical Characterisation

Mechanical characterisation checks whether the manufactured material can support the required loading conditions. In SEAMAC, this is relevant because LMD processing, graded composition and post-processing can all influence mechanical response.

Important mechanical properties include:

- hardness and hardness gradients;
- tensile behaviour where specimen geometry allows it;
- local strain response;
- fracture behaviour;
- fatigue resistance for cyclic loading applications;
- residual stress where it affects cracking or distortion.

For early FGM demonstrators, hardness mapping is often one of the most practical methods. It can be applied across a cross-section and compared with the intended material gradient. A smooth hardness transition may indicate successful grading, while abrupt changes may reveal mixing problems, phase formation or dilution effects.

Tensile and fatigue tests require careful specimen design. A graded material may not have a single uniform gauge region, so the test result depends on where the gradient is placed and how failure initiates. Test reports should therefore describe specimen orientation, gradient direction, build direction and post-processing state.

Mechanical results should be interpreted with metallography. A low strength or premature failure may be caused by lack of fusion, porosity, cracking, brittle phases, rough surface condition or residual stress. Without microstructural evidence, mechanical data alone can be misleading.

13.4 Surface Roughness and Geometrical Assessment

Surface roughness and geometry are key outputs of the LMD and PeP process chain. LMD creates the initial surface, while PeP and other post-processing methods modify it. Both stages must be measured if the process chain is to be improved.

Surface roughness assessment may include:

- tactile roughness measurement;
- optical profilometry;
- confocal microscopy;
- area-based surface texture parameters;
- before-and-after comparison at the same location.

Geometrical assessment may include:

- dimensional measurement of feature size;

- track height and wall width;
- waviness and form deviation;
- edge rounding after PeP;
- comparison with CAD or intended geometry;
- local material removal estimation.

AM surfaces are often directional. The measured roughness can differ depending on whether the measurement crosses or follows deposition tracks. The report should state measurement direction, cut-off or filter settings, scanned area and whether loose particles or outliers were removed from the analysis.

For PeP, surface measurement should also check whether improvement in roughness came at the cost of excessive material removal. A surface can become smoother while losing sharp edges or changing dimensions. This tradeoff is especially important for industrial parts and small demonstrators.

For FGMs, measurements should cover representative regions along the gradient because different materials may polish differently.

13.5 Interpretation of Results for Process Improvement

Characterisation is useful only if the results are linked back to process decisions. In SEAMAC, the main improvement loop connects powder preparation, LMD parameters, deposition strategy, PeP settings and final measurements.

A practical interpretation workflow is:

1. Define the intended result before manufacturing.
2. Record powder batches, blend ratios and LMD parameters.
3. Measure geometry, surface and microstructure after deposition.
4. Apply post-processing with documented parameters.
5. Measure the same or equivalent regions after post-processing.
6. Compare the result with the intended gradient and surface requirements.
7. Adjust process parameters, deposition strategy or PeP conditions.

When a defect or unexpected property appears, the interpretation should consider the full chain. A crack may reflect material incompatibility, excessive cooling rate or residual stress. High roughness may reflect LMD track geometry rather than PeP failure. Non-uniform polishing may reflect a composition change rather than poor operator technique.

For training, results should be discussed in terms of cause, evidence and next action. This helps learners move from observation to process improvement:

- observation: what was measured or seen;
- evidence: which data support the interpretation;
- likely cause: which process step could explain it;
- next action: which parameter or procedure should be tested next.

This approach supports both researcher onboarding and industry-oriented education because it treats characterisation as a decision tool rather than as a final report section.

14 Module 6: Defects, Risks and Troubleshooting

14.1 Common Defects in LMD of FGMs

Common LMD defects include porosity, lack of fusion, cracking, unmelted particles, excessive dilution, oxidation and geometry errors. Module 3 introduced these defects from the process perspective. This section focuses on how they appear in FGM production and why they require special attention.

In FGM builds, the material response changes across the part. A parameter set that produces stable tracks for one powder ratio may become unstable at another ratio. This can create local defects only in part of the gradient.

Important defect mechanisms include:

- insufficient energy input causing lack of fusion;
- excessive energy input causing deep dilution or keyhole-related porosity;
- unstable powder flow causing composition or bead-height variation;
- abrupt composition changes causing cracking or brittle phase formation;
- heat accumulation causing geometry drift and microstructural change;
- poor shielding or contamination causing oxide-related defects.

Defect evaluation should record the location relative to the build direction and gradient direction. This helps determine whether the defect is random, associated with a process transition, or linked to a specific composition range.

The most useful troubleshooting evidence combines visual inspection, cross-section microscopy, composition measurement and process records. A defect should not be classified only from surface appearance.

