

Weld Seam and Parameter Set — Additive Metal Manufacturing and the Metalworking Trade

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Weld Seam and Parameter Set

Additive metal manufacturing and the metalworking trade — a transdisciplinary study of the shift of control between craft, standard and equipment manufacturer

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Abstract

Additive manufacturing of metal is predominantly treated as a process question: as a problem of melt pool dynamics, powder quality, residual stress, part qualification. This work shifts the question. It does not examine how additive metal processes work, but what they do to an existing trade — to metalworking as a historically grown order of knowledge, training and responsibility.

The starting observation is a discrepancy between two qualification regimes. The welding regime — EN ISO 3834 for the shop, EN ISO 14731 for coordination, EN ISO 9606 for the person executing the work, EN ISO 15614 for the procedure — binds procedural responsibility to named persons and to a documented, transferable, auditable procedural document. The AM regime — ISO/ASTM 52920 for the production site, ISO/ASTM TS 52930 for the equipment — binds it to a site and to a qualified machine. For the person executing the work no standardised, portable counterpart to the welder qualification exists. The process parameter, documented as a WPS in the welding regime and portable with the person, is regularly the property of the equipment manufacturer in powder bed processes.

From this follows an asymmetry that can be read as an instance of the risk-control theorem: liability for the part (ρ) stays with the manufactur-

ing shop, while control over the process parameter (6) migrates to the equipment manufacturer. The work shows that this asymmetry is not evenly distributed across additive metal processes but grows systematically with distance from the welding arc. It develops a coupling axis from manual weld cladding via WAAM and DED to powder bed fusion and binder jetting, tests that axis against six disciplines — process engineering, materials science, standardisation, vocational education, business economics, occupational safety — and closes with a four-quadrant matrix of the risk-control situation together with concrete proposals: a person-bound procedural document for additive manufacturing in analogy to the WPS, a correction of the Austrian module assignment, and an argument for open parameter sets as a precondition of auditable manufacturing.

An empirical finding from the Austrian training regulations supports the thesis institutionally: the special module “Additive Manufacturing” does not belong to the modular apprenticeship in metalworking but to the mechatronics apprenticeship, and can be combined with the metalworking base module only in conjunction with three of nine main modules — not with the welding main module, the closest of all in process terms.

Keywords: additive metal manufacturing, metalworking trade, WAAM, directed energy deposition, powder bed fusion, EN ISO 3834, ISO/ASTM 52920, procedure qualification, apprenticeship, process parameter, risk-control asymmetry, occupational safety, repair manufacturing.

1 Introduction

1.1 Why not another process review

Extensive literature on additive manufacturing of metal exists. Process physics, material behaviour, defect formation, process monitoring and part qualification are well covered in review work; this study presumes that body of knowledge and does not repeat it. What takes up systematic-

ally little space in that literature is the question of how additive metal processes relate to the trade that has worked metal until now.

That relation is not trivial. Metalworking is not an application field that simply absorbs a new technology but an order of knowledge with its own architecture of responsibility. It has a vocational training path with a legally defined occupational profile, a system of testing and coordination, a family of standards that determines who may lay a load-bearing weld under which conditions, and a liability attribution bound to persons rather than to equipment. When a manufacturing process enters this structure whose central process variable is not documented but licensed, that is a change in the order and not merely an extension of the toolbox.

The work therefore asks: what happens to control over process knowledge when metal is made additively? Who carries the risk for a part, and who can decide on the conditions under which it came into being? And what institutional traces has this shift already left — in standards, in training regulations, in cost structures, in occupational safety practice?

1.2 Delimitation

The work does **not** address:

- the process physics of additive metal processes in review form — relevant literature exists and is referenced;
- process windows, parameter sets or manufacturing instructions at a depth that would permit reproduction;
- the polymer, ceramic and biological domains of additive manufacturing;
- defence, weapons and military applications as a development field.

It **does** address:

- the relation between additive metal processes and established metalworking processes as a question of competence, standards and responsibility;

- the normative architecture of both regimes in direct comparison;
- the vocational-law assignment of additive manufacturing in Austria;
- the economic situation of small and medium manufacturing shops facing this technology;
- the occupational safety situation compared with the established welding fume regime;
- the resulting risk-control situation as an analytical model.

1.3 Methodology

This is a narrative, transdisciplinary review with model building. It draws primarily on peer-reviewed literature, on published standard texts and standard previews, on official surveys and on legal sources (Austrian Federal Law Gazette, training regulations). Where market figures are used, the source class is disclosed; figures from commercial market research are marked as such and are not set against peer-reviewed findings.

The standard texts themselves are paywalled and are not reproduced here verbatim. The work reports their scope and architecture as they emerge from publicly accessible standard previews, standardisation overviews and professional publications. Anyone who has to furnish a concrete proof needs the full text; this reservation applies to every statement about standard content in this work.

The model building in section 9 is analytical, not empirically validated. The coupling axis (Model 1) orders processes by a qualitative criterion; the plotted curves depict a structural relationship, not measurements. This is a limitation and is recorded as such in section 12.

1.4 Ethical delimitation at work level

Additive metal manufacturing is closely entangled with defence, marine and aerospace programmes. Several of the relevant qualification guides originate in that environment, part of the process development is state- and military-funded, and several suppliers name defence explicitly as a target market. This entanglement matters for the control question and is

therefore described: it explains why qualification regimes emerged as they did, and who funded the development.

The work describes this situation; it does not advance it. It contains no process windows, no parameter sets, no design or manufacturing guidance with weapons relevance and no recommendations for defence-adjacent application. This delimitation applies to the entire work and to all derived works.

2 Defining the subject

2.1 Metalworking as a trade

“Metalworking” here does not denote the materials science of metals but the trade: the connection of vocational training, occupational practice, testing and responsibility attribution within which metal is worked industrially and in craft settings.

In Austria this trade is organised as a modular apprenticeship. The metalworking training regulations as amended in 2022 provide for a base module binding on all apprentices and nine main modules; training in the base module and the chosen main module lasts three and a half years, with a further main or special module four years. The nine main modules are mechanical engineering, vehicle body construction, metal and sheet construction, steel construction, forging, toolmaking, machining, welding and — since 2022 — safety technology.

This cut matters for the question at hand because it maps the trade’s process landscape: machining, forming, joining and cutting, hot working, heat treatment, surface protection. Each of these process groups has its own competence chain of materials knowledge, machine operation, testing and defect assessment. And each has its own answer to the question of where the process knowledge sits.

2.2 Additive metal processes

The process categories of additive manufacturing are fixed terminologically in ISO/ASTM 52900. For metal at industrial scale the relevant ones are:

Process class	Short code	Heat source	Feedstock form	Typical deposition rate
Laser powder bed fusion	PBF-LB/M	laser	powder 20–50 μm	low, build-volume bound
Electron beam powder bed fusion	PBF-EB/M	electron beam	powder 45–105 μm	low to medium
Directed energy deposition, powder	DED-LB/M	laser	powder, nozzle-fed	medium
Directed energy deposition, wire	DED-LB, DED-EB	laser, electron beam	wire	medium to high
Arc-based DED (WAAM)	DED-Arc	arc (GMAW, GTAW, PAW)	welding wire	high
Binder jetting	BJT	no melting during build	powder + binder, sintering	medium, multi-stage

The table orders by a criterion central to this work: by the proximity of heat source and feedstock to what the trade already masters. An arc, a welding wire and a shielding gas are objects a welding specialist handles daily. A 25 μm nickel-base alloy powder in an inert gas chamber is not.

