FINAL REPORT

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[1] Usually the contact person of the coordinator as specified in Art.1 of the grant agreement.
[2] The home page of the website should contain the generic European flag and the FP7 logo which are available in electronic format at the Europa website (logo of the European flag: http://europa.eu/abc/symbols/emblem/index_en.htm;
logo of the 7th FP: http://ec.europa.eu/research/fp7/index_en.cfm?pg=logos). The area of activity of the project should also be mentioned.

Contents

Glossary of Terms

AM	Additive Manufacturing
LMD	Laser Metal Deposition
OEM	Original Equipment Manufacturer
NDT	Non Destructive Testing
QA	Quality Assurance
QC	Quality Control
LE	Large Enterprise
SME	Small to Medium Enterprise
RTO	Research & Technology Organisation
CAD	Computer Aided Design
CAM	Computer Assisted Manufacturing
CNC	Computer Numerical Control
PSC	Project Steering Committee
FGM	Functional Graded Material
GMAW	Gas Metal Arc Welding (also known as MIG)
MIG	Metal Inert Gas
TIG	Tungsten Inert Gas
LUT	Laser Ultra-Sonic Testing

1 Executive Summary

AMCOR developed and demonstrated Laser Metal Deposition (LMD) systems and processes for the deposition of functional coatings and 3D geometric features onto metallic components supplied by industry that are subjected to in-service wear and corrosion. The purpose was to extend in-service working life whilst offering increased performance and reliability. This was demonstrated through the demonstration and validation of 5 industrial applications, one from each of the AMCOR end users identified during the course of the project (1) coating of cutting rollers for Denys, (2) coating of hydraulic piston rods for Bosch, (3) manufacture of automotive gears for VCST, (4) coating of steam turbine valves for Skoda and (5) repair of teeth on broaching tools for Ekin.

This was supported by the development; production and testing of a number of technical subsystems including (1) mixed material powder feeder specific for additive technology (2) real time melt pool monitoring system, (3) LMD nozzle powder flow sensor, (4) inline vision based control system for geometric scanning and part referencing and, (5) thermal modelling and (6) CAM tools software development.

All of the above was underpinned by the development and installation of two LMD systems, one based on gantry architecture and the other on industrial robotic manipulation. This gave knowledge driven and turnkey systems for the deposition and manufacture of the AMCOR demonstrators in an industrially relevant environment.

2 Project Context and Main Objectives

The overall aim of the AMCOR project was the development and demonstration of a flexible and automated manufacturing process for the repair, coating and near net shape production of components composed of hard wearing and corrosion resistant coatings, some with graded/buffered layers. AMCOR hoped to offer a step change in the performance and reliability of components for extended in-service life across a broad range of industries where wear was a key problem. This would be delivered by the combined development of material deposition procedures, supported by powder development, computational modelling and materials characterisation and testing, and of manufacturing systems integrating novel multiple powder delivery systems, automated tool path generation software and advanced novel sensing, monitoring and adaptive feedback systems. All of this would be underpinned by the development and installation of two LMD systems, one based on gantry architecture and one on industrial robotic manipulation. Both giving a vehicle to demonstrate technologies development and demonstration application. Further, the differing nozzle manipulation technologies, which come at a significantly differing cost, were compared on a cost performance relationship for each of the AMCOR demonstrators.

Being able to manufacture or clad components using novel materials, either as a continuous coating or in graded/mixed material layers, in a controlled manner, would have clear benefits in a range of industrial sectors. The benefits include reduction in waste material, joining of dissimilar materials, adding functional materials onto lower cost substrate and only adding features where needed by application. A number of these sectors were represented and demonstrated in AMCOR:

- **Industrial Drive and Control Systems:** Piston rods for hydraulic cylinders across a number of industrial sectors.
- **Mining:** A hard surface coating is required to improve the wear resistance of cuttings rollers
- **Tooling:** Possibility of repair and near net shape production of broaches used in metal working
- **Automotive / Gears:** The alternative near net shape production of prototype gears.
- **Power generators**: Valve stems for power generation.

Laser metal deposition (LMD) was the production technology used in the AMCOR project for the realisation of high performance metal-metal and metal-ceramic parts and claddings. This was applied to the manufacture and repair of existing components, enabling their wear and corrosion resistance to be improved while, for instance, operating under stress at high temperatures (requiring high temperature creep and/or fatigue strength

A schematic of the LMD process is given in Figure 2.1; LMD is fundamentally a fusion welding process, whereby the additive powder material (can also be wire) is fed directly into the laser induced melt pool, allowing a build-up of material for a functional coating. By using multiple layering techniques, graded layers are also possible along with the manufacture of near net shape 3D geometries. During processing, the clad material and a (small) portion of the substrate are molten and in contact with each other, allowing for mixing and the formation of a metallurgical bond. The process control possible over the process can give several distinct advantages compared with conventional surface cladding techniques such as Tungsten Inert Gas (TIG), Plasma Transferred Arc (PTA) and thermal spray. The main advantages of the LMD approach are as follows:

- Localised heat treatment with low heat input results in excellent metallurgical bonding with low dilution and low distortion of substrate material and low thermal stresses in material – making the process highly suitable for finite layers.
- Surface coatings can have extremely dense, crack-free and non-porous fine microstructures. The fine microstructure results from high cooling rate ($4x10^3 Ks^{-1}$ or even higher). The high cooling results in minimal dissolution of ceramic powder particles in the metallic matrix of cermet deposits retaining a high ductility in the matrix and the high wear resistant characteristics of the ceramic.
- Tight control of the blown powder stream gives high deposition positional accuracy, a uniform composition and coating thickness, but sometimes at the disadvantage of productivity.
- Sustainable and resource efficient manufacture with a possible 100% material usage offers reduced manufacturing costs, particularly where feedstock material cost is a significant factor.
- Flexible manufacturing with high degree of automation and integration of sensor for on-line monitoring and control.

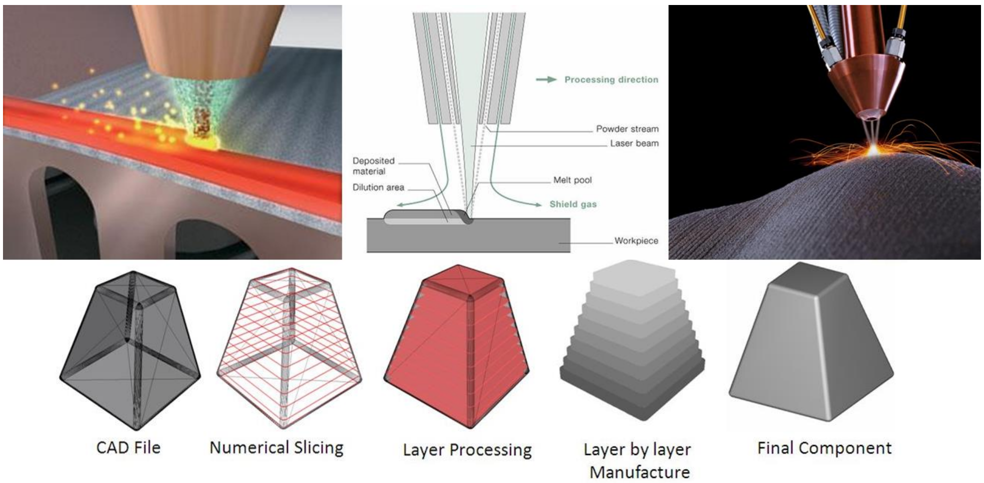


Figure 2.1: Schematic of LMD process

However, while LMD has shown remarkable developments in recent years, to enable the manufacturing development for mixed material coatings, graded coatings and monolithic structures in an industrial environment, there are a number of developments that needed to be achieved;

- **Deposition of Multiple Powder Materials:** The deposition of multiple materials and their relative volume control is critical to ensure homogenous mixing– particularly if different powder particles differ considerably in mass and geometry. Currently, powders can be premixed or mixed on delivery via two dispensing hoppers. However, either approach, coupled with current nozzle technology cannot guarantee full control over material distribution. A greater understanding of the flow of powder is needed by assessing the influence of the ratio between the particle carrier and the nozzle gas and relationship between nozzle geometry to address powder concentration and focus location from the nozzle exit.
- **Process control and monitoring:** Process control and monitoring is key to industrialisation of LMD processing. In-line scan path (with reactive adaption) and precise thermal management control is an essential development of AM capable of successfully depositing dual or multiple phases, required for FGM parts.
- **Increased Productivity:** One of the key development areas necessary is the productivity rate of LMD; as LMD often has lower productivity compared to other cladding processes such as thermal spraying, TIG, MIG and PTA. Thus, in order to create large parts economically high productivity processing is required. While a key benefit of AM is low-heat input, to achieve higher deposition rates, the use of higher heat inputs (higher laser power) is required, but without very careful control, this can cause problems, such as poor surface finish, and distortion, which need to be resolved.
- **Software development:** An important step in achieving optimised process conditions is the method of surface data collection and the preparation of tool paths. For FGM claddings, this often includes numerical slicing of the CAD file and generation of appropriate tool paths to allow fast, effective and efficient traversing of the LMD nozzle for area coverage – often for deposition onto conformal surfaces. There is currently no complete solution for automated tool path generation from sliced CAD data for multiple axis and multiple material processes. Most commercial software packages have evolved from laser cutting/marking applications and so are not best suited for building up surface claddings in layers. Often these software packages require a lot of user input to manually position the deposition vectors.
- **Material quality and performance**. It goes without saying that the deposited material has to be high quality in order to result in suitable material properties for FGM components. A better understanding of the microstructure and material properties formed during layer-wise rapid solidification is needed in areas like (anisotropic) mechanical properties, corrosion resistance, wear resistance, thermal stability of the rapidly solidified microstructure compared to after conventional manufacturing by casting, forging,. A better understanding of the material and deposition parameters affecting the thermal stresses in functional graded materials is needed. This then has to be combined with adaption to the control of the feedstock powders through the deposition nozzle to achieve homogenous distribution of graded materials.

Each of these areas of development was addressed within the AMCOR project. By overcoming each of these current deficiencies in knowledge based manufacturing, AMCOR was able to develop more robust manufacturing methods. These can potentially revolutionise industrial surface cladding, repair and near net shape production using both novel materials, material combinations and functionally graded layers.

The AMCOR beneficiaries worked together to develop two AM deposition systems, utilising a number of common parts and sub-systems. These two systems were then used to manufacture and demonstrate components across a range of industrial components. Figure 2.2 shows the AMCOR consortium and development concept for delivering automated and flexible LMD manufacturing systems.

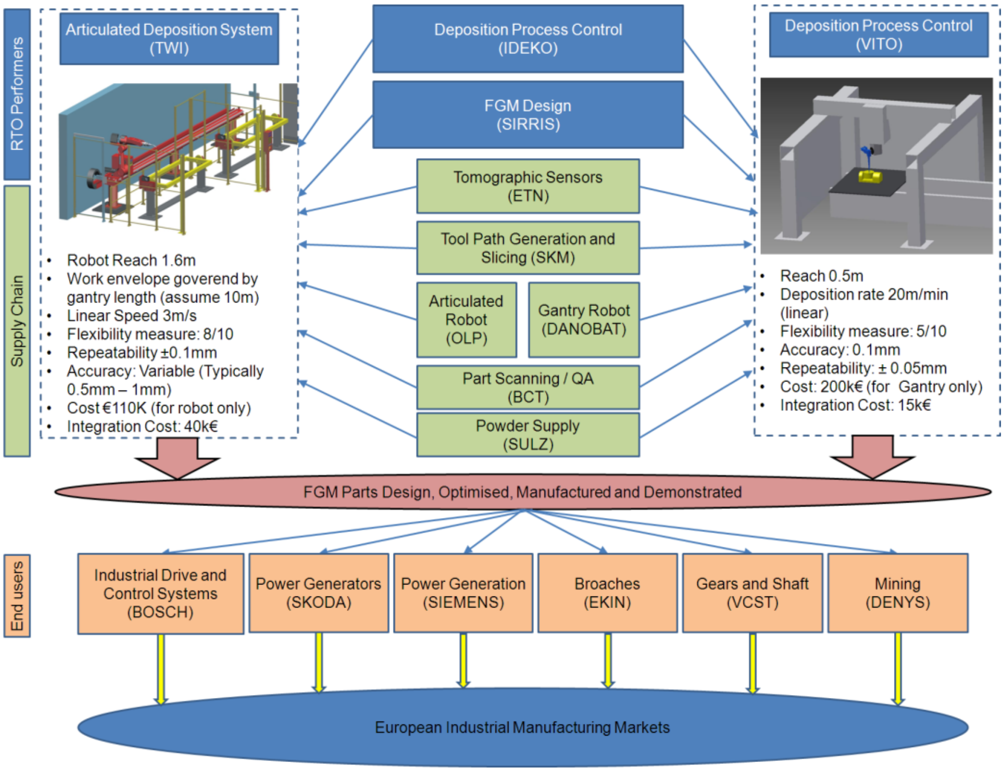


Figure 2.2: Outline of AMCOR Consortium and concept for developing flexible LMD manufacturing

Within the concept of AMCOR, the following objectives were determined and split into the following types:

Fundamental (Science) Objectives

1. Deposition Procedure and Powder Development for High Strength Components with High Corrosion and Wear Resistance
   Quantified Objective:
   a. Performance increase of >50% compared to state-of-the-art materials in terms of mechanical strength, ductility, wear and/or corrosion rate.
   b. Demonstrate ability to deposit material gradient from steel to more than 85 volume percentage ceramic (e.g. tungsten carbide) without crack generation in less than 4 mm build height.

Anticipated Month of Completion: **Month 17**

Engineering Technology

2. Tool Path Generation and Software
   Quantified Objective:
   a. Demonstration of automated tool path generation for 6 example CAD models - 1 supplied by each End-User

Anticipated Month of Completion: **Month 18**

3. Duel Powder Nozzle Deposition Head
   Quantified Objective:
   a. Integrated Nozzle, based on a co-axial multijet nozzle system (see Figure 1.2b), capable of delivering variable volume fractions (10-90%) of two powders (metal and a ceramic) into the melt pool created by the laser. mixed volume fractions of two powders at the substrate surface.
   b. Capable of a combined material deposition rate of at least 1.5 times greater than current co-axial multjet nozzle (6Kg/h).

Anticipated Month of Completion: **Month 15**

4. Real-time Process Monitoring and Control
   Quantified Objectives:
   a. Variation in degree of dilution with substrate decreased with >20% and geometrical accuracy improved with >50% compared to uncontrolled process.