14.2 Common Issues in PeP Post-Processing

PeP post-processing can improve surface condition, but incorrect process selection can create new problems. Common issues include non-uniform polishing, excessive material removal, edge rounding, pitting, matte etching, staining, water spots, local overheating and poor repeatability.

The causes can be electrical, chemical, thermal or geometrical:

- electrolyte unsuitable for the material;
- electrolyte conductivity or temperature outside the useful range;
- voltage or processing time too high;
- poor electrical contact;
- insufficient or non-uniform electrolyte flow;
- unfavourable part orientation;
- large variation in initial surface roughness;
- different material response along an FGM surface.

For multi-material or graded parts, a visible surface difference after PeP is an important warning. It may indicate that one material region polished faster, etched more strongly or formed a different oxide condition. This should trigger local roughness measurement and microscopy rather than immediate parameter reuse.

Troubleshooting PeP should begin with a documented comparison of before and after states. The operator should check whether the issue is local or global, whether it follows

geometry, whether it follows material composition, and whether the current response was stable.

14.3 Risk Factors in Process Integration

The SEAMAC process chain combines powder blending, LMD, PeP and characterisation. Risk increases when information is lost between steps or when one process is optimised without considering the next one.

Important integration risks include:

- powder blend documentation missing or incomplete;
- LMD parameters not linked to sample identifiers;
- gradient direction not marked before sectioning or PeP;
- post-processing applied without knowing the as-built surface state;
- PeP parameters selected for a uniform alloy and transferred directly to an FGM;
- characterisation performed at locations that do not represent the critical region;
- surface measurement made without recording direction or filter settings;
- results interpreted without considering the full process history.

A common integration problem is treating each step as a separate task. For example, an LMD operator may optimise for stable deposition, while the PeP operator later receives a sample with unknown material distribution and roughness. The result may be difficult to interpret even if both operations were performed carefully.

The risk-control measure is traceability. Each sample should carry a clear record of powder, LMD parameters, gradient orientation, post-processing parameters and measurement locations. This is especially important in training, where multiple learners may handle the same sample at different stages.

14.4 Troubleshooting Guidelines

Troubleshooting should be evidence-based and should change one major variable at a time where possible. The goal is not only to remove a defect, but to understand which process step caused it.

A practical troubleshooting sequence is:

1. Identify the symptom and location.
2. Check whether the issue follows geometry, build direction or gradient direction.
3. Review powder, LMD and PeP records.
4. Inspect the surface and cross-section where appropriate.
5. Compare with reference samples or earlier parameter sets.
6. Select one corrective action.
7. Repeat the trial with improved documentation.

Typical corrective actions include:

- adjust laser power, travel speed or powder feed for LMD instability;
- modify overlap or layer strategy for lack of fusion;
- reduce heat accumulation through path planning or dwell time;
- smooth the initial surface before PeP if the as-built topology is too severe;
- change electrolyte, voltage, temperature or processing time for PeP issues;
- add measurement locations along the gradient if the defect is composition-dependent.

Failure analysis training emphasises the need to collect findings before forming conclusions. In SEAMAC, this means preserving sample identity, recording observations and avoiding uncontrolled rework before the defect is documented.

The troubleshooting output should be a short technical record: symptom, evidence, likely cause, corrective action and result. This record becomes part of the training material for future users.

15 Module 7: Training Delivery and Knowledge Transfer Methods

15.1 Recommended Training Formats

SEAMAC training should combine short theory sessions, guided demonstrations, hands-on work and interpretation of real process results. The project sources describe virtual training, on-site training, staff exchanges, expert visits, joint summer schools and industry-oriented workshops as complementary knowledge-transfer routes.

Recommended formats include:

- introductory lectures for shared vocabulary;
- laboratory demonstrations for equipment familiarisation;
- hands-on practical sessions with supervised sample preparation or measurement;
- case-study discussions based on LMD, PeP and characterisation results;
- train-the-trainer sessions for staff who will later teach others;
- industry-oriented workshops focused on process chains and application relevance;
- short virtual sessions for preparation, follow-up and troubleshooting.

The format should match the audience. Researchers need enough technical depth to plan experiments and interpret results. Industry participants need a clear connection between process capability, quality risks and application value. New students need a structured path from AM fundamentals toward the full SEAMAC process chain.

The strongest format is a blended sequence: preparatory reading, short theory, practical demonstration, measurement exercise and group interpretation. This mirrors the way AM process knowledge is used in practice.

15.2 Suggested Structure for Technical Training Sessions

A technical training session should move from context to action to interpretation. This helps learners understand not only what to do, but why each step matters.