2.3 The distinction that matters

The common contrast between additive and conventional manufacturing is a process distinction: material is added rather than removed. For the question of this work another distinction carries further — that of the **location of process knowledge**.

In classical welding, process knowledge exists in three interrelated forms:

1. **embodied** in the skilled worker, whose ability is established in a time-limited, person-bound examination;
2. **documented** in the welding procedure specification (WPS), which derives from a procedure qualification record (WPQR) and is transferable between shops;
3. **supervised** by a named person with defined responsibility and authority.

In powder bed fusion it exists predominantly in a fourth form: **programmed in** to a parameter set that ships with the machine, was developed by the manufacturer, is treated as intellectual property and reaches the shop only as a licence to use. This fourth form has no counterpart in the trade's architecture of responsibility.

3 Axis I — Process engineering: the coupling line

3.1 WAAM as hinge

Arc-based additive manufacturing is, in terms of process physics, multi-layer weld cladding with path planning. Wire is melted by an electric arc and deposited layer by layer onto a substrate or the preceding layer; gas metal arc, gas tungsten arc and plasma arc welding serve as arc processes, and the motion is usually provided by an industrial robot or a gantry with manipulator.

This kinship is more than an analogy. It has practical consequences:

- **Equipment.** WAAM setups can be built from existing welding power sources and robots. The investment step is an order of magnitude smaller than for powder bed fusion.
- **Feedstock.** Welding wire is a standardised, widely available commodity with decades of documented metallurgy. This differs fundamentally from gas-atomised powder of narrow size distribution.
- **Defect types.** Lack of fusion, porosity, undercut, distortion and residual stress are known and classified phenomena in welding with established assessment rules.
- **Parameter access.** Wire feed, welding current, arc voltage, travel speed, interpass temperature and shielding gas are adjustable at the equipment and measurable in the shop. They are not hidden behind a software licence.

The last point is decisive. The process variables that determine the quality of a WAAM part are the same variables a welding coordinator is responsible for in any case. A study on EH36 steel shows that build strategy and bead pattern influence residual stress and distortion more strongly than the energy input — the highest residual stresses occurred with the in-out pattern, the lowest with the zigzag pattern. That is a finding about path planning, hence about a variable that sits in the shop, not with the equipment manufacturer.

Work at Graz University of Technology's Institute of Materials Science, Joining and Forming demonstrates the trade connection even more clearly: using the cold metal transfer process, it investigated how existing steel components can be reinforced by targeted material deposition, and converted the resulting hardness values into steel grade equivalents via ÖNORM EN ISO 18265. That is steel construction by additive means, assessed with the test methods of steel construction.

3.2 The other pole: powder bed fusion

In powder bed fusion the situation shifts. ISO/ASTM TS 52930 explicitly describes additive manufacturing in its introduction as a machine-centric process and sets out recommended practices for machine-related process qualification in serial production of metal parts by PBF-LB/M. The object of qualification is the equipment.

There is a technical reason. The process variables in powder bed fusion — laser power, scan speed, hatch distance, layer thickness, exposure strategy, beam diameter, beam offset, shielding gas flow, oxygen level — stand in a non-linear, material-specific relation to melt pool dynamics and hence to porosity, lack of fusion and microstructure. A parameter set is the result of extensive experimental series and cannot be substituted by experiential knowledge at the machine.

The consequence is a structural opacity that is recorded as a gap in the standardisation landscape itself. The standardisation roadmap of US standards work lists parameter control explicitly as a gap, and NIST notes that no standard programming language comparable to G-code for machine tools exists and that scan strategies are implemented inconsistently across equipment vendors — with the result that the same nominal strategy can produce markedly different part quality on different machines.

That is a remarkable statement: the process description is not merely closed, it is not even unambiguous between machines.

3.3 DED as transition field

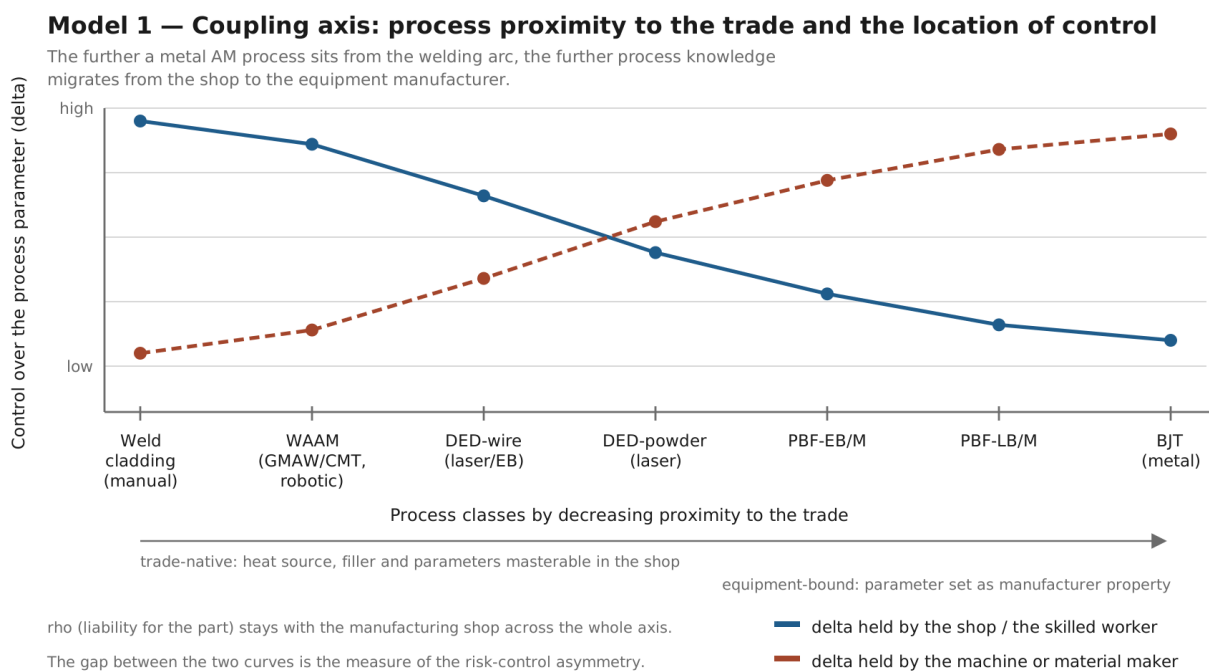
Between the two poles sits laser-based directed energy deposition. With powder bed fusion it shares the feedstock (for powder DED), the heat source and the supplier binding to parameter sets; with welding it shares the open process zone, the accessibility of the part during the process and, above all, application to existing parts.

This last property in particular makes DED the practically most important transition field. The repair job — a worn sealing face, a broken tool edge,

an eroded turbine blade tip — is a familiar operation in metalworking, handled until now by weld cladding. DED does not replace one process with a foreign one but refines an existing one: lower heat input, smaller heat-affected zone, less distortion, lower dilution, better metallurgical bonding with greater process control at the same time.