Anticipated Month of Completion: **Month 15**

5. Tomographic Powder Flow Sensor
   Quantified Objectives:
   a. Density distribution maps recording a time-lapse-history of powder flow from a stationary co-axial multijet nozzle, demonstrated with >99.9% accuracy (against measured powder collected).
   b. Density distribution maps recording a time-lapse-history of powder flow from a traversing co-axial multijet nozzle developed in this project (objective 2), demonstrated with >99.9% accuracy (against measured powder collected).

Anticipated Month of Completion: **Month 15**

Demonstration and Validation

6. Demonstration components
   Quantified Objectives:
   a. BOSCH:
      - Enhanced wear resistance (life time increased by >50%) of piston rods for hydraulic cylinders for marine drive system.
      - Increased reliability of the process: defect rate reduced by 50%. Decrease of primary materials usage with 50%.
   b. SKODA: Enhanced wear, corrosion and oxidation resistance (life time increased by >50%) of valve stems.
   c. VCST: Reduction of production time of prototype gears with more than 50% without deterioration of materials performance.
   d. DENYS: Enhanced abrasion resistance (life time increased by >50%) of cutting rollers for mining.
   e. EKIN: Enhanced wear resistance (life time increased by >50%) and possibility for repair of teeth on broaches used for metal working.

Anticipated Month of Completion: **Month 36**

3 AMCOR Partnership

The AMCOR consortium consisted of specialists in complementary fields particularly well qualified for the development of materials, laser metal deposition systems, testing and simulation, software, traditional and novel manufacturing methods and demonstration. In addition the consortium has sufficient expertise for the validation of the technologies with a specific focus towards increasing the technological base of EU manufacturing through the development and integration of the enabling technologies of the future. Much of the technology sub-systems development was driven by SME's forming a technology supply chain. All of this work is underpinned by end user application needs from a range of different industrial sectors.

Table 3.1: AMCOR Consortium

Participant no.	Participant organisation name		Country
1 (Coordinator)	TWI Ltd	TWI	UK
2	Vlaamse Instelling voor Technologisch Onderzoek	VITO	Belgium
3	Bosch Rexroth B.V.	BOSCH	The Netherlands
4	VCST Industrial Products	VCST	Belgium
5	BCT Steuerungs- und DV-Systeme GmbH	BCT	Germany
6	S.K.M. Informatik GmbH	SKM	Germany
7	Ideko S.Coop	IDEKO	Spain
8	SKODA POWER SRO	SKODA	Czech Republic
9	SIRRIS HET COLLECTIEF CENTRUM VAN TECHNOLOGISCHE INDUSTRIE VZW	SIRRIS	Belgium
10	Olympus Technologies Ltd	OLP	UK
11	Etalon Research LTD	ETN	UK
12	Danobat	DAN	Spain
13	EKIN SOCIEDAD COOPERATIVA	EKN	Spain
14	DENYS NV	DENY	Belgium
15	Oerlikon	SULZ	Switzerland

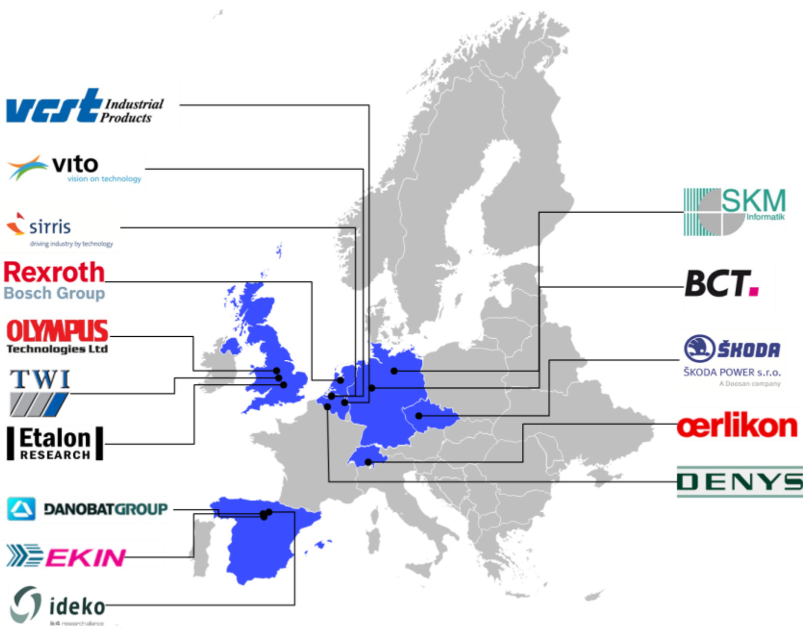


Figure 3.1: AMCOR European Collaboration.

4 Science and Technology Results

Overall work plan strategy

The overall work plan strategy for the *AMCOR* project is defined in the Pert diagram (see Figure 4.1). There are 3 phases to the project: (1) Component Road-mapping (component and material specifications), (2) Technology and Deposition Procedure development (LMD system, Software, Powder and Procedures development) and (3) Demonstration (LMD equipment industrialisation and components including validation).

Phase 1: Project Road-mapping (*component and material specifications*): This provided an holistic overview of the LMD hardware, component and materials specification, within the context of creating an automated LMD manufacturing cell for the near net shape repair, production and surface coating of hard wearing/corrosion resistant components using efficient and environmentally friendly manufacturing routes. Initially, the phase specified the LMD hardware performance (in line with project objectives) and enabled all of the individual technical sub-system activities to be undertaken. It also incorporated the technical and practical operating parameters achievable, including operating procedures. By the end of this phase of activity, the hardware, component demonstrators, materials and validation activity were all defined and concluding in the drafting of a specification document that was reviewed and updated as the project progressed. There was one milestone point associated with Phase 1; MS1 (M5) – *AMCOR* specification defined

***Phase 2:* Technology and Deposition Procedure development:**
Phase 2 built upon the actives in WP1 and used the specification document to gain understanding of the potential for the LMD systems and the defined materials. Technological sub-systems for off line programming, powder feeding and delivery, process monitoring and control were developed within the context of the preparation of robot and CNC based LMD systems (WP5 see below). All but the melt pool monitoring activity was employed in the final demonstration systems. Due to the effects of powder in the environment on camera lenses and associated equipment, the inline melt pool monitoring was demonstrated on a bench top system. All of the subsystem developments were orientated towards the automated manufacture with reproducible and quality control results for near net shape repair, production and protective surface coatings of complex shaped components. There were two milestone points associated with Phase 2;

- MS2 (M15) – Prototype hardware and software modules developed satisfying industrial requirements set in WP1.
- MS3 (M18) - LMD samples with designed material gradient showing improved performance and sustainability, 3D structures build up with geometrical accuracy as specified in WP1

***Phase 3:* Demonstration (technology and components including validation).**
This phase was the final culmination of activities on the project to demonstrate the use of the LMD hardware systems and components for manufacture in a typical industrial environment. This involved ‘real world’ field testing of some of the components at AMCOR end users, as identified and defined in WP1. Demonstration also focused to disseminate the developments of the project to the wider audience and sought to define future exploitation of the project results (e.g. post-project commercialisation and SME led systems integration). There were two milestone points associated with Phase 3:

- MS4 (M27) – Automated robotic and CNC system satisfying industrial needs (WP1)
- MS5 (M33) - Demonstrators for field testing produced to specifications outlined in WP1

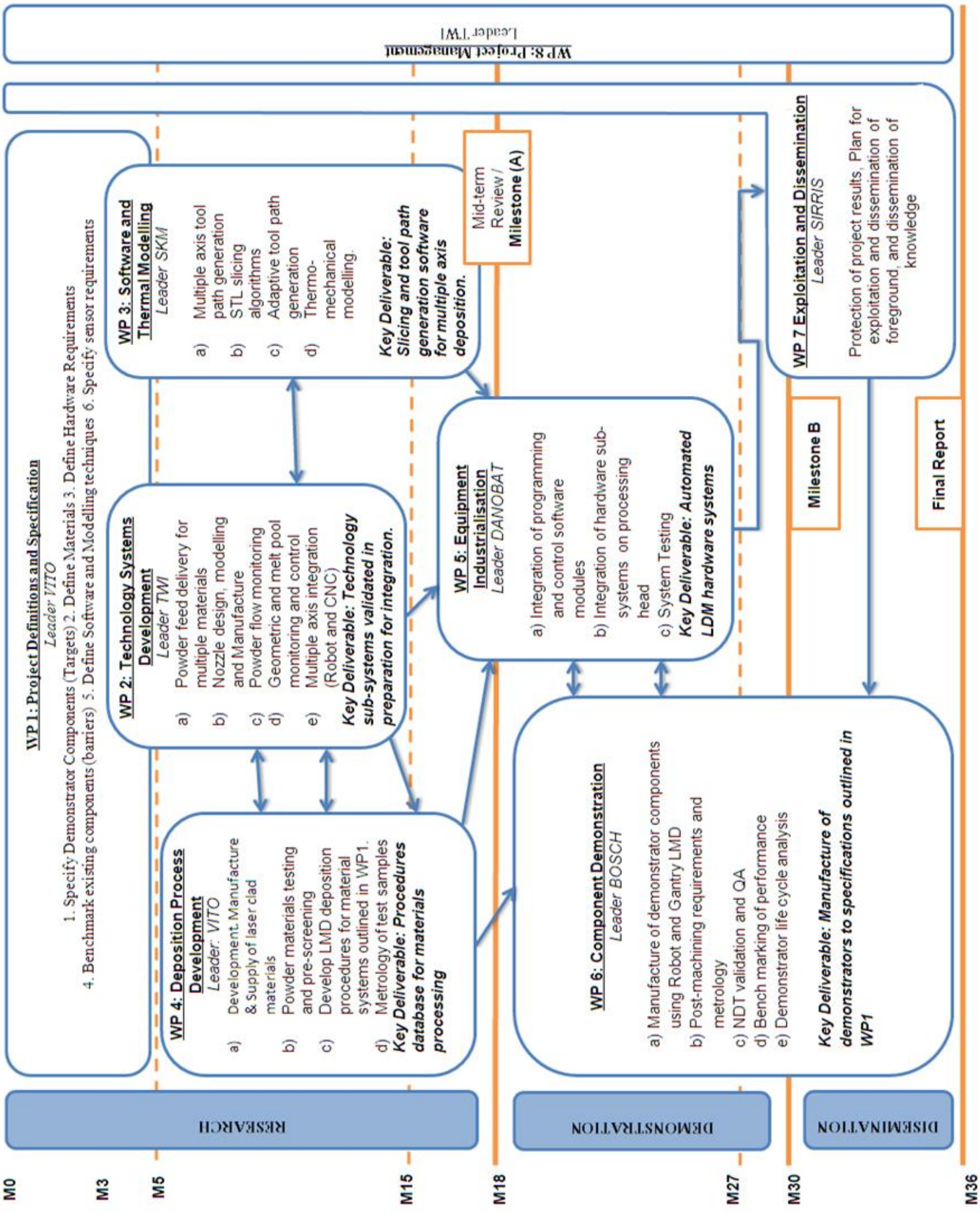


Figure 4.1: AMCOR Pert Diagram

4.1 Work Package 1: Project Definitions and Specification

Start month: ***Month 1***
Schedule Completion: ***Month 5***
Status: Completed

Task	Task Title	Start Month	Scheduled End Month	Status
1.1	Demonstrator Identification, Requirements and Benchmarking (BOSCH)	1	5	Complete
1.2	Technology Specifications and Assignment to Demonstrators (TWI)	1	5	Complete
1.3	Interfacing Specifications (BCT)	1	5	Complete
1.4	Testing (VITO)	1	5	Complete
1.5	Powder Material Recycling (Oerlikon)	1	5	Complete

Deliverable	Deliverable Title	Delivery Date	Status
D1.1	AMCOR Specification Document	8	Complete

4.1.1 Introduction and Objectives

This WP aimed at outlining the description, requirements and testing procedures associated with the demonstrator components supplied by the AMCOR end users. Using the integrated LMD hardware and procedures developed in AMCOR, these demonstrator components were either repaired, coated or additively manufactured (3D geometries). For most components, deposition was combined with post-machining steps. Alongside the demonstrator specification, the requirements of the LMD hardware, its integration and implementation with the technology subsystems was also defined within this work package.

The main objectives of the work package were:

- To specify component demonstrators and materials specifications (T1.1)
- To benchmark demonstrator performance and define performance targets (T1.1)
- To finalise the research development methodology and technology operation targets (T1.2-1.3)
- To define hardware sub-system performance targets (T1.2)
- To define component testing and analysis procedures (T1.4)
- To define the validation procedure of powder recycling (T1.5)

The outcome of this WP was deliverable 1.1 - AMCOR Specification Document. This document was a live document that evolved during the course of the project.

4.1.2 Key Technical Achievements

Task 1.1 Demonstrator identification, requirements and benchmarking
In total 5, demonstrators were selected from end users VCST (additive manufacturing of prototype automotive gear), EKIN (repair of broaching tools), BOSCH (coating of piston rods), SKODA (coating of valve stems) and DENYS (coating of cutting rollers for mining).

Within this task, Bosch piston rods and Denys cutting rollers were selected to determine reference levels of their environmental impact for their demonstrators. Figure 4.2 shows that the most important contribution to the environmental impact of the cutting rollers comes from the production of the disc and the tungsten carbide teeth. In comparison, Figure 4.3 focusses on the impact of the plasma transfer arc process. The impact is mainly determined by the tungsten carbide powder, electricity used for the coating process and the matrix (especially due to nickel, and also chromium for human toxicity cancer effects and silicon for water depletion).