A recommended session structure is:

1. State the learning objective and process context.
2. Introduce the relevant theory and terminology.
3. Show the equipment, sample or dataset.
4. Demonstrate the procedure.
5. Let participants perform a guided task where feasible.
6. Record observations and measurements.
7. Interpret the result as a group.
8. Connect findings to process improvement and safety.

For example, an LMD session can begin with process parameters and melt-pool stability, then show track examples and end with a defect interpretation exercise. A PeP session can begin with electrolyte and voltage concepts, then show before-and-after surface measurements. A characterisation session can begin with sampling strategy and end with linking micrographs to process records.

Every session should include:

- required prior knowledge;

- safety requirements;
- sample and equipment list;
- practical task;
- expected output;
- discussion questions;
- short record of what participants produced or observed.

This structure keeps training material reusable. The same session can be adapted for summer schools, researcher onboarding or industry workshops by changing the depth, duration and examples.

15.3 Use in Summer Schools and Internal Researcher Training

The SEAMAC summer school concept is intended to transfer technical knowledge to postgraduate students, doctoral candidates, researchers and trainers. The toolkit should support this by providing modular content that can be combined into lectures, demonstrations and practical exercises.

For summer schools, the modules can be organised as a process-chain sequence:

- fundamentals of metal AM and FGMs;
- powder and feedstock preparation;
- LMD process knowledge;
- PeP post-processing;
- characterisation and evaluation;
- defects, risks and troubleshooting;
- interpretation of results and industrial relevance.

For internal researcher training, the same content can be used in shorter onboarding blocks. New researchers should first learn terminology and safety, then shadow practical work, then perform supervised tasks and finally interpret results.

A useful internal training path is:

1. Read the relevant module section.
2. Review the local laboratory procedure.
3. Observe the process or measurement.
4. Assist with documentation.
5. Carry out a supervised task.
6. Discuss results with a senior researcher.

This approach preserves SEAMAC knowledge beyond a single event and supports continuity when new staff or students join the project environment.

15.4 Use in Industry-Oriented Training

Industry-oriented training should focus on application relevance, process capability, risks and decision points. Participants may not need the same depth of theory as researchers, but they need to understand what the process chain can do, what must be controlled and what evidence is needed before adoption.

Recommended industry training themes include:

- why FGMs may be useful for tooling and repair applications;
- how LMD enables material addition and local composition control;
- why post-processing is necessary for AM surfaces;

- how PeP may support complex surface finishing;
- what defects and quality risks must be checked;
- what characterisation evidence is needed for qualification;
- what information should be exchanged between industry and research partners.

Industry sessions should use case-study logic. Instead of presenting each process as a separate topic, the training should follow a sample from design objective through powder choice, deposition, post-processing, measurement and interpretation.

The expected output of an industry-oriented session should be practical. Participants should leave with a clearer understanding of:

- whether the process chain may fit their application;
- which material and geometry constraints matter;
- which data are needed for feasibility assessment;
- which follow-up experiments would reduce risk.

15.5 Training Material Types and Reusability

Training material should be modular so that it can be reused across different audiences and events. The same technical content may support a lecture, a laboratory handout, a case study or a self-study onboarding package.

Useful material types include:

- short theory notes;
- slide decks;
- laboratory procedures;
- safety checklists;
- sample preparation sheets;
- measurement templates;
- troubleshooting tables;
- case-study summaries;
- before-and-after image sets;
- discussion questions and short exercises.

Reusable material should avoid relying on undocumented local knowledge. Each item should identify its objective, prerequisites, required equipment or data, expected output and source basis.

For SEAMAC, reusability also means preserving the process-chain connection. A PeP exercise should refer back to the LMD surface state. A characterisation exercise should refer back to powder and process parameters. A troubleshooting exercise should require learners to inspect evidence rather than guess causes.

Editable Markdown is suitable for the toolkit because it can be updated as new modules, figures and examples are added. Detailed laboratory procedures may later be placed in annexes or local standard operating documents, while the module text remains stable training guidance.

16 Module 8: Good Practice Derived from SEAMAC Activities

16.1 Good Practice from TECHNION

TECHNION contributes strong practice in powder preparation, metal AM, process simulation, characterisation and defect interpretation. For SEAMAC training, the most important good practice is the connection between material preparation, process behaviour and measured results.

Good practice examples include:

- treating powder quality as a process input that must be characterised and documented;
- linking powder morphology, particle size and flowability to AM process stability;
- using process simulation and thermal reasoning to explain defects and microstructure;
- applying metallographic and microstructural characterisation to verify process outcomes;
- using defect and failure analysis methods to move from observation to root-cause thinking.