The literature on tool refurbishment reports considerable service life gains over conventional repair methods — in a frequently cited study by a factor of 3.4 to 8.0. For the control question, the figure matters less than the substance: repair is the application in which the trade retains its own competence, because assessment of the base material, preparation of the joint zone and post-processing remain in the shop.

3.4 Model 1



The coupling axis orders the process classes by decreasing proximity to the trade and plots two counter-running curves: control over the process parameter held by the manufacturing shop, and that held by the equipment or material manufacturer. Liability for the part stays with the manufacturing shop across the whole axis. The widening gap between the two curves is the measure of the asymmetry formalised in section 9.

The depiction is qualitative. It claims no metric scale but an ordering — and that ordering is the subject of the following five axes, each testing it from its own discipline.

4 Axis II — Materials science: two origins of microstructure

4.1 What the trade is used to

The materials science of the trade is predominantly a materials science of pre-processed semi-finished products. A quenched and tempered steel arrives as rolled bar, a structural steel as plate, a forged part with fibre-oriented structure from forming. The property values of these products are standardised, described directionally and assured through delivery conditions. The skilled worker processes a material whose microstructure they did not create.

The exception is welding. There the skilled worker creates a solidification structure — weld metal with dendritic solidification, plus a heat-affected zone with altered base material structure. Welding metallurgy is therefore the only part of the trade's materials knowledge in which solidification, cooling rate, interpass temperature, hardening and residual stress must be mastered in practice.

4.2 What additive metal manufacturing creates

Every fusion-based additive metal process creates a solidification structure — one that arises over hundreds or thousands of cycles of repeated local melting and reheating. From this follow properties systematically different from rolled and forged structures:

Feature	Rolled / forged structure	Weld metal	Additively created structure
Grain form	deformed, often elongated	dendritic, layer-wise	dendritic, frequently epitaxial across layers
Anisotropy	forming-induced, known	pronounced across the seam	pronounced along the build direction
Residual stress	from heat treatment	from bead sequence	from layer and path sequence, often high
Typical defects	segregation, laminations	porosity, lack of fusion, cracks	lack of fusion, keyhole porosity, microcracks
Property values	standardised, assured	demonstrated via WPQR	dependent on part, layer and orientation

The decisive word in the last row is “assured”. For rolled and forged materials there are delivery conditions; for weld metal there is the procedure qualification; for additively created material states there is, in many cases, only the part test itself.

4.3 The re-authentication problem

In practice the gap is closed by post-treatment: stress-relief annealing, solution annealing, hot isostatic pressing, machining of functional surfaces. These steps are not add-ons but a constitutive part of the process chain; without them the property values of many additively made parts are not dependable.

For the control question it is notable that these post-treatment steps lie entirely within the trade. Heat treatment, machining, surface finishing and testing are established metalworking competences. The shop loses

control over the build process and retains it over the entire downstream chain — and over liability for the result.

4.4 The powder question

In powder processes the feedstock itself is a distinct level of control. Powder for laser powder bed fusion typically has a particle size distribution between roughly 20 and 50 μm , for electron beam powder bed fusion coarser at roughly 45 to 105 μm . Powder quality influences build-to-build consistency, freedom from defects, mechanical properties and reproducibility between machines.

Powder is reused. In the process, surface oxide composition, morphology and flow behaviour change; a study on two nickel-base alloys found a slightly altered surface composition in reused compared with virgin powder. For the shop this means: traceability of the powder lot, the number of reuse cycles and the sieving regime are quality-determining variables that must be documented — and which, unlike the parameter set, genuinely sit in the shop.

The picture emerging along this axis is more differentiated than the control thesis alone suggests: on the materials side the shop retains more control than the parameter question implies. The asymmetry is concentrated in the build phase.

5 Axis III — Standardisation: two qualification regimes

5.1 The welding regime

Quality requirements for fusion welding of metallic materials are governed by the EN ISO 3834 series, graded into comprehensive, standard

and elementary requirements. The series is not a stand-alone document but the node of a system:

- **Coordination.** EN ISO 3834 requires the manufacturer to have appropriate welding coordination personnel at its disposal, whose tasks and responsibilities must be clearly defined and who must have sufficient authority to initiate necessary measures. The tasks and responsibility of this person are governed by EN ISO 14731.
- **Execution.** Welders are qualified under EN ISO 9606, operators of mechanised and automatic processes under ISO 14732. This qualification is bound to the person, time-limited and portable between shops.
- **Procedure.** The welding procedure specification (WPS) must be qualified by a procedure test; the corresponding record (WPQR) follows EN ISO 15614.
- **Testing.** Non-destructive testing personnel are certified under EN ISO 9712.

This system is invoked by numerous product and application standards, among them EN 1090 for steel and aluminium structures, EN 15085 for railway vehicles, EN 13445 for pressure vessels and ISO 17660 for reinforcing steel. Anyone manufacturing in these fields cannot bypass the family.

The structural feature is: **procedural responsibility is bound to named persons, and process knowledge is a documented, transferable, auditable artefact.**

5.2 The AM regime

The corresponding architecture for additive manufacturing is younger and cut differently.

ISO/ASTM 52920:2023 sets requirements for part manufacturers using additive techniques, independent of the material and manufacturing method used; the standard specifies criteria for AM-relevant processes as well as quality-relevant characteristics along the process chain and

defines activities and sequences within an AM production site. It presupposes an existing quality management system and supplements it. Environment, health and safety aspects are explicitly not comprehensively covered; for these it refers to equipment manufacturer guidelines and to further standards in the series.

ISO/ASTM TS 52930:2021 governs installation, operational and performance qualification (IQ/OQ/PQ) for PBF-LB equipment; a corresponding technical specification for PBF-EB equipment appeared in 2025. ISO/ASTM 52904 addresses the powder bed process for critical applications. For non-destructive testing on additively made parts the technical reports ISO/ASTM TR 52905 and TR 52906 exist; ISO/ASTM 52948 classifies imperfections in metallic powder bed parts.

The standard itself names the re-qualification obligation on changes to the qualified additive system — among those listed are hardware, firmware, power source, machine repair, machine relocation and feedstock specifications. Each such change must be evaluated for its quality impact; where an impact is established, re-qualification is required.

This list is instructive. It contains firmware. A software state held by the equipment manufacturer is thereby a qualification-relevant state of the manufacturing process — and one the shop does not control.

5.3 The void

What has no counterpart in the AM standards family is the person layer of the welding regime.

There is no standardised qualification of an AM coordinator comparable to EN ISO 14731, with defined responsibility and authority. There is no person-bound, time-limited and portable examination of the executing specialist comparable to EN ISO 9606. What exists instead are role definitions within a quality management system, in-house training records and a heterogeneous market of industry- and vendor-specific personal certificates.

For the individual shop this means: competence is not transportable. A specialist who has worked qualified on one manufacturer's machine brings to another shop with a different machine no formal record equivalent to a welder's certificate. For the occupation it means: there is no institution on which an independent, vendor-neutral occupational competence in additive metal manufacturing could be anchored.