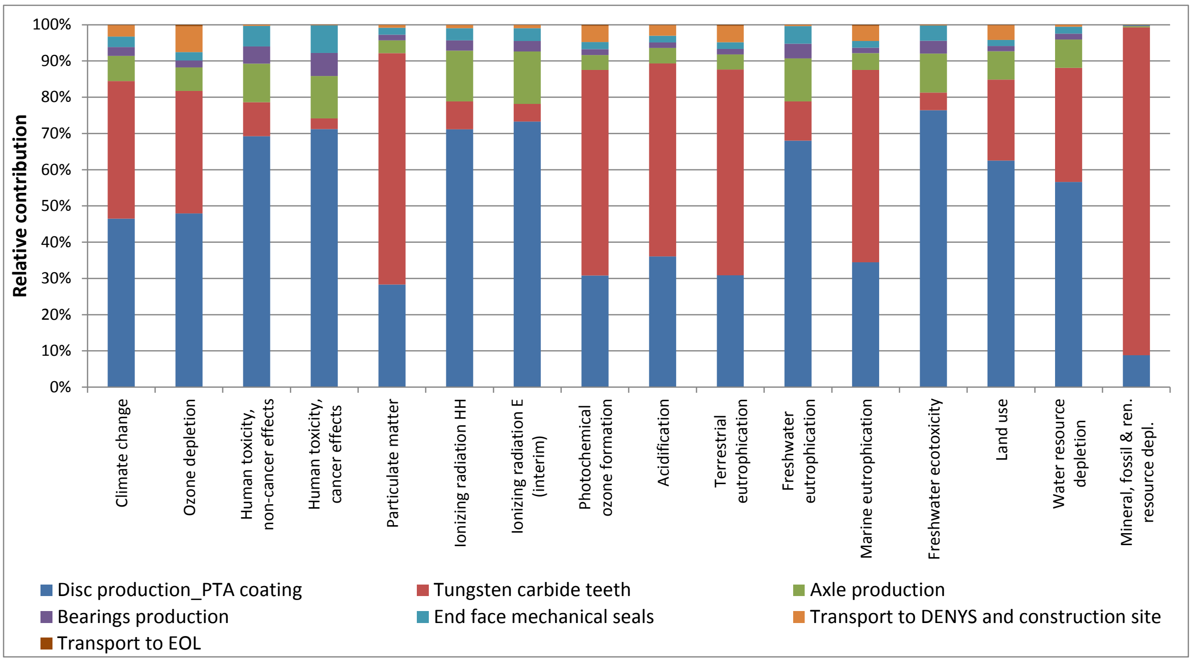


Figure 4.2: Impact assessment of Denys cutting rollers

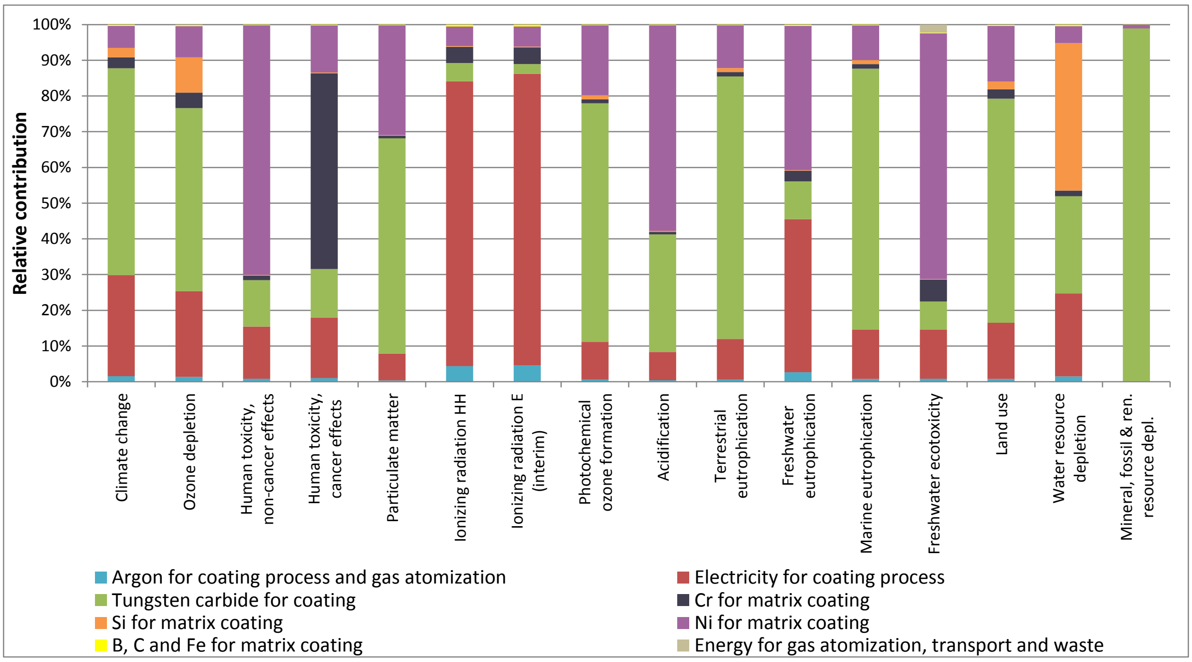


Figure 4.3: Impact assessment of the PTA process during the manufacture of Denys cutting rollers

Task 1.2 Technology Specifications and Assignment of Demonstrators

This task focussed on specifying the technology developments made within the project and the integration of new technology into the two AMCOR LMD systems at TWI and VITO. Figure 4.4 shows the individual modules of each technology system. Note, that the Ideko melt pool monitoring system developed in the project was only installed on the CNC system (and tested offline) while the BCT laser scanner and software was only installed at TWI on the robotic LMD system.

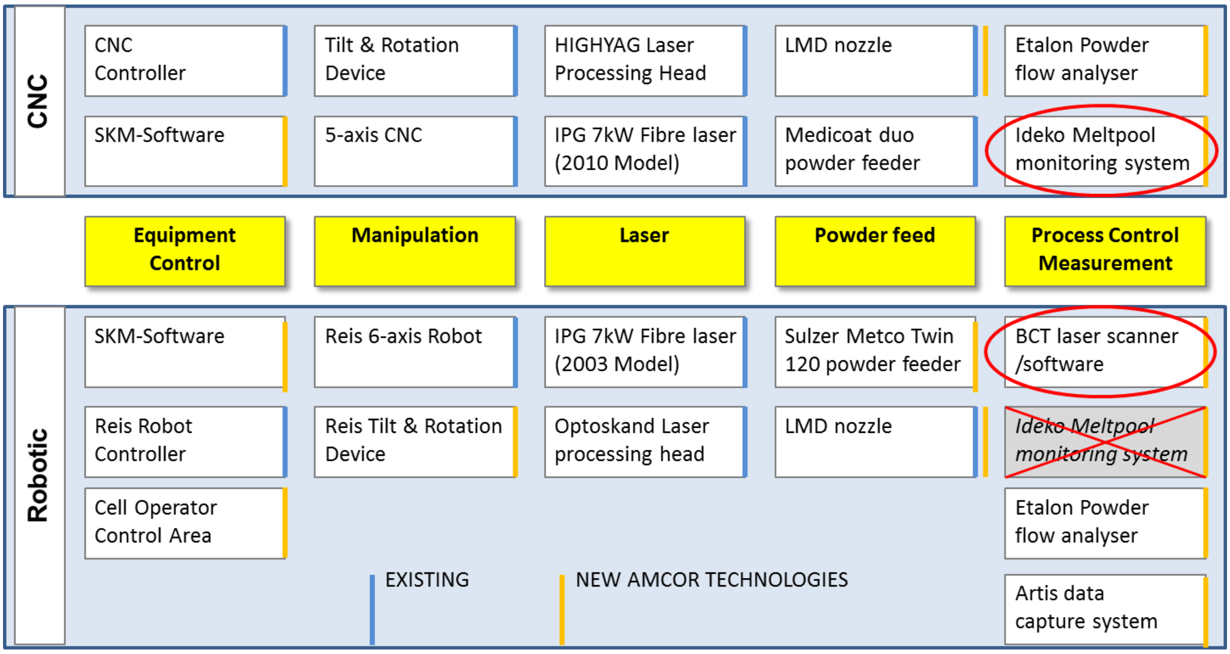


Figure 4.4: Individual technology modules of the two AMCOR LMD systems. The NC machine based system is located at VITO in Belgium and the Robot based system is at TWI in the UK.

Table 4.1: Assignment of End User Demonstrator components to each AMCOR system and the technical justification for the assignment.

Demo Owner	Robot LMD System located at TWI	CNC based LMD system located at Vito
VCST		High geometrical accuracy requested by end user. CNC machine has higher accuracy than robot
Bosch Rexroth		Process monitoring & control will be developed on CNC (reliability very important)
Skoda	Tilt/rotary with tail stock to handle cylindrical components. Rectangular beam for thin, flat coatings. Access to NDT for surface inspection.	
Ekin	Repair application & relatively small features. Geometric scanning system and experience of conventional welding of material onto hard substrates.	
Denys		Already expertise at Vito on the development of cutting rollers.

Task 1.3 Interfacing specifications
The interfacing specification was fully outlined in the AMCOR specification document D1.1. This provided information on the communication interfaces between the various technologies modules/components used within AMCOR. As with other areas of AMCOR technology development, the type of data and information transferred between system components changed as development and integration progressed. This resulted in a number of iterative changes of the specification document.

Task 1.4 Testing
This task focussed on defining the testing protocols for each of the chosen powder systems and the demonstrators within the AMCOR project. These were defined with help from end users and research beneficiaries within the consortium. A summary of the agreed testing to be carried out, mainly in WP6 in the latter stages of the project, can be seen in table 4.2 below.

4.1.3 Deviations from work plan

All tasks within WP1 were delayed by 3 months due to the involvement and amount of work toward finding a suitable integrated LMD solution for the diversity of demonstrators within AMCOR. This delay caused a small delay during the start-up phase of WP4.

4.1.4 Progress beyond current state of art

In this WP no developments in the area of technologies, hardware, software or materials have been done. The aim here was to derive a new and efficient integration of subsystems using pre-existing equipment and ideas.

Table 4.2: Outline of testing to be carried out on each demonstrator.

Application	Lab-scale testing	Prototype testing, mainly in DEM phase
VCST Gear	Microscopy, dimensional control & hardness	Dimensional control & hardness Visual inspection (Pore/cracks)
		Wear against Hertzian loading Resistance against bending
EKIN Broaches	Microscopy, dimensional control & hardness	Dimensional control Visual inspection (Pore/cracks)
	Wear: small test setup of a broach	Broaching process in x thousands parts
BOSCH REXROTH Hydraulic piston rods	Microscopy, dimensional control & hardness Chemical composition: XRF	Dimensional control Visual inspection (Pore/cracks) XRF & BR internal procedures
	Bending test Abrasion & scratch testing Impact test	Wear and corrosion: see lab-scale test
	Corrosion: Salt droplet & evt. ASTM G48, salt spray, AASS/CASS	
SKODA Steam inlet valve for turbines	Microscopy, dimensional control & hardness Temperature cycling test	Dimensional control & surface hardness Visual inspection & Penetration test Magnetic test
	High-cycle fatigue Pin-on-disc test at 600 – 650°C Short-term high-temperature oxidation test	Scaled-down valve spindles under real condition; short-term test (one or several months long)
DENYS Cutting rollers	Microscopy & hardness Penetrant	Dimensional control Visual inspection (Pore/cracks) &penetrant
	Abrasive wear Indentation test	Labscale test setup Drilling as usual and monitor wear frequently

4.2 Work Package 2: Technologies Development

Start month: ***Month 3***
Schedule Completion: ***Month 15***
Status: Completed

Task	Task Title	Start Month	Scheduled End Month	Status
2.1	Robot LMD System: (TWI)	1	8	Complete
2.2	CNC LMD System: (DAN)	1	8	Complete
2.3	Powder Feed and Nozzle development: (TWI / Oerlikon)	1	10	Complete
2.4	Tomographic Powder Flow Density Sensor: (ETN)	1	15	Complete
2.5	Real Time Melt Pool Monitoring and Control System: (IDEKO)	1	15	Complete
2.6	Vision Based Control System: (BCT)	1	15	Complete

Deliverable	Deliverable Title	Delivery Date	Status
D2.1	Installation of LMD Robotic System at TWI	8	Complete
D2.2	Dual powder feeder and nozzle installed on Robotic LMD for initial validation trials.	10	Complete
D2.3	Tomographic Powder Flow Density Sensors (2) for inline trials	15	Complete
D2.4	Process monitoring & control system for multi-layer & -material build up delivered for validation	15	Complete

This WP aimed at the installation and the development and integration of technology subsystems onto the robotic LMD system. The powder flow sensor was also validated on the gantry LMD system.

4.2.1 Key Technical Achievements

Task 2.1 Installation of LMD robotic system at TWI.

As outlined in D1.1 the AMCOR specification document, the Robot based LMD system at TWI was an integration of several additive manufacturing related technologies supplied by multiple different manufacturers. One problem with this approach, but one that is commonly seen with research and development systems, is the lack of control systems integration i.e. the use of one HMI (human machine interface) for all equipment control.

Within the AMCOR project effort focussed towards creating an Operator Control Area that puts all necessary equipment controls within easy reach of the Robotic LMD cell operator.

In order to successfully deposit onto some of the AMCOR demonstrator components, for example the long cylindrical type components supplied by both Bosch and Skoda, additional manipulation capability was required to be installed into the robotic LMD cell at TWI. This included the installation of a fully interpolating tilt/rotary set of axes. This consisted of a large payload capacity (500Kg) tilt/rotary table with a large diameter faceplate (600mm), and an associated tailstock that can be positioned at any distance (along the axis of rotation) away from the from the tilt/rotary table up to a maximum of 3.0m. A REIS RV60-40 robot manipulator was also chosen and integrated with a reach of 2500mm and a payload of 40Kg. Figure 4.5 shows the AMCOR robot cell.

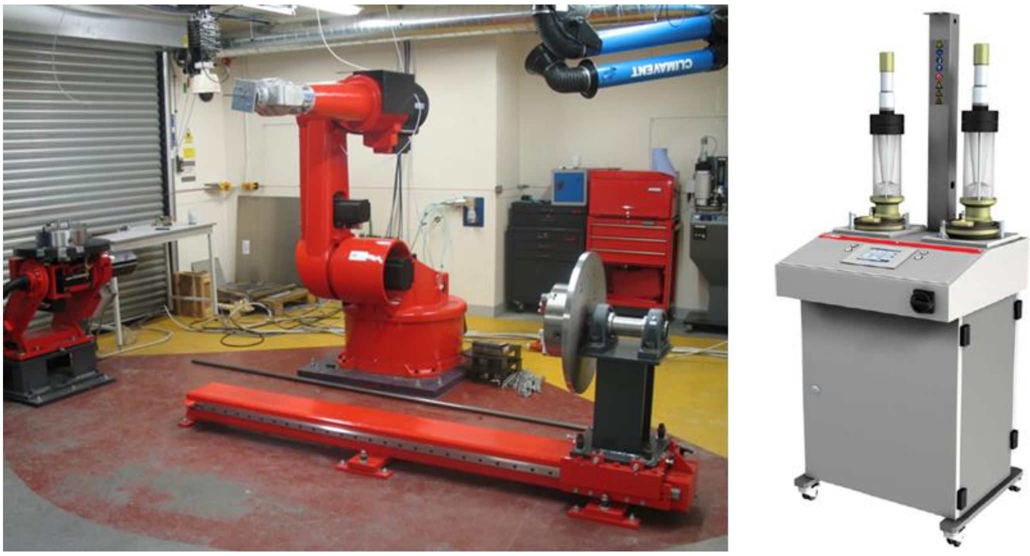


Figure 4.5: AMCOR robot LMD cell and FGM powder feeder prototype developed within the AMCOR project.

Task 2.3 Powder Feed and Nozzle development.