For training delivery, TECHNION material also shows the value of combining broad AM context with practical examples. Learners should understand the wider AM landscape, but the training should return to the specific SEAMAC chain: powder blends, LMD, post-processing and characterisation.

The transferable lesson is that technical training should not isolate materials, process parameters and measurements. In AM of FGMs, they form one connected system.

16.2 Good Practice from TUBAF

TUBAF contributes strong practice in post-processing, PeP process understanding, PeP machine concepts and training around surface integrity. For SEAMAC, this expertise is essential because LMD-produced surfaces must be post-processed and evaluated before the process chain can be considered complete.

Good practice examples include:

- treating PeP as a controlled process window rather than a fixed recipe;
- connecting voltage, current, electrolyte condition, temperature and flow to polishing results;
- considering workpiece geometry, orientation and local surface area during PeP planning;
- evaluating multi-material and FGM surfaces as special cases;
- measuring surface quality before and after polishing;
- addressing safety issues around high voltage, hot electrolyte and chemical handling.

TUBAF training material also shows the value of hands-on process observation. PeP behaviour is dynamic, so learners benefit from seeing how current response, electrolyte state and surface result are connected.

The transferable lesson is that post-processing should be designed together with AM manufacturing and characterisation. A polished surface is not automatically a qualified surface; it must be measured and interpreted.

16.3 Good Practice Established at UL

UL acts as the central implementation environment for the SEAMAC process chain. The project material identifies UL activity in LMD, process-chain development, PeP test-rig development, training organisation and industry-oriented knowledge transfer.

Good practice established at UL should focus on integration:

- combining LMD and post-processing into one process-chain view;
- marking sample identity and gradient direction throughout experiments;
- linking process parameters to characterisation results;
- using partner knowledge from TECHNION and TUBAF to build local capability;
- preparing training material that can support future summer schools and researcher onboarding;
- maintaining industry relevance through demonstrators and workshops.

UL good practice is not only technical. It also includes building the organisational capacity to continue training beyond the project. This means preserving editable material, documenting lessons learned and making knowledge transferable to new researchers, students and industry participants.

For future use, UL should keep module content, sample records, figures, measurement templates and training schedules in a maintainable structure. This supports continuity after individual events or staff exchanges end.

16.4 Lessons Learned from Technical Exchanges and Training Events

SEAMAC technical exchanges and training events show that sustainable knowledge transfer requires more than presenting slides. The most useful learning happens when theory, equipment, samples, measurements and interpretation are connected.

Key lessons include:

- prepare participants before hands-on sessions with short theory and safety material;
- keep sample documentation clear across institutions and process steps;
- use real process results to teach interpretation;
- include both successful and problematic examples;
- connect AM, post-processing and characterisation rather than teaching them as isolated topics;
- adapt depth and terminology to the audience;
- preserve training outputs so they can be reused.

Staff exchanges and expert visits are especially useful when they produce local capability. A good exchange should leave behind documented procedures, example datasets, contact points and a clear path for follow-up questions.

Summer schools and workshops should include time for discussion of results. Learners should compare observations, identify likely causes and decide what they would change in the next experiment. This creates a bridge between training and research practice.

The overall lesson for the toolkit is that modular content must remain editable. As new SEAMAC results become available, examples, figures and troubleshooting guidance should be added without rewriting the whole document.

17 Conclusions

The SEAMAC D3.2 toolkit brings together technical and non-technical knowledge developed through the project into a structured resource that can support future training, knowledge transfer and capacity building. Its overall value lies in connecting the technical process chain of additive manufacturing with the wider organisational, administrative and innovation-related competences needed for sustainable use and transfer of the developed know-how.

From the technical perspective, the toolkit captures the main knowledge areas addressed in SEAMAC, including powder preparation and handling, laser metal deposition, fabrication of functionally graded materials, plasma electrolytic polishing, characterisation, interpretation of results and practical training delivery. In this way, it supports the transfer of critical technical knowledge on AM of FGMs to new researchers at UL and to external users who need a structured overview of the process chain.

From the non-technical perspective, the toolkit supports knowledge transfer related to research management, proposal preparation, administration, technology transfer, intellectual property and interaction with the industrial environment. These elements are essential for ensuring that the technical capacities strengthened through SEAMAC can be effectively maintained, disseminated and further developed beyond the project duration.

Taken together, the two parts of the toolkit reflect the broader SEAMAC objective of strengthening additive manufacturing capabilities through both scientific excellence and institutional capacity building. The document is therefore intended not only as a record of project learning, but also as a reusable and updateable reference for future training activities, onboarding of new staff and researchers, summer schools, and further cooperation with academic and industrial partners.

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