5.4 The industry workarounds

That this gap creates pressure in practice is evident from how it is circumvented. For WAAM the relevant literature names several established certification paths outside the AM standards family: ASME Boiler and Pressure Vessel Code Section IX, QW-600; AWS D20.1 as the specification for fabrication of metal components using additive manufacturing; API Standard 20S for additively manufactured metallic components. For the marine sector a DNV classification guideline exists, for military aviation a paper of the UK military airworthiness authority. For WAAM specifically, BSI published PAS 6012 in 2020, a guide sponsored by Innovate UK.

The conclusion to be drawn from this list is notable: **the most accessible qualification paths for arc-based additive manufacturing run through welding codes, not through AM standards.** Whoever wants to qualify WAAM uses the apparatus built for welding — because that apparatus qualifies persons and procedures, not only equipment.

5.5 Model 2

Model 2 — Two qualification regimes compared

The welding regime qualifies persons and procedures; the AM regime qualifies sites and equipment.

Welding regime (trade) Fusion welding of metallic materials	AM regime (equipment) Industrial additive manufacturing
Shop EN ISO 3834-2/-3/-4 Quality requirements for welding fabrication	Shop ISO/ASTM 52920 Requirements for AM processes and production sites
Person (coordination) EN ISO 14731 Welding coordinator with defined responsibility	Person (coordination) no standardised counterpart to ISO 14731 roles are to be defined, not certified
Person (execution) EN ISO 9606 / ISO 14732 Welder qualification: personal, time-limited, portable	Person (execution) no standardised, portable personal qualification competence holds per site and per machine
Procedure EN ISO 15614 -> WPQR -> WPS documented, transferable, auditable	Equipment / process ISO/ASTM TS 52930 (IQ/OQ/PQ), 52904 parameter set frequently manufacturer property
Testing EN ISO 9712 (NDT personnel)	Testing ISO/ASTM TR 52905 / TR 52906 (NDT on AM parts)

Structural finding

In the welding regime a named person carries procedural responsibility. In the AM regime the site carries it — the person becomes the operator of a qualified machine.

5.6 Qualification cost as a barrier to entry

The gap has a price. NIST describes three routes to qualification: statistically based through extensive empirical testing, equivalence-based through demonstrating equivalence with an already qualified material or process, and model-based through computational prediction with minimal verification testing. It notes at the same time that the high cost of statistically based qualification encourages companies to keep the resulting data proprietary.

This is a feedback mechanism: the expense of qualification creates the interest in secrecy, secrecy prevents the shared data base, and its absence keeps qualification expensive. A trade publication puts the effort for qualifying new parameters for more demanding serial components with dynamic load cases at quickly more than EUR 200,000 — an order of magnitude that rules out any in-house parameter development for a shop with ten employees.

Here the circle closes back to the control question. The asymmetry is not only a consequence of licensing policy but also of testing costs. Whoever lacks six-figure qualification budgets takes the parameter set they are given.

6 Axis IV — Vocational education: where additive manufacturing was institutionally filed

6.1 The Austrian finding

The preceding axes described the shift of control in technical and normative terms. Vocational education supplies an institutional piece of evidence for it that can be checked against legal sources.

The modular apprenticeship in metalworking comprises nine main modules and four special modules. The special module **“Additive Manufacturing (AM)”** is not one of those four. It belongs to the mechatronics apprenticeship and is governed by the mechatronics training regulations. For metalworking it is accessible only by the detour of § 8 para. 4 of the Vocational Training Act: under that provision a combination of the metalworking base module and the main modules mechanical engineering, tool-making or machining with the additive manufacturing special module of the mechatronics apprenticeship is possible.

Three of nine main modules. The other six are excluded — among them:

- **welding**, the main module whose process is identical to WAAM in process terms;
- **steel construction**, in which additive reinforcement of existing structural members is being researched;
- **forging**, the forming trade whose structure formation stands opposite the additive solidification structure;

- **metal and sheet construction, vehicle body construction, safety technology.**

The admitted combinations follow a recognisable logic — they are the three modules most strongly characterised by CNC machine operation and toolmaking. Additive manufacturing was institutionally filed as **machine operation competence**, not as **materials and joining competence**.

6.2 The occupational profile confirms the assignment

This reading can be tested against the content of the special module. The occupational profile names among its activities: creating and optimising support structures; applying company-specific software including data export from design; preparing the manufacturing processes, for instance through finite element analysis for topology optimisation, AM simulation for geometry conformity, build volume optimisation and part orientation; operating the company-specific machines and systems; adjusting the parameters during manufacturing; executing and monitoring the manufacturing process; post-processing additively made parts, including removal of support structures, surface treatment, heat treatment and machining, as well as testing the parts; and finally maintenance and servicing of the systems.

As examples of the parameters to be adjusted during manufacturing, the occupational profile names print speed, layer height and mass throughput at the print head.

These are process variables of material extrusion. A mass throughput at the print head does not exist in powder bed fusion, and a “print speed” is not a meaningful control variable there. The occupational profile of the only additive special module in the Austrian apprenticeship landscape is, judging by its own examples, **written for polymer printing**.

It does not follow that the module is worthless — support structures, part orientation, topology optimisation and post-processing are relevant across processes. It does follow that metal-specific competence — solidification

metallurgy, residual stress, powder handling, inert gas management, feedstock traceability, defect assessment on additive microstructures — is not represented in the occupational profile.

6.3 The orders of magnitude

The modular metalworking apprenticeship is among the most frequently chosen apprenticeships in Austria. The distribution across main modules also shows which parts of the trade are affected by the module assignment.

Main module	Apprentices (order of magnitude)	AM special module combinable
Mechanical engineering	approx. 4,800	yes
Machining	approx. 1,800	yes
Metal and sheet construction	approx. 1,480	no
Steel construction	approx. 800	no
Toolmaking	approx. 760	yes
Welding	approx. 490	no
Vehicle body construction	approx. 360	no
Forging	approx. 70	no
Safety technology (since 2022)	single digits	no
Total metalworking	approx. 10,100	—

The figures come from the labour market administration's occupational information service and should be read as orders of magnitude, not as reference-date values. The total declined in the decade before the survey from almost 11,500 to around 10,100.

Two observations:

First, the combination option arithmetically reaches roughly 7,400 of the approximately 10,100 apprentices, hence the majority — but not those sub-trades whose processes stand closest to additive metal manufacturing. The roughly 490 welding apprentices, whose arc competence would be directly WAAM-compatible, are excluded.

Second, the welding main module is at just under five per cent of apprentices a small module in any case. The trade base that could carry the closest additive path is narrow — and is not institutionally addressed.

6.4 Movement at the margins

The situation is not static. In Styria the additive manufacturing special module was taken into teaching at the Eibiswald vocational school on an initiative of the mechatronics guild. This shows that implementation is being advanced at individual sites — and at the same time through which channel: through mechatronics.

6.5 What follows

The vocational-law assignment is not incidental. Occupational profiles determine which competence counts as constitutive of the occupation, which examinations are taken, which content is taught in vocational schools and which claim a skilled worker can assert on the labour market. If additive metal manufacturing is assigned to the trade not as a materials process but as machine operation, then precisely that form of competence is institutionalised which corresponds to the control asymmetry: the ability to operate a qualified machine, not the ability to take responsibility for a procedure.