During project progression, the end-user requirements became more defined and it became clear that the primary requirement for LMD nozzle technology was consistency of powder flow rather than a need to deposit multiple materials for functional layers. The functional graded material requirement originally envisaged for the demonstrators during the proposal phase of the project proved largely unnecessary. For this reason, the AMCOR consortium agreed that an existing commercially available nozzle should be purchased for the project rather that wasting resource in developing a new nozzle. However, it was also recognised that a better powder feeder system would be required to deliver powder more consistently to the nozzle. This included mixing of different powders at source rather than in the nozzle. For this reason, a commercial deposition head was sources for integration onto the robot LMD system. This head consisted of a Fraunhofer-ILT 3-Beam type LMD nozzle with specific features including good powder focusability, 3D build capability, and a solid robustness making it less susceptible to powder blockages and minor knocks. This nozzle was also capable of supplying both powder and an inert shielding gas to the substrate. This nozzle was integrated to a Trumpf variable optic process head and a Trumpf 6KW disc laser made available at TWI. For powder feeding a Oerlikon Twin 120 series powder feeder was chosen and integrated to the robotic LMD system. This system is well established and based on a rotating disc metering and delivery system. Furthermore, within the AMCOR project Oerlikon developed a next generation powder feeder specic for additive manufacturing which was based on the 120 series systems (see Figure 4.6). The developed system gave imrproved powder feeding accuarcy and improved control over mixed powders.

Task 2.4 Tomographic Powder Flow Density Sensor

The tomographic sensor was designed and built to detect a number of powder flow problems, each of which could adversely affect the quality of the LMD deposition:

- By mapping the distribution of powder exiting the nozzle, blocked, damaged, or misaligned jets can be identified.
- By measuring the position of the powder's "focal point", coincidence with the laser's focal point can be checked.
- By providing a real-time "video rate" measurement, fluctuations in powder flow can be identified.

As part of Task 2.4, a technology demonstrator prototype was designed and constructed. During this process, it was established that the sensors' LED emitters and photodiode array detectors could feasibly be housed (along with all the associated signal processing electronics) inside the ring casing, thereby doing away with fibre-optic cabling to link the two (as had initially been intended).The demonstrator hardware therefore comprises a single sealed ring-shaped sensor, containing 13 sets of emitter and detector modules. These continously measure the attenuation of light, caused by powder flowing within the sensor's central measurement area. The modules take it in turns to light their emitters, and thereby make independent attenuation measurements, 400 µs apart. The current detector modules comprise 20 individual photodiodes, which are sampled simultaneously by 16-bit ADCs (see Figure 4.7).

By virtue of being a completely self-contained unit; the tomographic sensor only requires a power connection and a USB connection to a PC. Installation within TWI's Robotic LMD cell therefore comprised little more than positioning the sensor within the work area, and connecting it to a laptop. The associated software provides a real-time display of the reconstructed powder density field, and this assists with positioning the LMD nozzle centrally within the sensor's central measurement area. Within AMCOR the sensor was used to successfully check for nozzle damage (or misalignment), and correct, unfluctuating powder flow rates, prior to deposition.

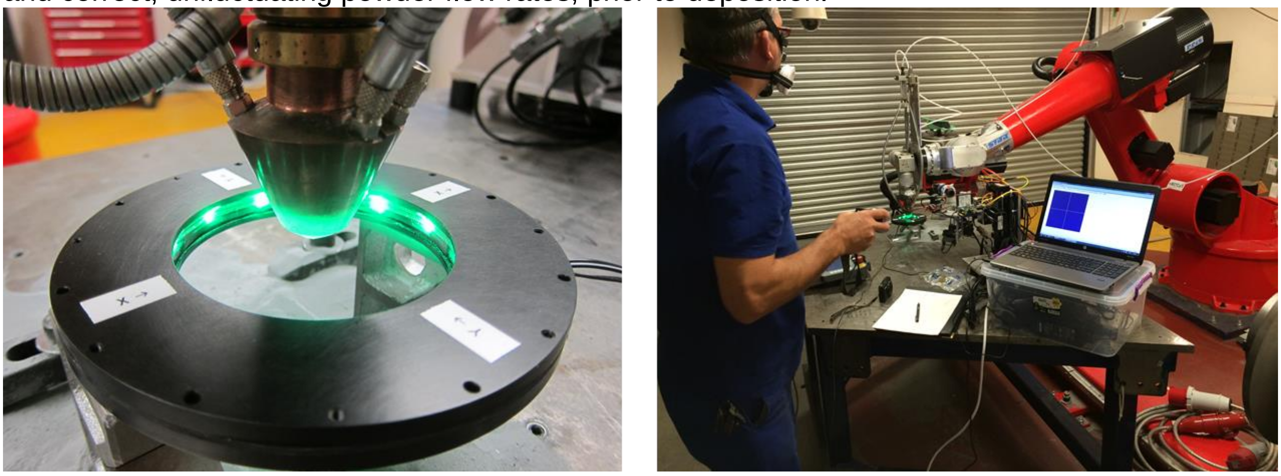


Figure 4.7: 3-jet LMD nozzle positioned above the tomographic sensor and integrated onto the robotic LMD system.

As a result of feedback given by end-users, it has been established that offline measurement of nozzle powder flow is of greater interest to LMD users than online measurement. As a result, Etalon Research simultaneously developed an alternative, camera-based, powder flow measurement sensor. The table below summarises the advantages and disadvantages of this approach vs. the tomographic sensor.

Table 4.3: Comparison between tomographic sensor and camera based sensor

	Tomographic sensor	**Camera-based sensor**
Advantages:	• Is capable of performing powder flow measurements in-situ. • Physically smaller sensor. • Higher-speed measurements.	• Higher-resolution measurement. • Simpler, cheaper hardware.
Disadvantages:	• Lower resolution. • Measurement accuracy dependent on powder characteristics.	• Can only ever be an "offline" measurement.

The camera based system uses a laser, formed into a thin horizontally-oriented light-sheet, and a camera mounted beneath and to one side of the jet (see Figure 4.8).

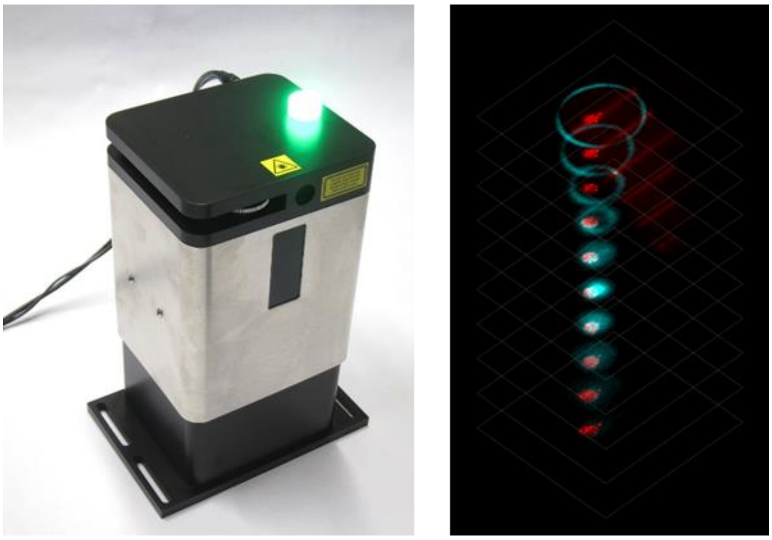


Figure 4.8: Camera based LMD power flow sensor

The camera based flow sensor coupled with software developed in AMCOR offers a unique 3D powder distribution measurement system with simultaneous referencing information of the laser.

Task 2.5 and Task 2.6 Process monitoring and control

These tasks focused on the development of the geometric scanning system and the melt pool monitoring system.

Process Monitoring

In order to be able to use the TWI Robot for laser scanning, BCT and Olympus UK developed a solution that did not require any external tracking device, but was able to gather the required robot data from the machine controls.

One of the key achievements to make the scanning possible is a PLC / NC routine written by Olympus. This routine enables the robot to store tool centre point data along with sending out trigger signals to the sensor controller. The laser sensor controller then gathers one scan line for each incoming trigger signal and sends out the scanned data.

These two data sets - tool centre points and scanned laser lines - were used by BCT to calculate a digital part representation in a common coordinate system.

Furthermore, BCT was able to implement some compensation functions. These functions are required in order to compensate deviations of the scan data. The deviations occur when the robot is moved and the part is scanned multiple times with different tool tilt angles. To use these compensation features a reference sphere was mounted within the working area of the robot.

Early developments trying to find a generic solution for laser scanning on machine tools as well as on robots were unsuccessful due to restrictions within the laser scanner used within the AMCOR project. BCT had to fall back to a solution that could not be used with the VITO LMD machine tool. Before the AMCOR project, no commercial solutions were available for scanning on industrial robots without using an external measurement device e.g. laser tracker.

Process Control Monitoring

A camera based monitoring system for melt pool dimensions was also developed and demonstrated offline on the AMCOR gantry LMD system. The system allowed the monitoring of the melt pool to give better understanding of the effects of the process parameters on weld quality and melt pool dimension (see Figure 4.9). During the AMCOR project the system was only validated in an off line environment because powder contamination of lenses proved to be a problem and a more robust system would have to be developed before going into in-line operation.

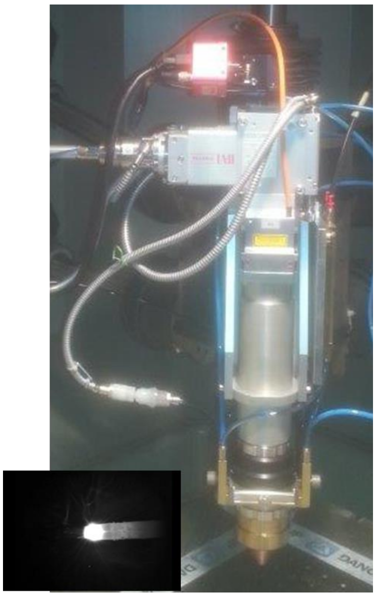


Figure 4.9: Camera based melt pool monitoring system

4.3 Work Package 3: Software and Thermal Modelling

Start month: ***Month 3***
Schedule Completion: ***Month 18***
Status: Completed

Task	Task Title	Start Month	Scheduled End Month	Status
3.1	STL Slicing Software for Multiple Axis FGM Manufacturing: (SKM)	3	18	Complete
3.2	Multiple Axis Tool Path Generation Software: (SKM)	3	18	Complete
3.3	Adapted Tool Path Generation Software: (BCT)	3	18	Complete

Deliverable	Deliverable Title	Delivery Date	Status
D3.1	Release of 10 axis, multi material adaptive slicing and tool path generation software	18	Complete
D3.2	Thermomechanical model developed and validated	18	Complete
D3.3	FEM study of impact of material properties and LMD deposition strategy on residual stress development	18	Complete

This WP focused on the development of highly automated CAM programming software, for up to 10 axis, for robotic and CNC nozzle manipulation. Alongside this work, there was also a focus on the development of an automated process flow to automatically compensate deviations in the actual deposited material compared to the LMD toolpath generated from the original CAD model. This was supported by modelling to predict thermal stresses and distortions during LMD processing.

4.3.1 Key Technical Achievements

Task 3.1 STL Slicing Software for Multiple Axis FGM Manufacturing.

Within the framework of the AMCOR project the requirement of a flexible and automated approach resides in the software it has developed and in particular, the generation of a suitable tool path from processed CAD data. The software developed was suitable for multiple axes robotic and CNC based LMD. These new functionalities were implemented in commercial DCAM software of SKM.

Within the DCAM software a new functionality has been implemented enabling the definition of a graded material structure as a function of build height within the part. The variation in composition between two powders can be freely adapted by defining points within the graph shown in Figure 4.10.

In most additive manufacturing processes the slicing planes should be parallel horizontal 2D planes. However, the benefit of laser metal deposition is the possibility to build up structures in a multi-axis way on existing 3D freeform surfaces with a varying build direction depending on the location in the part. In the AMCOR project, this multi-axis build up was applied for the VCST gear. For this demonstrator component the slicing planes should be concentric cylindrical planes with increasing diameter. This new functionality is implemented in the SKM software as shown in the figure 4.10.

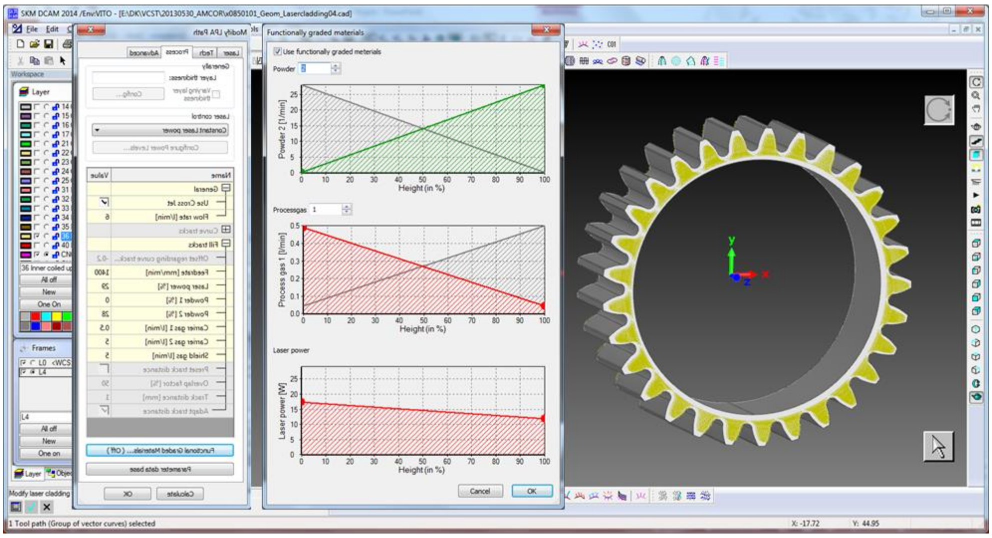


Figure 4.10: Screenshot of AMCOR plugin to DCAM software for multiple material deposition.

Task 3.2 Multiple Axis Tool Path Generation Software.

For the robotic LMD at TWI, SKM has developed a module for 8-axis deposition with the modeled robot cell installed at TWI. This partial solution was tested for the EKIN demonstrator part and for coating the Skoda demonstrator (see Figure 4.11).