Standardisation and vocational education thus show the same pattern from two independent directions. This is the strongest piece of evidence in this work, because the two source types are institutionally independent of one another.

7 Axis V — Business economics: entry thresholds and the repair niche

7.1 On the source situation

Market figures for additive metal manufacturing must be handled with care. For 2025, estimates of the global metal AM market circulate ranging from around 6.0 via 6.7 to 17.2 billion US dollars — a spread of nearly threefold. The divergence is explained by differing scopes (machines, materials, services, parts) and by the fact that the reports are commercial market research products for sale. None of these figures is treated here as a finding.

More dependable is a structural finding from the annual industry survey: in 2025 AM services grew by 15.5 per cent, while system sales rose by only 3.6 per cent. Value creation is shifting from the machine to the service. For the manufacturing shop this is the economically relevant information: the market it could enter is a services market.

7.2 The entry threshold

Three cost blocks determine access.

Equipment. Industrial metal AM systems lie in a price range given in the industry literature as roughly 500,000 to over 4 million US dollars; added to this is peripheral equipment for powder handling, inert gas supply, post-processing and testing. This is an order of magnitude that effectively excludes small and medium shops — by the same source around 70 per cent of manufacturing businesses worldwide.

Feedstock. Metal powders suitable for AM are priced at a multiple of conventional bulk materials; the literature names factors in the range of twenty to fifty times. This figure comes from market research and is to be weighted accordingly, but it reflects a ratio well known in practice.

Post-processing. The share of post-processing — heat treatment, separation from the build plate, support removal, machining, surface finishing, testing — in total cost is given as 30 to 60 per cent. Here too the source reservation applies; the order of magnitude is, however, supported by the materials argument in section 4: the downstream chain is not an appendage but constitutive.

To this is added the qualification effort for in-house parameter sets named in section 5.6. In sum a threshold emerges that consists not of a single item but of their addition.

7.3 Where the break-even lies

The rules of thumb for process selection have been stable for a long time and are not abolished by additive manufacturing: for simple geometries and rising quantities the conventional route — casting, forming, machining — remains economically superior. Additive processes pay off where geometric complexity, part consolidation, personalisation or tool-free production are genuinely exploited.

A case study on metal material extrusion found a cost reduction of about 13.7 per cent against CNC machining, while identifying the post-processing steps — debinding, sintering, machining — as a substantial cost driver. That is a characteristic result: the advantage is real but narrow and dependent on the downstream chain.

For the control question an uncomfortable consequence follows. The applications in which additive metal manufacturing is clearly economically superior are predominantly high-value, geometrically complex parts in regulated industries — hence precisely those in which the qualification effort is highest and the parameter binding strongest. The economic incentive leads into the quadrant of greatest asymmetry.

7.4 The repair niche

There is an exception, and for small and medium shops it is the most interesting one.

Repair and refurbishment shift the cost logic: here the additive process does not compete with an efficient serial route but with procurement of a new part, whose lead time and price are determined by foundry or forging queues, tooling, or simply the unavailability of the original manufacturer. For large parts — valve bodies, furnace headers, pipe fittings, clamping elements — the industry literature names conventional procurement times of several months.

For the economics of the repair itself, individual findings exist: repair of drive shafts by directed energy deposition was put at about half the cost of new manufacture; for tools and dies, service life gains by a factor of 3.4 to 8.0 over conventional repair methods are reported. These figures come from single studies and are not generalisable, but they mark the direction.

Decisive is the control situation. In repair the shop remains master of the operation: it assesses the base material, defines joint zone preparation, selects the filler, performs the post-processing and takes responsibility for the testing. With arc-based execution the process parameter additionally sits in the shop. This is the only application in which risk and control stay together — and at the same time the one with the lowest investment threshold.

7.5 Spare parts without a manufacturer

A related constellation deserves its own mention: parts whose original manufacturer no longer exists or no longer supports the component in question. Here the conventional route falls away entirely, and additive manufacturing competes not with a cheaper process but with replacement of the whole installation.

For a trade whose classical strength is the maintenance of existing technology, this is a point of connection requiring neither large series nor certification apparatus — but materials assessment, redesign, manufacture and testing. These are existing competences.

8 Axis VI — Occupational safety: one known and one new regime

8.1 What the trade already knows

Welding fume is a hazardous substance regulated for decades, well covered by measurement and organisationally controlled. Extraction at source, respiratory protection, workplace limit values, exposure reduction programmes and occupational health surveillance are established practice in metalworking shops. The trade has, put differently, a functioning culture in dealing with particulate and gaseous process emissions.

8.2 What powder processes add

Additive metal manufacturing with powder brings three hazard types that are new in this combination.

Inhalation exposure. Metal powders for AM lie in the micron and partly submicron range. Nickel-, chromium- and cobalt-base alloys are toxicologically relevant: nickel metal powders and nickel compounds are classified under the European CLP Regulation as carcinogenic category 1 on inhalation, can damage organs on prolonged exposure, and are classified as respiratory and skin sensitisers of category 1.

Dermal exposure. An official hazard evaluation at a US powder bed and DED facility found elevated levels of chromium, cobalt, molybdenum and nickel on wrist wipes of employees in the powder bed room after work; personal clothing and personal protective equipment likewise showed contamination, and powder had migrated throughout the production area. A further survey quantifies the increase on the wrists over work tasks at up to 2.6 µg chromium, 1.6 µg cobalt and 5.2 µg nickel per pair of wrists.

Fire and explosion hazard. Fine metal powders are reactive and ignitable under certain conditions; suspended dust clouds can burn and explode. A documented incident at an additive manufacturing facility in Massachusetts in 2013 — fire and explosion after ignition of titanium and

aluminium powder, one person injured — led to an official penalty of nearly 65,000 US dollars for failure to eliminate known ignition sources.

8.3 The decisive finding: the risk sits in the manual work

Several independent surveys arrive at a consistent pattern.

Measured exposure values in the facilities studied lie predominantly below the respective workplace limit values. A survey at eight shops with PBF-LB, PBF-EB and binder jetting processes found that the machines and the printing process itself released no nano- and respirable particles, because they are enclosed systems — as were most depowdering stations and sieves. Emission levels did not differ by AM technique but by the equipment and work routines in the manual steps before and after printing. Peak particle concentrations occurred during open powder handling and during maintenance and cleaning of the machines.

A study at a DED machine with Inconel 718 found particle emissions predominantly in the submicron range above background concentration, while the measured health-relevant metals lay considerably below the applicable exposure limits.

From this follows a statement of practical significance for occupational safety: **the hazard is not inherent to the process but dependent on organisation.** It does not arise in the enclosed process but in handling the powder — in filling, depowdering, sieving, cleaning, maintenance, in separating parts from the build plate and in grinding.

That is good news for the trade. Organisation-dependent hazards are exactly the class of risks it is used to controlling: through work instructions, extraction, separation of areas, personal protective equipment, cleaning regimes and instruction. The competence exists; it has to be transferred to a different substance.

8.4 The normative gap at this point

It is notable that ISO/ASTM 52920 explicitly does not comprehensively cover environment, health and safety aspects and refers for this content to equipment manufacturer guidelines and further standards in the series. The central qualification standard of industrial additive manufacturing thus partly delegates occupational safety to the equipment manufacturer.