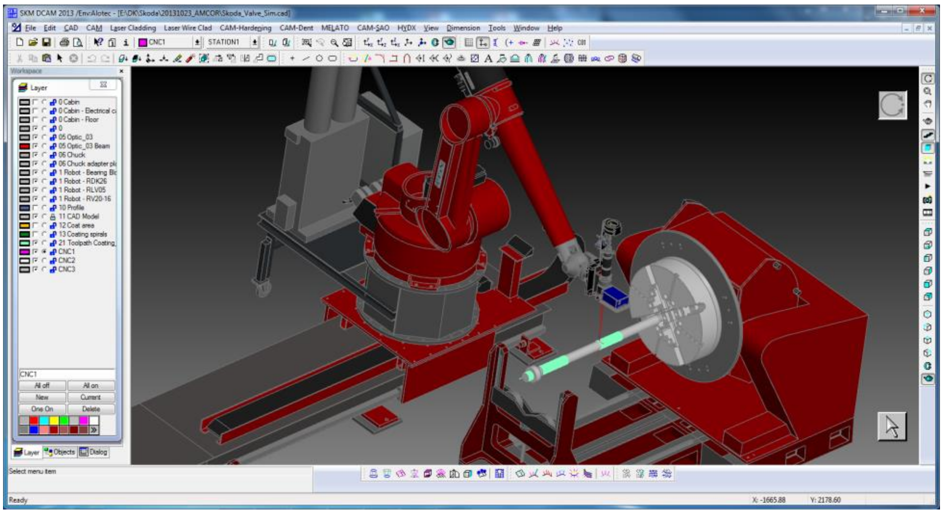


Figure 4.11: Screenshot of AMCOR plugin to DCAM software for robotic LMD.

Task 3.3 Adapted Tool Path Generation Software.

This task focused on the development of a thermo-mechanical model to simulate the transient thermal behaviour during the laser cladding process. The transient thermal analysis forms the basis for the prediction of the residual stresses. The model was validated with measured comparisons to actual geometric deformations following LMD (see Figure 4.12). This information was then used to help adapt toolpaths during processing.

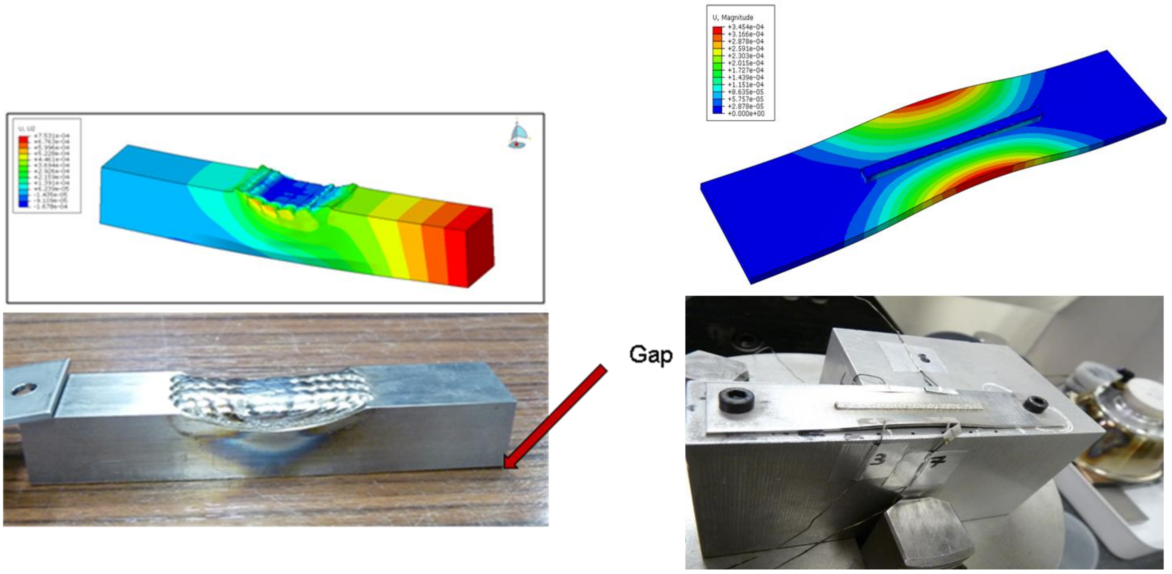


Figure 4.12: Validation of Thermo-mechanical models.

On the effect of Young's modulus and yield properties of the cladding, the 2D simulations indicate that in the case of uniform thermo-mechanical properties between base and cladding, an intermediate layer with half the stiffness does not seem to reduce the strain concentrations near the interface. Only very soft layers (with Young's modulus 30 times smaller than the base material) are likely to have a clear positive effect on local hot spots.

Reducing yield and tensile properties of the first layer did not indicate a beneficial effect on the strain concentrations near the interface. In case of non-uniform material properties, as for example the stellite cladding on AISI316 substrate, an intermediate layer with half the stiffness has a definite positive effect on the strain concentration near the interface.

For overlapping or superimposed cladding tracks, there is a stress relaxation on the previous track due to the heating provided by the deposited track, and also a change in the stress profile due to the strains and stresses developed during the cooling down of the deposited track. The highest stresses are located in the zone between 2 clad tracks and also in the interphase between the clad tracks and the plate.

Parameters leading to lower thermal gradients tend to produce lower stresses and lower distortions on the plate. Specifically the preheating of the plate (followed by process velocity) are the most influential parameters regarding the lowering of the stresses. This information was fed back to SKM and BCT who were developing software for toolpath generation and toolpath modification.

4.4 Work Package 4: Deposition Process Development

Start month: ***Month 5***
Schedule Completion: ***Month 18***
Status: Completed

Task	Task Title	Start Month	Scheduled End Month	Status
4.1	Powder Development, Manufacture, Supply and Characterisation (Oerlikon)	5	12	Complete
4.2	Pre-screening Assessment of Material Properties after LMD (VITO)	5	12	Complete
4.3	Metrology and Post-machining Requirements (BCT)	5	16	Complete
4.4	Process Reliability Study (TWI)	5	16	Complete
4.5	Selection of LMD Procedures for Demonstration Phase (VITO)	5	18	Complete

Deliverable	Deliverable Title	Delivery Date	Status
D4.1	Screened Materials suitable for Demonstrator procedures development	12	Complete
D4.2	Post LMD Machining Requirements	14	Complete
D4.3	Procedures database for materials processing by LMD (Demonstrator Development)	18	Complete
D4.4	Selection of LMD procedures for production of demonstrators	18	Complete

4.4.1 Introduction and Objectives

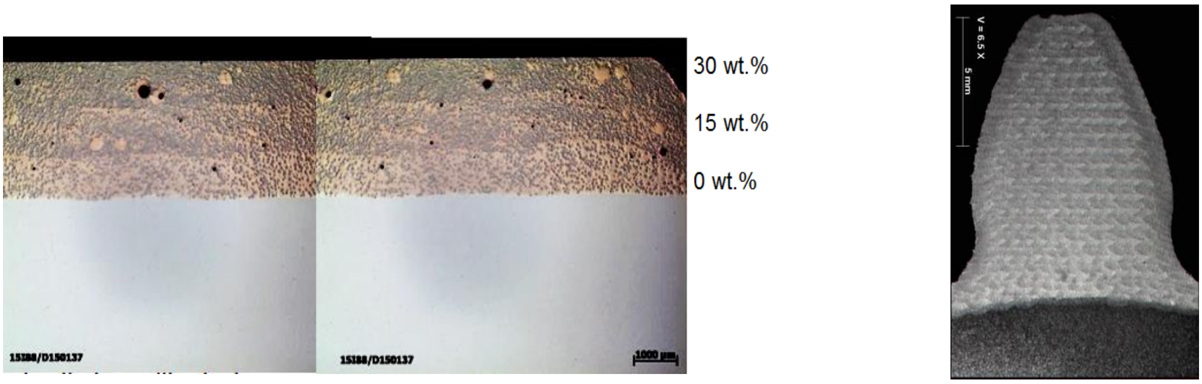
This WP aimed at developing and pre testing the gradient material and the metal deposition procedures for the two LMD systems (Gantry and Robot). A first stage involves development of powders, which are then deposited by LMD using different strategies. The deposits were fully characterized. This information together with powder efficiency, cost, productivity, reproducibility and machinability formed the basis for the selection of LMD procedures to be tested in the demonstration phase (WP6).

4.4.2 Key Technical Achievements

Task 4.1 Powder development, manufacture, supply and characterisation
Single material as well as multiple layer & multiple material deposits have been specified for the 5 demonstrators. The initial selection of powders (about 15) is detailed in Amcor deliverable D4.1.
Apart from the Denys demonstrators (cutting rollers for mining), all deposits are produced from metal alloy powders. For the Denys demonstrator, a wide variety of mixtures composed of a nickel alloy binders and tungsten carbide powder have been used as feedstock. The content of carbide powder was varied across the different layers.

Task 4.2 Pre-screening assessment of material properties after LMD.
Pre-screening of all materials was performed by visual inspection, metallographic analysis, indentation and 2-body abrasive wear testing, as illustrated in the figures below. In the demonstration phase of the project application oriented materials characterisation was completed by the end users. Full details of this task are found in the Amcor deliverable report D4.1. In general, new LMD deposits were manufactured with higher hardness and wear resistance than the reference material (e.g. PTA coating, conventional hardened steel) of the demonstrators. Crack-free metallic

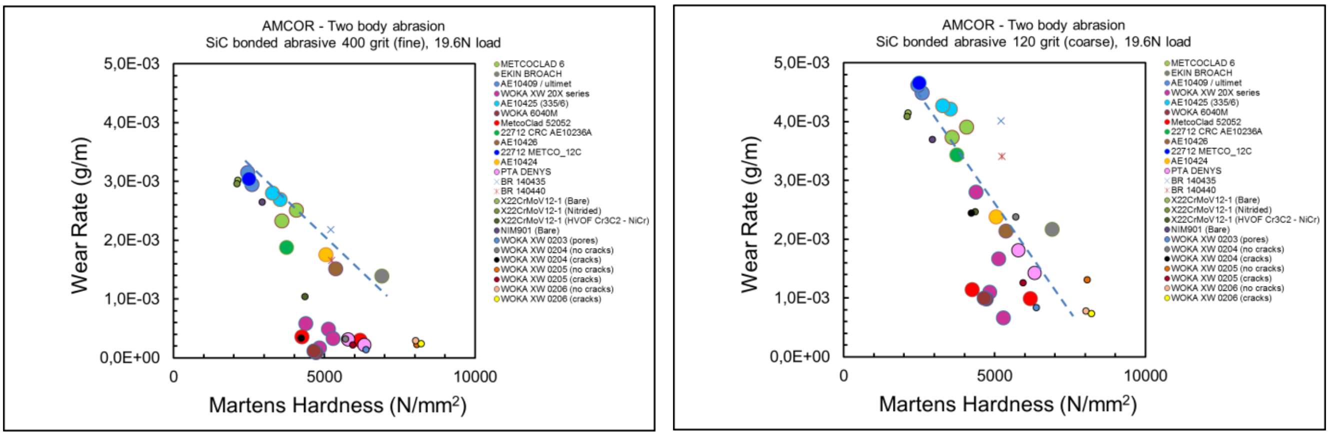
deposits were produced with hardness up to 800HV. For metal-ceramic deposits, a maximal carbide concentration of ~75wt%, being about 60vol%, has been attained in crack-free deposits. Further details on the results of the deposition trials are given in WP6.



(a) Multi-layer Nickel alloy – Tungsten carbide deposit

(b) Harder steel at skin and more ductile steel in core

Figure 4.13: Metallographic sections of multi-material deposits: (a) Nickel alloy with up to 60 vol% WC and (b) 2 steel combinations at resp. skin and core.



(a) (b)

Figure 4.14: Two-body abrasive wear rate against (a) fine and (b) coarse abrasives for different LMD deposits as a function of their hardness.

Task 4.3 Metrology and post machining requirements

Post LMD requirements were defined and collated (see Amcor deliverable D4.2 and a summary given in the table below). From the perspective of post-processing, the new manufacturing approaches and the improvement of the wear and corrosion resistance, did not present any new problems. The post-processes had to be adjusted to the new materials used, but did not need to be completely reorganised.

Part	Owner	Description	Post-processes	Consequence
1	Bosch	Hydraulic cylinder for offshore	Milling, grinding	No changes to procedure used today
2	Denys	Roller for tunnel drilling machines	n/a	none
3	Ekin	Broaches	Grinding	Same grinding technology used as in conventional production
4	Skoda	Valves for steam turbines	Grinding Ra=0,8µm Straightness 50µm	Produce part with some overmeasure
5	VCST	Gear	Grinding	Drastic change to procedure today; hobbing eliminated

Task 4.4 Process reliability study.
Vito's developments included both cladding of simple cylindrical surfaces with promising high performing materials and the deposition of complex geometric shapes to tight tolerances. Oerlikon used their significant experience with MMC's to investigate further possible improvements when using the LMD process in relation to Denys demonstrator. TWI developments including observations of process reliability and validation through the use of CT scanning to ensure no further cracking tool place during material preparation work.

Task 4.5 Selection of LMD procedures for demonstration phase
The best performing LMD setup and material concepts relevant to each End User application were identified based on lab-scale LMD tests and materials characterisation (see Amcor Deliverable D4.4). This information served as the starting point for the production of demonstrators in WP6.

4.4.3 Deviations from work plan

- There was a substantial delay in D4.4, in particular with regards to TWI deposition activities. Due to the highly crack sensitivity of the SKODA deposition material (Triballoy 800) and the substrate of the Ekin broaching tools (M35), a new induction heater had to be source which allowed the development of programmable heat up and cool down rates which could be further managed in process. This delayed the start of the production of Ekin & Skoda demonstrators in WP6.
- Because of the multitude of material concepts and time constraints, materials characterization in WP4 only covered metallographic analysis, indentation testing and abrasion wear testing. It was decided to move more demonstrator specific materials testing to WP6. This including life cycle impact of two the demonstrators.

4.4.4 Progress beyond current state of art

- LMD process parameters have been optimised for powders that are not considered commercially available for LMD. Knowledge has been gained about their microstructure, hardness, stiffness and abrasive wear resistance at lab-scale.
- Deposits with high hardness (≥800HV) and promising abrasive wear resistance have been deposited crack-free.
- The LMD process has been developed for the automated and local deposition of multi-material 3D features on 3D components with high geometrical accuracy.
- The repair of the Ekin broach, which included the deposition of M2 tool steel onto a M35 substrate, was successfully achieved without cracking or delamination of the deposited material or substrate. The key was in the careful selection of different substrate temperatures during deposition and cool down. Previous to the AMCOR project, no method had been found to successful deposit the required materials.