For the control question this is a further building block: not only the process parameter but also part of the description of protective measures reaches the shop as a manufacturer document — while responsibility under national worker protection law remains unchanged with the employer.

8.5 The reversal for WAAM

For arc-based additive manufacturing the powder problem falls away. In its place come welding fume, arc radiation, ozone and shielding gas displacement — a hazard profile for which complete protection concepts exist in the trade. Arc-adjacent additive manufacturing is therefore also the more compatible variant in occupational safety terms, which confirms the coupling axis of section 3 from a further side.

9 Synthesis: the risk-control situation

9.1 Two quantities

The six axes can be drawn together into two quantities.

ρ (rho) — risk bearing. Who is liable for the part: under civil law toward the customer, under product liability law toward third parties, under occupational safety law toward employees, and professionally toward the accepting body. In contract manufacturing this is regularly the manufacturing shop.

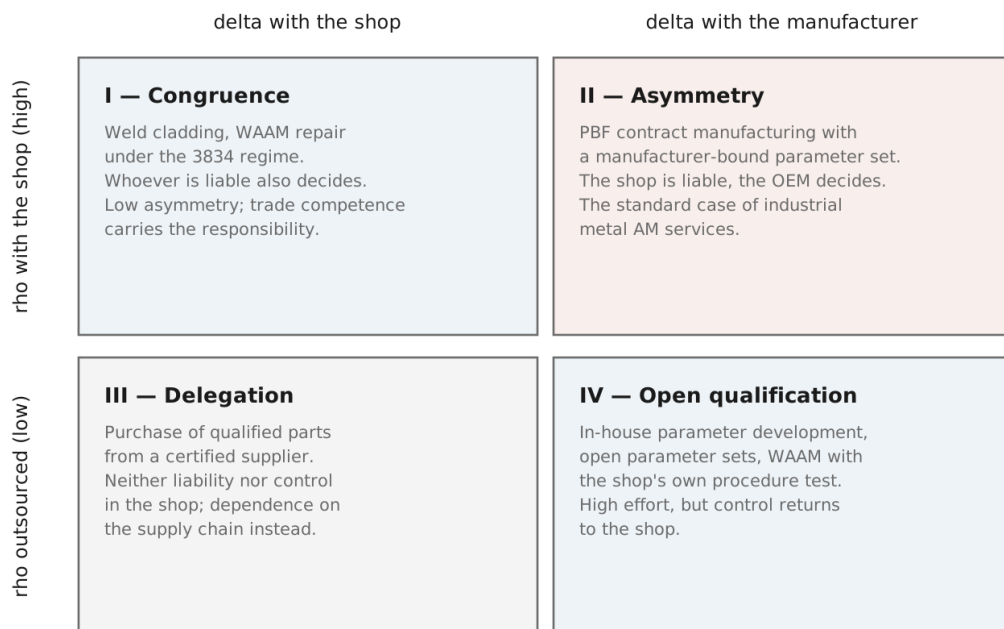
δ (delta) — control over the risk-determining variables. Who can describe, change, test, reproduce and justify the process: the parameter set, the exposure strategy, the firmware, the material specification.

The core statement of this work is: **with increasing distance from the welding arc, the difference between ρ and δ grows without ρ diminishing.** Liability does not travel with control.

9.2 Four constellations

Model 3 — Four constellations of the risk-control situation

Axes: who is liable for the part (rho) x where the process knowledge sits (delta).



Quadrant II is the most common situation for small and medium manufacturing shops.

Quadrant IV is the only path on which control is regained through the shop's own work.

Quadrant I — Congruence. Weld cladding and WAAM repair under the EN ISO 3834 regime. The shop is liable and in control. The procedure is demonstrated by WPQR, the executing person qualified under EN ISO 9606, the coordination named under EN ISO 14731. The asymmetry is low because the qualification regime structurally excludes it.

Quadrant II — Asymmetry. Powder bed contract manufacturing with a manufacturer-bound parameter set. The shop is liable, the equipment

manufacturer controls the central process variable and the firmware whose change can trigger re-qualification. This is the standard case of industrial metal AM services.

Quadrant III — Delegation. Purchase of qualified parts from a certified supplier. Neither liability nor control sits in the shop; in exchange there is full dependence on the supply chain and a loss of in-house manufacturing depth.

Quadrant IV — Open qualification. In-house parameter development, open parameter sets, arc-based processes with the shop's own procedure test. The effort is high; in exchange control returns to the shop. This quadrant is the only path on which the asymmetry is reduced through the shop's own work rather than redistributed by contract.

9.3 Why this is not merely a contractual problem

It is tempting to want to solve the asymmetry contractually: through indemnity clauses, guarantees from the equipment manufacturer, liability caps toward the customer. This falls short for three reasons.

First, the employer's responsibility under occupational safety law cannot be assigned by contract. Second, professional accountability — toward a testing body, an authority, a court — requires a process description the shop must be able to produce and explain; a licence does not replace a description. Third, the asymmetry is epistemic, not merely legal: whoever does not know the exposure strategy cannot recognise a systematic error as systematic. They see scrap, not its cause.

9.4 Placement within the work line

The situation developed here is a domain instance of the general risk-control theorem grounded elsewhere in this work line. Metalworking is a particularly clear case because it has a functioning counter-example in its own house: the welding regime shows that a technology with considerable hazard potential and high process dependence can be ordered through a person- and document-bound qualification system. The question

is not whether such a thing is possible. The question is why it was not built for additive manufacturing.

10 Beyond the textbook state: four proposals

The following proposals go beyond the state reported above. They are formulated as research and design desiderata, not as established findings.

10.1 A procedural document for additive manufacturing

The welding procedure specification is a remarkable artefact: it turns a complex, experience-bound procedure into a written, auditable document transferable between shops, whose validity is grounded in a procedure test. Its principle is not process-bound.

What is proposed is the development of a corresponding document for additive processes — an **additive procedure specification** derived from an additive procedure test and having the following properties:

- **completeness** in the sense that all risk-determining variables are named, including the software states whose change ends validity;
- **transferability** between shops and between machines of the same type, with a defined procedure for demonstrating equivalence;
- **auditability** by a third party able to read the document and hold it against the part;
- **person binding** of a responsible coordination function with defined authority.

The principal objection is obvious: full disclosure of the parameter set collides with the business model of equipment manufacturers. The objection is legitimate and not readily resolved. A workable middle path would be a two-tier solution — a shop-accessible part containing all variables necessary for assuming responsibility and for failure analysis, and a deposited

part held by a notified body that becomes accessible in the event of an audit or a damage case. This model is known from other regulatory fields and would need to be examined for transferability.

10.2 A person qualification for additive metal manufacturing

In parallel, a person-bound and portable qualification corresponding to the welder qualification would need to be developed — not as an operator licence for a machine but as evidence of procedural competence. The subject of examination would be material behaviour, defect types and their causes, powder and wire handling, process monitoring, assessment of test results and the limits of the process.

Experience from the welding regime suggests such an examination should be time-limited and contain a practical part. It would be the institutional locus at which a vendor-independent occupational competence can emerge.

10.3 A correction of the module assignment

For Austria concretely: the combination option of the additive manufacturing special module should be extended to the main modules welding, steel construction, metal and sheet construction and forging, and the occupational profile of the special module should be supplemented by a metal-specific layer — solidification metallurgy, residual stress and distortion, powder and wire handling, shielding gas management, feedstock traceability, defect assessment on additive microstructures, the interface to non-destructive testing.

In the medium term it should be examined whether arc-based additive manufacturing would not be more appropriately carried as an extension of the welding main module than through a special module of a different apprenticeship. In terms of process physics it belongs there.

10.4 Open parameter sets as a precondition of auditability

The debate on open parameter sets has so far been conducted predominantly as a question of innovation and adoption: closed parameters slow diffusion, prevent the use of materials not supplied by the manufacturer and force redundant development work. These arguments are correct but not the strongest ones.

The stronger argument is auditability. A manufacturing operation whose central process variable is accessible neither to the shop nor to a testing body cannot be fully reconstructed in the event of a dispute. Where parts are safety-relevant, this is a structural deficit of the chain of evidence — irrespective of how well the quality management system is otherwise run.

That the situation is not uniform is shown by the counter-movement at individual equipment manufacturers offering open parameter control alongside validated, locked settings and opening interfaces to machine data. This development would need to be recorded systematically: which equipment classes permit which access, on what terms, with what consequences for warranty and qualification? To the author's knowledge no such survey exists; it would be a research undertaking in its own right.

10.5 Summary of the desiderata

Desideratum	Addressee	Effort	Effect on the asymmetry
Additive procedure specification with deposit model	Standardisation (ISO/TC 261, CEN/TC 438)	high	structural
Person-bound AM qualification	Standardisation, testing bodies, social partners	medium	structural
		low	indirect, long-term

Desideratum	Addressee	Effort	Effect on the asymmetry
Extension of module combinations (AT)	Vocational training law, social partners		
Survey of parameter accessibility by equipment class	Research	low to medium	knowledge-generating

11 Interests and disclosure

The author runs a fabrication workshop focused on polymer-based additive manufacturing and holds a Werkmeister qualification in mechanical engineering as well as completed training in two further trades. From this follows a practical interest in a manufacturing landscape in which small shops can control their own processes. This perspective is operative in the framing of this work and is disclosed here rather than being presented as neutral.

The author does not operate metal additive processes, has no contractual relationship with equipment or material manufacturers in the metal AM industry and received no funding, commission or benefit in kind for this work. The work is privately financed.

Market figures used stem in part from commercial market research and from supplier publications; they are marked as such in the text. Standard texts were not evaluated in full; see section 1.3 and the limitations.

An AI language model was used as a research and writing tool in producing this work. The choice of question, the line of argument, the model building and responsibility for the content lie with the author.

12 Limitations

1. **Standard texts do not underlie the work in full.** Statements about standard content rest on publicly accessible standard previews, standardisation overviews, certification literature and professional publications. For a dependable individual proof the respective full text must be consulted. This concerns in particular the statement about the void in person qualification in section 5.3: it is a negative finding and as such only as dependable as the completeness of the standards overviews consulted.
2. **The coupling axis is qualitative.** Model 1 depicts an ordering, not a measurement. An operationalisation — for instance through the number of shop-accessible versus locked process variables per equipment class — would be possible and remains outstanding.
3. **The vocational education analysis is limited to Austria.** The German, Swiss and EU-wide situation was not surveyed. Whether the assignment pattern described — additive manufacturing as mechatronics competence — recurs internationally is an open and testable question.
4. **Market figures are heterogeneous and partly interest-bound.** The orders of magnitude named in section 7 are not to be read as findings. The spread of estimates for the same market year is disclosed in section 7.1.
5. **The occupational safety findings come from a limited number of facility surveys,** predominantly from North America and Scandinavia. Transfer to small shops with less developed infrastructure is not readily admissible — on the contrary, the finding that the hazard attaches to the manual steps suggests that the situation in poorly equipped shops is less favourable than in those studied.

6. **Single studies on repair economics are not generalisable.** The factors named relate to particular parts, materials and operating conditions.
7. **The proposals in section 10 are untested.** In particular the deposit model for parameter sets is an analogy whose legal and practical viability would need examination.

13 Conclusion

Additive manufacturing of metal is negotiated in public and in much of the professional debate as a question of possibilities: which geometries, which materials, which quantities. This work has asked a different question — that of the order into which the process enters.

The finding has two parts. In process terms, additive metal manufacturing is not a uniform object but a series running from a trade-native pole — multi-layer weld cladding with path planning — to an equipment-bound pole at which the central process variable no longer sits in the shop. Institutionally this series has already left its mark: in a standards family that qualifies sites and equipment where the older one qualifies persons and procedures, and in a training regulation that assigns additive manufacturing to machine operation and closes it to the sub-trades closest to it in process terms.

That both observations point in the same direction although they come from independent source types is the principal result. There is no reason to assume this development was necessary. The welding regime proves within the same trade that a highly process-dependent, safety-relevant manufacturing process can be ordered through person-bound examinations and a transferable procedural document. The blueprint exists. It was simply not used for additive manufacturing.

For the individual shop the practical conclusion is sober: the niche in which risk and control stay together is arc-adjacent, repair- and refurbishment-oriented additive manufacturing. It is the one with the lowest investment threshold, the best-known hazard profile, the most accessible qualification paths and the greatest proximity to existing competence. That is not a retreat into the easy option but the point at which a trade can take up a new technique without surrendering control over its own work.

14 References and sources

Standards and technical specifications

1. ISO/ASTM 52900 — Additive manufacturing: General principles, fundamentals and vocabulary.
2. ISO/ASTM 52920:2023 — Additive manufacturing. Qualification principles. Requirements for industrial additive manufacturing processes and production sites. <https://www.iso.org/standard/76911.html>
3. ISO/ASTM TS 52930:2021 — Additive manufacturing. Qualification principles. Installation, operation and performance (IQ/OQ/PQ) of PBF-LB equipment. <https://www.iso.org/standard/79527.html>
4. ISO/ASTM TS 52949:2025 — Additive manufacturing of metals. Qualification principles. IQ/OQ/PQ of PBF-EB equipment.
5. ISO/ASTM 52904 — Additive manufacturing of metals. Powder bed fusion process to meet critical applications.
6. ISO/ASTM 52948:2026 — Additive manufacturing of metals. Powder bed fusion. Classification of imperfections.
7. ISO/ASTM TR 52905:2023 — Additive manufacturing of metals. Non-destructive testing and evaluation. Defect detection in parts.
8. ISO/ASTM TR 52906:2022 — Additive manufacturing. Non-destructive testing. Intentionally seeding flaws in metallic parts.