4.4.5 Future Aspirations

- The expertise acquired by TWI within WP4 related to LMD procedures and methodology for deposition of novel materials. This acquired knowledge will be used to assist members of TWI who have similar wear and corrosion applications. The results of AMCOR have caught the attention of many TWI members. This has led to a 250K euro core research project that continues the work of AMCOR for TWI members, primarily in the sectors of oil and gas , power generation and tool making.
- The expertise acquired by Vito within WP4 related to LMD procedures and methodology for deposition of novel materials will be valorised by the recent spinoff of Vito, LCV. LCV will offer LMD services to industry, including LMD of the novel materials investigated within AMCOR.
- Oerlikon plans to put new powders for LMD, which have been tested within AMCOR, on the market.

4.5 Work Package 5: Equipment Industrialisation

Start month: ***Month 15***
Schedule Completion: ***Month 27***
Status: Completed

Task	**Task Title**	**Start Month**	**Scheduled End Month**	**Status**
5.1	Integration of Software Modules	15	22	Complete
5.2	Assembly of Processing Head and Tomographic Sensor	15	22	Complete
5.3	Integration of Laser Scan Sensor in Machine.	15	22	Complete
5.4	Assembly of Automated CNC and Robot LMD Machine	15	24	Complete
5.5	Pilot Trials	15	27	Complete

Deliverable	**Deliverable Title**	**Delivery Date**	**Status**
D5.1	Integration of software modules onto LMD hardware and tested for demonstrator suitability.	22	Complete
D5.2	Integration of LMD processing head on Robotic system.	24	Complete
D5.3	Robot system configuration for multi-material LMD	27	Complete
D5.4	CNC system configuration for multi-material LMD	27	Complete

4.5.1 Introduction and Objectives

In WP2 several technologies were developed to optimise the laser metal deposition process, leading to new equipment, software and components. The main goal of WP5 was to integrate these developments into two systems in order to obtain two fully functional LMD systems suitable for AMCOR demonstrator manufacture in a productionised way. In order to take full advantage of the possibilities offered by LMD processes, the two systems were chosen to be a CNC based system and a robot based system. The final goal of WP5 was to validate the two complete systems to be used for process development for the different applications on WP6.

4.5.2 Key Technical Achievements

Two fully functioning systems for laser metal deposition have been obtained within the timeframe of the AMCOR project. These systems are (see Figure 4.16):

- A CNC based LMD system, with a closed loop monitoring system to adjust the melt pool size to the target value for each particular point; and a powder monitoring system to ensure a proper powder distribution.
- A Robot based system, including a laser scanner to measure on line the geometry of the part, and be able to correct (if required) the program responsible for the Laser Metal Deposition.

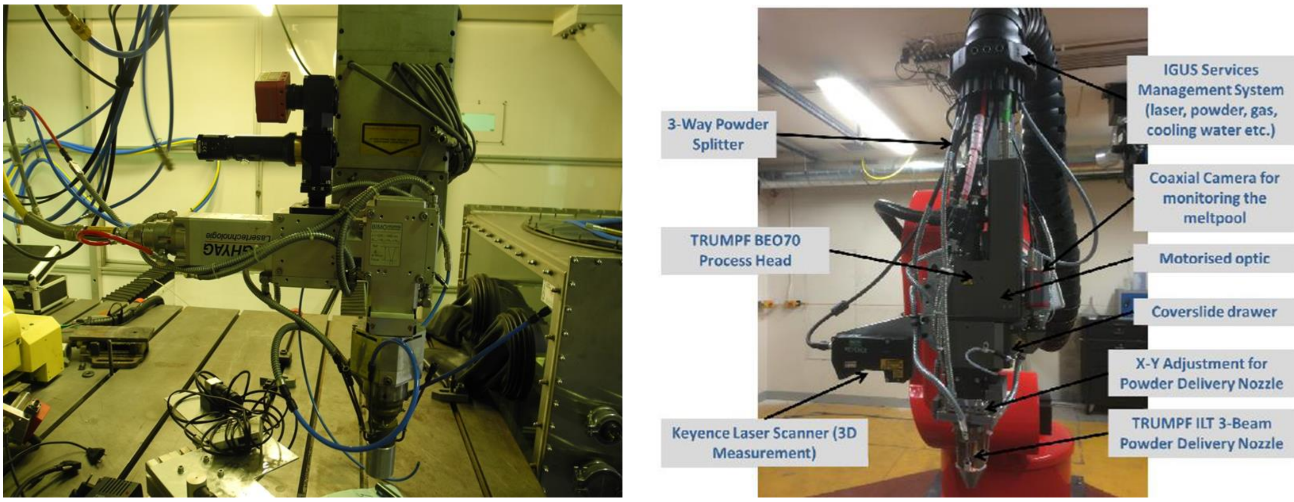


Figure 4.16: CNC and Robotic based LMD systems.

Both of these systems are able to work with CNC programs generated by the DCAM CAD-CAM software developed in AMCOR that allows defining the trajectories, parameters, and parameters for the closed loop control for the laser cladding process.

BCT integrated software modules for the adaptive process, together with SKM, and the integration of a laser scanning system in cooperation with TWI and Olympus UK. For the software integration BCT had to provide an appropriate digital representation of the part geometry that could be used by SKM for the generation of tool paths for the LMD process. This is the outcome of the scanning solution developed within the AMCOR project. The scanning system was integrated on the TWI Reis robot in cooperation with AMCOR partner OLP. The sensor head used was mounted near the LMD nozzle in order to be able to scan quickly before or after the LMD process. The sensor requires a controller and power supply which are mounted on the robots shoulder and connected with the robot controls via a trigger cable. Both systems also had integrated the powder flow sensor to ensure consistency of material supply prior to the cladding process.

4.5.3 Deviations from work plan

- Due to a delay in delivery of the process monitoring & control system (WP2), only limited testing related to process reliability could be performed in WP4. Testing of the monitoring & control system was moved to the demonstration phase and primarily conducted as an offline demonstration study.
- Due to the complexities of integrating an in process line scanner with the robot controller at TWI, this activity was delayed. Solutions were found and eventual demonstration took place using the Ekin demonstrator in WP6. This primarily involved the mapping of the deposition site and location of existing teeth so that an appropriate toolpath to build a broken tooth could be carried out whilst avoiding collisions with the existing neighbouring teeth.

4.5.4 Progress beyond current state of art

The relevance of the key technical achievements when compared with the current state of the art is the integration of two systems oriented to the manufacture of coatings and 3D structures for single and mixed material components (tool path generation, closed loop control…), and including quality control for the system and process (tomographic sensor, and geometric inspection).

The scanning solution integrated without any external tracking devices is far less expensive and complex to integrate and handle within machining cells than scanning solutions available before the AMCOR project.

4.5.5 Future Aspirations

The main beneficiaries of the results of WP5 are the partners involved with the integration of the complete systems: Vito and Danobat for the CNC based laser equipment and TWI and Olympus for the Robot based equipment.

Also, the developers of the different technologies (BCT, Etalon, IK4-IDEKO, SKM) benefit from this WP, and the insight gained regarding the use and integration of their technology in an industrial system. This complements the knowledge obtained by these partners on WP2, where the main part of the development of the different technologies has been performed. The knowledge about integration of scanning solutions on industrial robots will be used and refined within national development projects to be later used in commercial solutions.

4.6 Work Package 6: Component Demonstration

Start month: ***Month 18***
Schedule Completion: ***Month 36***
Status: Completed

Task	Task Title	Start Month	Scheduled End Month	Status
6.1	Preparation Phase:	18	22	Complete
6.2	Laser Cladding of Demonstrator Components:	18	28	Complete
6.3	Post-Machining and Metrology	18	32	Complete
6.4	NDT Validation and Quality Assurance	18	34	Complete
6.5	Performance Benchmarking	18	34	Complete
6.6	Demonstrator Life Cycle Impact	18	36	Complete
6.7	Performance/Cost Analysis of Robot vs. CNC:	18	36	Complete
6.8	Commercial Feasibility Study for CNC LMD:	18	36	Complete

Deliverable	Deliverable Title	Delivery Date	Status
D6.1	Manufactured LMD demonstrators For DENY	32	Complete
D6.2	Manufactured LMD demonstrators for SKODA	32	Ongoing
D6.3	Manufactured LMD demonstrators for BOSCH	32	Complete
D6.4	Manufactured LMD demonstrators for VCST	32	Complete
D6.5	Manufactured LMD demonstrators for EKIN	32	Ongoing
D6.6	Benchmarking study of demonstrator performance	34	Ongoing
D6.7	Life cycle Impact of 2 demonstrators	36	Ongoing
D6.8	Cost – performance analysis of robot vs. CNC based LMD	36	Ongoing

4.6.1 Introduction and Objectives

This work package focused on the scale up of the deposition procedures from the development phase to the demonstration phase using the LMD equipment and integrated technology sub-systems. Performance benchmarking of the two LMD AMCOR systems was also conducted and a life cycle impact of two demonstrators was performed.

During the preparation phase, detailed specification of the demonstrators was carried out. Operating conditions of each demonstrator were analysed and cladded areas of all demonstrators were identified. Requirements on quality of the coatings including content of volumetric and surface defects, final machining, surface roughness, etc. were established. Functional properties of the laser cladded coatings as hardness, wear resistance, oxidation resistance at room or elevated temperatures were also specified. Based on the above mentioned specifications and substrate materials (all defined in Deliverable 1.1), the most suitable material for laser cladding process was chosen. Laser deposition experiments on trial substrate samples were carried out at first to monitor basic properties of laser deposit such a hardness, elemental composition, structure analyses, and content of defects. Optimization of laser claddings on trial substrates was carried out before application of the claddings on active components.

4.6.2 Key Technical Achievements

Manufactured LMD demonstrators For DENY

Two types of demonstrators have been produced by Oerlikon and Vito for benchmark testing: lab-scale samples (Demonstrators 1) and real cutting rollers (Demonstrators 2). Details of the materials and manufacturing procedure are given in deliverable 6.1. In general, the laser deposited structures are composed of a nickel alloy matrix with embedded hard tungsten carbide particles. The content and type of nickel matrix and carbide particles has been varied.

The Demonstrators 1 samples were subjected to coarse and fine abrasive wear, and lab scale impact wear. The two best performing materials from the abrasive wear testing were tested with the lab scale impact tester. From the latter tests a significant influence of the substrate material was found.

The Demonstrators 2 were tested in the field in an actual tunnelling situation. Cutting discs were coated by Oerlikon and VITO. The laser deposited structures do not show improved performance at very high loading conditions while at lower loads (as at the sides of the cutting rollers and during light abrasive wear testing) improved performance is observed. The former is more dominant during cutting in hard underground at unusually high tunnelling loads.

However, the absence of any tungsten carbide insert damage and pull-out on rollers that were laser clad indicates superiority of laser cladding over the PTA clad coating approach where this damage mechanism was prevalent.

Manufactured LMD demonstrators for SKODA

This work covered the production development of hard facing valve stems from steam turbine shafts for Skoda. The stems operate at elevated temperatures and is subject to wear and oxidisation. Therefore the stems require high resistance against creep, high steam oxidation resistance, a high temperature strength and high wear resistance. Current production techniques include a) nitriding of the critical surfaces for operating temperatures up to 550°C and b) HVOF sprayed Cr_3C_2-NiCr coating for operating temperatures 550 - 600°C.

Roughly 10% of the valve stems processed using the current techniques fail earlier than the guaranteed lifetime is achieved. The failures are usually caused by surface damage and oxidisation, or jamming of the valve stem on the guide bushes due to component diameter growth. The manufacturing cost of a 1m long stem with sprayed HVOF coating on the functional surfaces, or nitride surfaces, costs roughly 5000 Euros. The costs associated with the replacement of damaged valves are estimated to be 70,000 Euros, (which does not include the related costs of the downtime of the whole turbine set).

A fundamental aspect to the development of the process was the controlling of the cooling rate. LMD is a process which inherently provides a fast cooling rate and the advantages and disadvantages associated with this. A key objective in this work was to develop the means of controlling the thermal profile during the process, by means of carefully application of pre-heating and post-heat cool down.

An induction heating system was used as a means of controlling the cooling rate of the deposited material. This was controlled by (a) pre-heating the substrate material to the required temperature, and (b) applying post-deposition heating to the component.

Tribaloy T-800 was found to be an extremely crack sensitive material. With the relatively low heat input of the process, it was found that without further process development, T-800 would require an applied pre-heating temperature beyond the limitations of the substrate material (>600°C). In this particular case, it was a difficult task to deposit the T-800 alloy without the presence of cracks to achieve an acceptable quality. This meant that the focus of the development targeted crack free deposits by means of heat control. X22CrMoV12-1 steel scales at around 650°C. To avoid unwanted changes to the substrate material, pre-heating trials were carried out to a maximum of approximately 600°C. Ideally pre-heating temperatures would have been in excess of 600°C.

It was found that for single layer clads, heavily diluted depositions produced crack free results. This caused undesired effects to the hardfacing surface properties. Therefore multiple clad layers had to be deposited to achieve the required surface properties. It was found not to be possible within the project scope to be able to deposit multiple layers of Tribaloy T-800 with the absence of detrimental cracking.

Mixing nickel with the T-800 alloy reduces the number of hard Laves phases in the clad microstructure. This provided an easier solution in terms of crack susceptibility, with trade-offs in changes to microstructural and mechanical properties. These changes include reductions in (a) hardness, (b), resistance to abrasion and (c) resistance to adhesive wear. The technique of mixing two powders while depositing provides the conditions for alloying under the beam, this is a novel process which requires strict control for further development.

Controlling the cooling rate by reducing the differential temperatures between the solidifying alloys and solid surrounding material is crucial in mitigating cracking. Multi-alloy powder feeding and subsequently alloying under the laser beam was introduced as a novel process in aiding the deposition difficulties with Tribaloy T-800 onto the X22CrMo12-1 substrate, but the hardware used is not yet optimised for this application at this time. The addition of nickel powder to the deposited material reduces the crack initiation susceptibility. This was observed when comparing T-800 powder deposits with deposits of T-800 powder and nickel powder mixtures. Upscaling the depositions from small area coatings is not as simple as increasing the tool path distance. Careful work must be done to create the same working conditions across the entire deposition.

Manufactured LMD demonstrators for BOSCH

Several prototype scale demonstrators with S355 base materials were supplied by Bosch to VITO. VITO performed the cladding of these demonstrators with materials supplied by Oerlikon. It was found that the hardest material from WP4 could not be clad crack-free within the set pre-heating window. Finishing to size and surface structure was subsequently done at Bosch.

Benchmark testing showed that none of the cladding materials meet all the (e.g. iron content, corrosion, hardness, bending) requirements. It was found that, depending on the cladding material used, the laser cladding process parameters can have a significant influence on the resulting coating properties. Judging from the amount of cladding defects found in the NiCrBSi material, the cladding process for these materials needs to be further optimized. The hardness of the material has proven to be a good indicator of the finishability of the coating. However, one materials does show enough potential to be a very promising material for further research and possibly upscaling.

Manufactured LMD demonstrators for VCST

Demonstrator gears have been successfully produced using a new production procedure including Laser Metal Deposition as one of the key processes, as was the main conclusion of D6.4.
The requirements for the demonstrator in terms of porosity, hardness, fatigue strength, and reduction in lead time have been met.

Dual material has good results and can be seen as an alternative, although it makes production more complicated. Testing did not reveal a better material behavior than the single material gears.
Additional improvement can be found for the bending fatigue by having more clad-material at the root of the teeth as bending stress will go on into the material and now this is shaft-material with current lower material properties.

Prototype production times can be cut by 25-30% provided certain practical preconditions are met with regards to laser availability. It was found that laser clad prototypes are not suitable for testing complicated inner bodies, or noise and vibration characteristics.

Manufactured LMD demonstrators for EKIN

This work covers the development of the repair of Ekin broaching tools by Laser Metal Deposition (LMD). Currently there is no cost effective repair solution that has been developed for broaching tools manufactured by Ekin. The current state-of-the-art production process is by taking the solid material, rough machining, then heat treatment and then grinding. It is envisaged that grinding will still be required as a finishing process after LMD.

The average life of one broach is limited to 5000 machined parts due to wear. In addition, 2% of broaches suffer broken teeth during the early stage of the life of the part. These broken broaches are then rejected and replaced. The cost of one broach varies from 800 to 130,000 Euros the most expensive one with a lead time of months. One single broken tooth is enough to discard the broach.

The Ekin substrate material is an extremely hard M35 steel which gives additional complications when depositing M2 tool steel. It is uncommon in LMD applications for a substrate to be the harder material and this produced some unexplored effects. M2 tool steel needs to be deposited at elevated temperatures because of its high hardenability and therefore crack sensitivity. However, a balance also has to be achieved as the heat affected zone (HAZ) within the substrate is also prone to post deposition cracking. Deposition onto a cool substrate will cause rapid cooling of the weld metal which promotes transformation to brittle martensite, which can be prone to cracking. Therefore, during deposition, the substrate temperature ideally needs to be kept at least 100 degrees above the M_s Temperature of the steel. For multi-pass welding (as in the case for the Ekin requirements) most of the weld zone remains austenitic throughout the entire deposition of each layer. Hence, monitoring the temperature of the layers during multi-layering techniques becomes critical as well as during the post deposition cool down phase. Preheating temperatures up to 500 °C have been used when depositing M2 tool steel onto the Ekin broach tool (repair of individual teeth).

The equipment and methods developed allowed the successful deposition of M2 tool steel material onto a very hard M35 substrate in the location of a broken tooth with no evidence of cracking, delamination or defects in the substrate material, interfacial region or deposited material. This showed that M2 tool steel can be applied by LMD onto similar M35 steel alloys. Material deposited by LMD can achieve the same microstructural qualities and requirements as a part produced by subtractive manufacturing techniques. It can be concluded that LMD may be used as a viable and effective repair strategy for broaching teeth of hard tool steel. Due to the sensitivity of the M2 and M35 materials to cracking, the substrate preheating regime has to be tailored to the specific dimensions of the substrate, the location of the repaired site on the substrate, the size of the LMD deposit and the location of any neighboring deposition sites. Successful first broaching trials have been performed. However more historical data over performance must now be collated.

Life cycle Impact of 2 demonstrators

This work focused on:

- The life cycle assessment of piston rods with a plasma transfer arc (PTA) protection layer, piston rods with a high velocity oxy-fuel (HVOF) protection layer and piston rods with a laser metal deposition (LMD) protection layer.
- The life cycle assessment of cutting rollers with a plasma transfer arc (PTA) protection layer and cutting rollers with a laser metal deposition (LMD) protection layer.

All life cycle phases from cradle to grave are taken into account. The ILCD Midpoint method was selected to calculate environmental impacts.

For the piston rods, the environmental profiles show that the most important contribution to the environmental impact of the piston rods, comes from the production of the piston rod itself, not from the coating, though there are differences in the type of coating applied.

When looking at the coating process only, significant differences in the environmental profiles are observed. This can be explained by the large variation in weight of the powder used for the coating. Additionally the composition of the coatings differs and there is a difference in electricity used to apply the coating.

To make a fair comparison, the lifetime of the piston rods should be included. The lifespan of a PTA coated piston rod is 4 times less than the lifespan of an HVOF coated piston rod and 1,27 times less than the lifespan of an LMD coated piston rod. Including this life span in the calculations, is clearly an advantage for the HVOF coated piston rod.

For DENYS cutting rollers the environmental profiles show that the most important contribution to the environmental impact of the cutting rollers comes from the production of the disc and the tungsten carbide teeth. The type of coating has a small influence on the environmental impact of a cutting roller.

When looking at the coating process only, the environmental impact is determined by the raw materials and the electricity used. The PTA coating process has a higher impact, mainly due to the higher amount of electricity consumed. The consumption of electricity has a significant contribution to many impact categories, such as ionizing radiation, climate change and freshwater eutrophication. The environmental impact of the tungsten carbide powder production for both types of coating is mostly related to the use of energy for extraction and refining of tungsten, and to the depletion of tungsten in the natural environment. Nickel causes environmental impact mostly by emissions resulting from mining and production processes.

Since the type of coating has a small influence on the environmental impact, the results are very similar for both types of cutting roller. However, when comparing drilling into rock with a cutting roller with a different type of coating, the difference in lifetime needs to be taken into account. The lifetime has a large influence on the result of the comparison. However, although lab tests suggest a larger lifetime for the cutting rollers with LMD coating, this could not yet be confirmed by field tests. Therefore, at the moment no final conclusion can be made on the impact of drilling with cutting rollers with a PTA protection layer versus a LMD protection layer.

Cost – performance analysis of robot vs. CNC based LMD

The ability to cover large areas with a relatively low cost robot in combination with a linear or several Cartesian axes, make the robot solution more attractive in terms of cost per unit of work space.

If a part is to be used largely un-machined then the accuracy of the CNC machine could justify the additional cost over a robot system. However, the advantage maybe lost for very complex geometries where the additional freedoms of articulation offered by a robot could become beneficial.

If the material being used has to be produced in a controlled atmosphere (e.g. argon) then the construction of a CNC machine makes it easier to enclose the working area as a sealed chamber.

In terms of CAM software, for very complex geometries complex computation (and therefore expense) is required to manipulate a robotic LMD system. Hence, software costs and time to prepare a tool path can be much higher for a robot.

A summary chart of the relative benefits of both types of machines is as follows:

Feature or requirement of the application	Robot	CNC Based
Cost	+	
Accuracy and stiffness. Acceleration required (machine dynamics).		+
Number of axes	+	
Volume	=	=
Requirement for communication with other systems (closed loop control, part inspection…)	=	=
Requirement for the part to be in enclosed atmosphere or similar…		+
Payload (if the part is to be moved)	=	=

4.6.3 Deviations from work plan

There were some three months delay at the start of this WP6. Nonetheless, all demonstrators cladded at VITO and Oerlikon, were tested by the end-user in due time. However, due to a technical problem at TWI, some extra time was needed to perform the final tests of these demonstrators. TWI decided to finish all the work at their own expense in the two months after official project end. All demonstrators' tests are thus executed.

4.6.4 Future Aspirations

Bosch has stated to invest in a new 20kW laser cladding system for the cladding of large hydraulic piston rods. Oerlikon has provided the powder hopper developed in the AMCOR project for this system. Future developments are in the direction of harder, more wear resistant cladding materials. Ekin are currently active in apply for further EC funding to continue the work of AMCOR and conduct further validation trials as well as focus repair procedures on a larger range of broaching tools.

5 Project Impact, wider social implications and exploitation and dissemination

The dissemination actions of AMCOR have taken place through various available media: conferences; workshops and AMCOR project website. The targeted topics have been: laser metal deposition and additive manufacturing and surface coatings including wear and corrosion resistant applications.

5.1 Project Impact

The following lists the project Impact on the AMCOR SME partners.

BCT

BCT is a software developing company focused on solutions for adaptive repair and manufacturing. Adaptive in this sense means to take the shape of each part into consideration before starting the individual machining process. Historically most applications are located in the area of aero engines dealing with parts like turbine and compressor blades as well as handling other high added value components. The technologies supported are mainly material removing processes like milling and grinding.

In the recent time three trends could be observed.

1. The parts to be processes are getting more complex. Therefore capturing the individual parts by tactile measuring a couple of point is no longer sufficient. The tasks require high speed measuring of a huge number of points.
2. The second trend is the growing importance of additive manufacturing processes during repair and new part manufacturing.
3. And the third trend to be observed is the increasing demand to use robot systems instead of *classical* machining concepts.

The AMOCR project addresses all three aspects. Additive manufacturing technologies are developed and fast scanning of part geometries is required to support the processes with reliable geometrical information. Based on the measuring data the material addition process is started. The technologies are used in combination with classical machining concepts (Vito) as well as using robots (TWI/Olympus).

Efficient development of new software functionalities, new concepts in combination with sensor and machines/robots is always a challenging task for SMEs. Support of the process developers is required as well as support of the machine tool or robot manufacturer. If these partners do not see a quick return of their investment by selling systems in a short period of time, getting the essential support is extremely complicate or even impossible.

The situation within a research program like AMCOR is completely different. Partners are willing to contribute and to support each other to develop solutions which are beneficial for all partners involved. Of course there is the objective to develop solutions with a market potential, but it is not expected to have a ready to market product at the end of the collaboration. Work is focused on the examination of basic concepts and fundamental aspects.

Within AMCOR, BCT got the chance to start the development of robot based scanning applications. Different methods have been developed. The proof of the concept showed that e.g. the favourite approach using a time stamped method to combine laser and position information presented unexpected restrictions. In combination with the robot integrator (Olympus) a solution could be found to overcome this obstacle. Based on this, BCT is able to improve the scanning capabilities using robots and to integrate new functionality into BCT's software systems.

Another positive effect of the AMCOR project from the perspective of BCT is the knowledge gained about the LMD process and its specific programming requirements. BCT's systems have to cooperate with other components of the process chain. The knowledge about the specific needs of LMD programming systems helps to develop corresponding interfaces and to link the BCT systems to such components.

The developments made in AMCOR pave the ways for future BCT developments and will be fed into the ongoing improvement of our solutions. The collaborations started in AMCOR will be utilised during future developments. So the AMCOR project supports BCT improving its solutions and to strengthen its market position on a global market.

ETALON

Etalon Research is a small company that designs and builds highly specialised measurement instruments, primarily for use in either academic or industrial research work. The AMCOR project therefore offered an exciting opportunity not only to develop instrumentation for a completely new market, but also to start work with the intent – from the very start – of creating a product for sale to a wider market.

Prior to the start of the AMCOR project, Etalon had perceived that its main benefit would simply be the opportunity to fund further development of a previously applied technology (tomographic reconstruction of optical attenuation measurements), and apply that measurement approach to a new field. It was envisaged that this would lead to the commercialisation of an LMD-specific powder measurement and alignment sensor that was based around the tomographic technology.

During the AMCOR project, however, the exposure and contact that Etalon had with the project's commercial end-users and LMD researchers (both of whom are part of the intended target market for the nozzle powder alignment sensor) meant that it was quickly established that the commercial appeal of the sensor could be increased significantly by utilising an alternative measurement technique. As such, Etalon switched from a tomographic measurement technique for the nozzle powder flow sensor, to a camera-based system which offered the additional – important – advantage of enabling simultaneous LMD nozzle powder *and* laser alignment.

The access to end-users – provided during AMCOR – also gave Etalon more opportunities to test prototype hardware than would normally be afforded to an SME without pre-established links to the potential customer base. As a result, at the end of the project, Etalon now has a customer-tested and approved, prototype nozzle alignment product that is close to being ready for commercial sale. This should open a completely new market to the company, with associated financial returns.

Involvement in the AMCOR project has also provided Etalon with exposure to several other areas of the LMD process where measurement requirements exist, but which are currently un-met. These therefore provide potential future business opportunities, and the company now has a network of contacts by which to make use of them. Finally; involvement in AMCOR has also given Etalon valuable experience in the management of a large collaborative project, which will undoubtedly be of use in the future.

SKM

SKM DCAM is a flexible offline-Programming system applicable for several tasks in the CNC and robotic environment, focussed on laser material processing and additiv manufacturing.
It has emerged since more than 25 years in developed and is used worldwide. Various functions supports you in the preparation of CAD data and in the generation of tool paths.

The workflow for programming is carried out based on the workflow CAD-Data-Import → RobotCell-Modeling→Measured-data-acquisition/processing → structure data → Tool-path-calculation/editing (Technology database) → Simulation (orientation, axis-values, reachability) → Postprocessor (configurable for CNC and robots).

As part of the collaboration were AMCOR essential areas of DCAM described workflows and its functionality improved.

In particular, the area slicing features for Multiple Axis FGM Manufacturing, because conventional strategies available for demonstration of the partners were not applicable.
The development work for the treatment of Scanlines, various CAD functions, the process parameter data base for customized strategies for slicing and features for tool path calculation and modification, including element-sorting and group-merging functions, kinematic functions with orientation adaption, tool change and simulation and the user interface has the product DCAM furthered strategically.

The research results for the adapted tool path generation with a special DataFlow (closed loop control, user parameters, rules, Measuring results, xml) are important for process-integrated solutions.

In addition to many CAM-Software business opportunities of improvement of CAM-Strategies (based on the demonstrator parts) and adaptive approaches for for multiple axis FGM are concrete developments and solutions with BCT (interface for scanning system) and TWI (SKM DCAM + Reis robot cell) and further projects with SIRRIS and Olympus are in planning.
AMCOR the project had for SKM very many positive effects of strategic DCAM platform for further development, for concrete business and to strengthen its market position on a global market.

OLYMPUS
Olympus Technologies Ltd is a robot system integrator that has worked in most conventional industrial applications for robots, particularly welding and cutting technologies.

Having worked previously in applications for shaped metal deposition and coating and cladding with MIG and TIG technologies there has in recent years been a surge of interest in using lasers in combination with metal powder in similar applications.

Conventionally the use of these deposition processes involved time consuming programming and empirical development of parameters to achieve the shapes and material properties required in the end products.

Participation in the AMCOR project to integrate laser power source, optics, powder feeding equipment, scanning and monitoring equipment gave Olympus the opportunity to greatly enhance their knowledge of and experience of working with these technologies to provide more efficient and productive systems.

The approach of cooperative development of the technology within the AMCOR Partnership was refreshing and fruitful. The building of relationships with other partners has led to business opportunities post AMCOR to combine our products and skills to our mutual benefit of all and to the end user customers who are able to acquire system solutions that are well proven in test during AMCOR.