9. ISO 27548:2024 — Additive manufacturing of plastics. Environment, health and safety.
10. EN ISO 3834-1 to -5 — Quality requirements for fusion welding of metallic materials.
11. EN ISO 14731 — Welding coordination: tasks and responsibilities.
12. EN ISO 9606 — Qualification testing of welders.
13. ISO 14732 — Welding personnel: qualification testing of welding operators and setters.
14. EN ISO 15614 — Specification and qualification of welding procedures.
15. EN ISO 9712 — Non-destructive testing: qualification and certification of personnel.
16. ÖNORM EN ISO 18265 — Metallic materials: conversion of hardness values.
17. BSI PAS 6012:2020 — Additive manufacturing. Wire arc. Guide. https://www.bsigroup.com/siteassets/pdf/en/insights-and-media/insights/brochures/pas_6012.pdf
18. AWS D20.1 — Specification for Fabrication of Metal Components using Additive Manufacturing.
19. API Standard 20S — Additively Manufactured Metallic Components for Use in the Petroleum and Natural Gas Industries.
20. ASME Boiler and Pressure Vessel Code, Section IX, QW-600.
21. ASTM WK69732 — New Guide for Additive Manufacturing: Wire Arc Additive Manufacturing. <https://www.astm.org/workitem-wk69732>

Legal sources (Austria)

1. Metalltechnik-Ausbildungsordnung (metalworking training regulations), BGBl. II No. 97/2022. https://www.ris.bka.gv.at/Dokumente/BgblAuth/BGBLA_2022_II_97/BGBLA_2022_II_97.html
2. Mechatronik-Ausbildungsordnung (mechatronics training regulations), BGBl. II No. 196/2019 as amended by BGBl. II No. 195/2021.
3. Berufsausbildungsgesetz (Vocational Training Act), BGBl. No. 142/1969 as amended, in particular § 8 para. 4.

4. Austrian Federal Economic Chamber: Modular apprenticeship in metalworking. <https://www.wko.at/oe/gewerbe-handwerk/metalltechniker/ausbildungsordnung-modulare-lehre>
5. Occupational profile, special module Additive Manufacturing (mechatronics apprenticeship). <https://www.mechatroniklehre.at/de/lehrberuf-mechatronik/spezialmodule/additive-fertigung>
6. AMS Berufslexikon: metalworking technician, main modules and apprentice numbers. https://www.berufslexikon.at/berufe/3451-MetalltechnikerIn-Hauptmodul_Maschinenbautechnik/

Peer-reviewed literature

1. Ali, M. H.; Han, Y. S. (2023): A Finite Element Analysis on the Effect of Scanning Pattern and Energy on Residual Stress and Deformation in Wire Arc Additive Manufacturing of EH36 Steel. *Materials* 16(13), 4698. <https://doi.org/10.3390/ma16134698>
2. Sharifi, S. S.; Fritsche, S.; Holzinger, C.; Enzinger, N. (2023): Selection of Parameters for Optimized WAAM Structures for Civil Engineering Applications. *Materials* 16(13), 4862. <https://doi.org/10.3390/ma16134862>
3. Gierth, M.; Henckell, P.; Ali, Y.; Scholl, J.; Bergmann, J. P. (2020): Wire Arc Additive Manufacturing (WAAM) of Aluminum Alloy AlMg5Mn with Energy-Reduced Gas Metal Arc Welding (GMAW). *Materials* 13(12), 2671. <https://doi.org/10.3390/ma13122671>
4. Li, L.; Zhang, X.; Liou, F. (2021): Experimental and Numerical Investigation in Directed Energy Deposition for Component Repair. *Materials* 14(6), 1409. <https://doi.org/10.3390/ma14061409>
5. Directed Energy Deposition (DED) Process: State of the Art. *International Journal of Precision Engineering and Manufacturing-Green Technology*. <https://doi.org/10.1007/s40684-020-00302-7>
6. Advanced Repairs of Metal Parts through Laser-Directed Energy Deposition: A Practical Review of Industrial Use Cases. *Arabian Journal for Science and Engineering*. <https://doi.org/10.1007/s13369-025-11023-x>

7. A review on qualification and certification for metal additive manufacturing. *Virtual and Physical Prototyping*. <https://doi.org/10.1080/17452759.2021.2018938>
8. Process parameter optimization of metal additive manufacturing: a review and outlook. *Journal of Materials Informatics*. <https://doi.org/10.20517/jmi.2022.18>
9. Health hazards of particles in additive manufacturing: a cross-disciplinary study on reactivity, toxicity and occupational exposure to two nickel-based alloys. *Scientific Reports* (2023). <https://doi.org/10.1038/s41598-023-47884-1>
10. Occupational exposure and health surveys at metal additive manufacturing facilities. *Frontiers in Public Health*. <https://doi.org/10.3389/fpubh.2023.1292420>
11. van Ree, M.; du Preez, S.; du Plessis, J. L. (2023): Emissions and Exposures Associated with the Use of an Inconel Powder during Directed Energy Deposition Additive Manufacturing. *International Journal of Environmental Research and Public Health* 20(13), 6206. <https://doi.org/10.3390/ijerph20136206>
12. Skin, Clothing, and Surface Contamination with Metals at a Powder Additive Manufacturing Facility. *Safety* (2026) 12(2), 54. <https://doi.org/10.3390/safety12020054>
13. Evaluating the cost competitiveness of metal additive manufacturing: a case study with metal material extrusion. <https://doi.org/10.1016/j.cirpj.2023.05.005>
14. A Review of Non-Powder-Bed Metal Additive Manufacturing: Techniques and Challenges. *Materials* (2024) 17(19), 4717. <https://doi.org/10.3390/ma17194717>

Official and institutional sources

1. NIOSH (2025): Evaluation of Metals Exposure in a Metal Powder Additive Manufacturing Facility. Health Hazard Evaluation Report 2023-0034-3409. <https://www.cdc.gov/niosh/hhe/reports/pdfs/2023-0034-3409.pdf>

2. NIST: Qualification for Additive Manufacturing Materials, Processes, and Parts. <https://www.nist.gov/programs-projects/qualification-additive-manufacturing-materials-processes-and-parts>
3. NIST: AM Machine and Process Control Methods for Additive Manufacturing. <https://www.nist.gov/programs-projects/am-machine-and-process-control-methods-additive-manufacturing>
4. Regulation (EC) No 1272/2008 (CLP Regulation), classification of nickel metal and nickel compounds.

Industry and supplier sources (marked as such)

1. Metal AM: Exploiting your metal Additive Manufacturing data assets. <https://www.metal-am.com/articles/exploiting-your-metal-additive-manufacturing-data-assets-faster-industrialisation-and-new-revenue-streams/>
2. Metal AM: Safety management in metal Additive Manufacturing. <https://www.metal-am.com/articles/safety-management-in-metal-3d-printing/>
3. AWS Welding Digest (2026): Beyond the Bead — Applying Wire Arc Additive Manufacturing to Large-Scale, High-Demand Components. <https://www.aws.org/magazines-and-media/welding-digest/2026/march/beyond-the-bead-applying-wire-arc-additive-manufacturing-to-large-scale-highdemand-components>
4. Dyndrite: The Importance of Open Parameters in Additive Manufacturing. <https://www.dyndrite.com/blog/the-importance-of-open-parameters-in-additive-manufacturing>
5. EOS: Openness as the Engine of Software Innovation in Metal AM. <https://www.eos.info/content/blog/2026/software-openness-in-metal-additive-manufacturing-part-2>
6. Wohlers Report 2026, as reported in industry coverage (AM services +15.5 %, system sales +3.6 % in 2025).
7. 3DPrint.com (2026): 3D Printing Predictions 2026 — Industrial Production in Metal Additive Manufacturing. <https://3dprint.com/322917/3d->

printing-predictions-2026-industrial-production-in-metal-additive-manufacturing/

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