Directly as a result of AMCOR, Olympus has been able to integrate an AMCOR type system for a new SME business in the UK which is providing a sample service to other customers and this is expected to lead to further production systems in the near future for industrial applications.

The following lists the project Impact on the AMCOR RTO and LE partners.

TWI

- TWI has benefitted from the development of new processing parameters for LMD processing of new materials including Tribaloy alloys and tool steels. This has enabled capability for the manufacture of different coatings of a range of substrates.
- Integration of a new robotic LMD system which has planned future work for coatings applications to benefit TWI members,

VITO

- Vito has created a spinoff company LCV in October 2015. All laser cladding / metal deposition activities will be transferred from Vito to the spinoff. LCV will offer LMD services to industry, comprising AMCOR developments. The spinoff will offer initially an employment for 3 persons.
- The participation of Vito in a European project with highly qualified, renowned partners has strengthened Vito's and LCV's position and prospection activities.
- LCV aims at continuing the collaboration with AMCOR partners

BOSCH

- New collaboration between Oerlikon and BOSCH is being initiated for the development of new hydraulic piston rod coatings.
- A new laser cladding system is being installed at Bosch. Collaborations between the AMCOR partners were indispensable
- Contact with Etalon concerning the powder flow measurement equipment will be intensified.

VCST

- Familiarization of laser cladding technology which was new to VCST at the start of AMCOR.
- New collaboration with Vito
- New vision-based measuring technology introduced
- Contact with new heat-treatment company for small, specialised treatments

5.2 Website

The project website is available at http://www.amcor-project.eu/. It allows the public dissemination of the AMCOR programme and the controlled exchange of documents between beneficiaries via a secure login page.

5.3 Dissemination

To support the dissemination of the AMCOR project a flyer (see Figure 5.1) and a poster (see Figure 5.2) was printed at the beginning of the project and agreed by all partners. Both the flyer and poster was available to all beneficiaries to use as required when attending public events. Copies of both could be downloaded and printed from the member's area of the project website when required.

Figure 5.1: The AMCOR flyer

Figure 5.2: The AMCOR poster. The Figure shows the poster located at TWI, Sheffield, UK.

During the course of the project a series of technical posters were produced. During the final PSC review meeting, it was agreed by all beneficiaries to use these posters as the basis for an AMCOR project brochure. This brochure is a compilation of the process results and some general information about the project. The printed version will be available at the end of the project and handed over to the beneficiaries. A PDF version will also be made available on the public side of the project website.

- Lessons learned: Help from a professional graphics consultant is beneficial to realise an adequate style of the dissemination material
- Lessons learned: Costs for layout and printing should be foreseen in the project budget

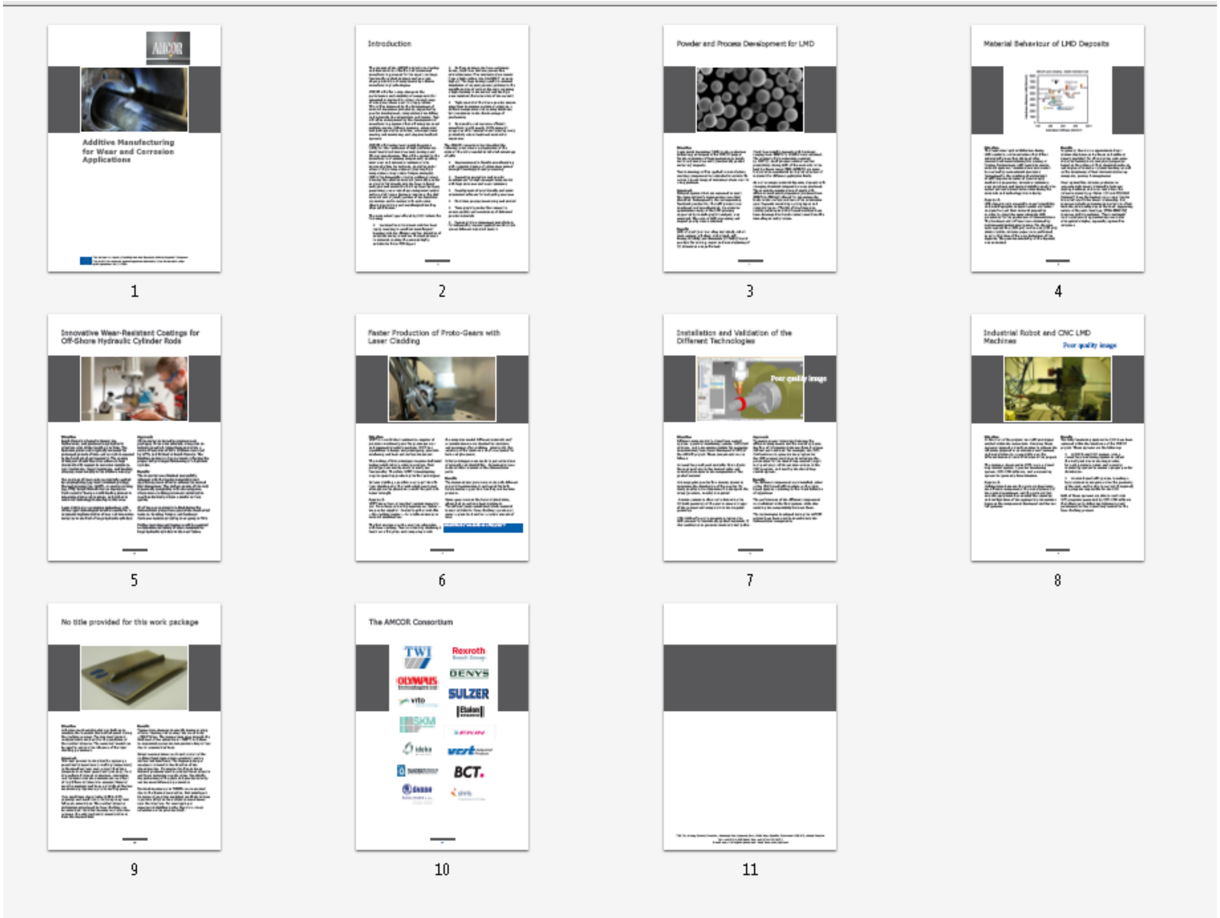


Figure 5.3: The AMCOR project Brochure.

5.4 Dissemination: Dissemination Activities

		LIST OF DISSEMINATION ACTIVITIES						
No.	Type of activities[15]	Main leader	Title	Date	Place	Type of audience [16]	Size of audience	Countries addressed
			PLANNING / IDEAS					
1	Oral presentation to a scientific event	BCT STEUERUNGS UND DV-SYSTEME GMBH	Adaptive machining for efficient turbine component repair.	24/04/2013	Turbine Forum 2013 - Nice	Industry	>100	International
2	Oral presentation to a scientific event	TWI LIMITED	TWI Additive Manufacturing	22/01/2014	UK	Industry	>50	UK
3	Organisation of Workshops	SIRRIS HET COLLECTIEF CENTRUM VAN DE TECHNOLOGISCHE INDUSTRIE	FoF Cluster Workshop - Publication M18	24/04/2014	Brussels	Industry - Policy makers	> 50	EU
4	Exhibitions	VLAAMSE INSTELLING VOOR TECHNOLOGISCH ONDERZOEK N.V.	Maintenance 2014	26/03/2014	Antwerp Expo	Industry	5,492 visitors	EU
5	Exhibitions	S.K.M. INFORMATIK GMBH	Automatica 2014	03/06/2014	Munich, Germany	Industry	34,500 visitors from more than 100 countries	EU
6	Exhibitions	S.K.M. INFORMATIK GMBH	SKM Technology Day	01/09/2014	SKM, Schwerin, Germany	Industry	731 exhibitors from 42 countries	EU
7	Oral presentation	BCT STEUERUNGS UND DV-SYSTEME	New Developments and Challenges in	21/10/2014	DMG Mori Aerospace	Industry	unknown	EU

	LIST OF DISSEMINATION ACTIVITIES							
No.	Type of activities[15]	Main leader	Title	Date	Place	Type of audience [16]	Size of audience	Countries addressed
	to a scientific event	GMBH	Adaptive Machining		Programme			
8	Posters	SIRRIS HET COLLECTIEF CENTRUM VAN DE TECHNOLOGISCHE INDUSTRIE	Aerospace Days B2B	15/10/2014	B2B Paris Orly	Scientific community (higher education, Research) - Industry	>50	EU
9	Oral presentation to a scientific event	BCT STEUERUNGS UND DV-SYSTEME GMBH	Challenges and New Developments in Adaptive Machining.	25/02/2015	3rd ICTM- Int. Conf. on Turbomachinery Manufacturing	Industry	>100	International
10	Oral presentation to a scientific event	DENYS NV	Denys Open Day	06/02/2015	Deys, Wondelgem	Industry	+/- 800 employees	EU
11	Posters	VLAAMSE INSTELLING VOOR TECHNOLOGISCH ONDERZOEK N.V.	Project Poster	03/03/2015	Rapid Pro 2015 Fair , Netherlands	Industry	close to 10.000 visitors	EU
12	Organisation of Workshops	SIRRIS HET COLLECTIEF CENTRUM VAN DE TECHNOLOGISCHE INDUSTRIE	FoF Impact Workshop	29/04/2015	Brussel, Belgium	Industry - Policy makers	unknown	EU
13	Oral presentation to a scientific event	VLAAMSE INSTELLING VOOR TECHNOLOGISCH ONDERZOEK N.V.	Process development and material properties of gears manufactured by laser metal deposition	04/07/2015	EUROPM2015	Scientific community (higher education, Research)	800 participants	EU

		LIST OF DISSEMINATION ACTIVITIES						
No.	Type of activities[15]	Main leader	Title	Date	Place	Type of audience [16]	Size of audience	Countries addressed
						- Industry		
14	Posters	VLAAMSE INSTELLING VOOR TECHNOLOGISCH ONDERZOEK N.V.	AMCOR Project Poster	10/06/2015	EUROFINISH2015	Industry	1850 visitors	EU
15	Posters	SIRRIS HET COLLECTIEF CENTRUM VAN DE TECHNOLOGISCHE INDUSTRIE	AMCOR Project Poster	10/06/2015	Rapidtech 2015	Industry	>3500 visitors	EU
16	Oral presentation to a scientific event	S.K.M. INFORMATIK GMBH	SKM Technology Day	01/09/2015	SKM, Schwerin, Germany	Industry	unknown	EU
17	Organisation of Workshops	VLAAMSE INSTELLING VOOR TECHNOLOGISCH ONDERZOEK N.V.	FoFAM Workshop representing AMCOR	22/09/2015	Brussels	Industry	unknown	EU
18	Oral presentation to a scientific event	VCST INDUSTRIAL PRODUCTS BVBA	AMCOR Project and Possibilities	30/09/2015	VCST,	Industry	unknown	EU
19	Oral presentation to a scientific event	TWI LIMITED	Funding and AM	17/03/2015	ILAS 2015, UK	Scientific community (higher education, Research) - Industry	unknown	International
20	Oral presentation	TWI LIMITED	Strategic Research Agenda for AM	30/07/2014	SFF Conference, USA	Scientific community	unknown	International

		LIST OF DISSEMINATION ACTIVITIES						
No.	Type of activities[15]	Main leader	Title	Date	Place	Type of audience [16]	Size of audience	Countries addressed
	to a scientific event					(higher education, Research) - Industry		
21	Oral presentation to a scientific event	TWI LIMITED	AM Strategy in Europe	11/05/2015	Brussels	Industry	unknown	EU
22	Organisation of Conference	TWI LIMITED	AM Capability at TWI	17/09/2014	EWI/TWI Seminar, USA	Scientific community (higher education, Research) - Industry	unknown	International
23	Oral presentation to a scientific event	TWI LIMITED	AM Capability at TWI for Space and Defence Applications	18/02/2015	AM for Defence and Space, UK	Industry	unknown	International

5.5 Exploitation

This section provides detailed information about the key exploitable results gained from the project. Table 5.1 summaries the results

Table 5.1: Overview of AMCOR exploitable results.

Exploitable Result No.	Key exploitable result	Lead Partner	Foreground IPR
1	LMD procedures and methodology for deposition of novel materials	VITO/TWI/ OERLIKON	Process knowledge focused on the production of complex geometries and surfacing by LMD, with the application of crack sensitive materials, for wear and corrosion resistant applications
2	Applying procedures (provide a service) for LMD Thermal Modelling	Sirris	Process knowledge on transient thermal modelling specific to the LMD process.
3	LMD FGM CADCAM Software	SKM	Knowhow on CAM software tools for path planning (including graded materials) by LMD
4	Tomographic flow sensors for powder flow measurement	Etalon	Opto-mechanical and coding knowhow for LMD powder flow sensor.
5	AMCOR LMD Robot Equipment	Olympus	Installation and integration of robot hardware specific for LMD processing.
6	AMCOR LMD CNC Equipment	Danobat	Experience in design, optimisation and validation of CNC hardware for industrial viability for laser cladding systems. Improved knowledge in new manufacturing technologies to open new markets.
7	Closed loop control software	Ideko	Laser cladding monitoring. Laser cladding monitoring for FGM. Closed loop control for laser cladding (single material and FGM). Adaptive cladding (process parameters) to the part geometry.
8	In-process geometrical control	BCT	Software system and knowledge. Knowhow on robot based scanning applications and different methods of integration.
9	Generic solution for scanning in machine tools and robots	BCT	Interface module supporting line scanning on robots establishing a generic solution for

Exploitable Result No.	Key exploitable result	Lead Partner	Foreground IPR
			scanning on machine tools and robots.
10	FGM Powder Feeder	OERLIKON	Commercial product for the dispensing of powder materials specific for additive manufacturing applications.
11	Manufacturing, repair, or surface coating for broaches	EKIN	Knowhow on the use of LMD for the repair of Broaching tools.
12	Protection layer on cutting disks	Denys	Knowhow on the use of LMD for the coating and repair of down hole cutting discs.
13	Unique coating on hydraulic cylinder rods	Bosch	Knowhow on the use of LMD for the coating of hydraulic cylinder rods
14	Prototype parts partially made out of laser cladding	VCST	Knowhow on the use of LMD for the manufacture and repair of automotive gears
15	Improvement of lifetime and performance of components of valves introducing steam into steam turbine for power generation	Skoda	Knowhow on the use of LMD for the coating and repair of steam turbine components.
16	New wear and corrosion resistant powders; FGM material combination design service (specification of best blends/layer thicknesses to use); New wear corrosion resistant coatings made with blends and alloys	OERLIKON	Knowhow on the performance criteria of powders for corrosion and wear resistance when applied by LMD.