Computerized Refurbishment

Frank Gärtner, Alexander List, Sören Nielsen, Hongjian Wu, Zahra Arabgol, Levke Wiehler, Julio Gutiérrez de Frutos, Chunjie Huang, Thomas Klassen
Institute of Materials Science
Helmut Schmidt University
Hamburg, Germany
*frank.gaertner@hsu-hh.de

Marcel Lewke, Alexander Fay
Institute of Automation Technology
Helmut Schmidt University
Hamburg, Germany
*marcel.lewke@hsu-hh.de

Dhruvit Rashikbhai Gabani, Jens Gibmeier, Astrid Pundt
Karlsruhe Institute of Technology
Karlsruhe, Germany

Tiago Werner, Kai Hilgenberg, Mauro Madia, Thomas Böllinghaus
Bundesanstalt für Materialforschung und –prüfung
Berlin, Germany

Leonhard Holzgaßner, Peter Richter
Impact Innovations GmbH
Haun/Rattenkirchen, Germany

Nils Clausing, Henry Loitz
H.LoitzRobotik,
Hamburg, Germany

Philipp Keuter, Moritz to Baben
GTT-Technologies
Herzogenrath, Germany

Markus Steierl, David Erich Schimbäck, Thorsten Rösler
Airbus Defence and Space GmbH
Manching, Germany

Holger Debuch, Thomas Gartner
Lufthansa Technik AG
Hamburg, Germany

Abstract **– High performance aerospace parts are typically scrapped and replaced, as soon local damages exceed certain tolerances, because available classical repair techniques so far fail to guarantee required part strengths. As solid state deposition technique, cold spraying offers the potential for restoring damaged areas to original shape while retaining part properties, thus saving costs and conserving resources. So far, however, the needed efforts are high and thus costly: process parameter sets, robot kinematics as well as pre- and post-processing must be individually adjusted and controlled. For easier process adoption, a holistic concept is developed that includes all critical individual boundary conditions, i.e. analysis and categorizing of defects, pre-machining, repair, and post-treatment in one digital description and computerized process chain. By that, the required part properties profile can be guaranteed even for batch size one. The concept includes developing the algorithms for an integrated manufacturing environment as well as for collecting needed experimental input data. The complex interplay of influences is addressed by an interdisciplinary engineering approach involving materials science, fluid mechanics and automation technology. Finally, the collaboration with industrial partners will allow for a fast transfer into real production environments.**

Keywords – Cold Spray, Repair, Additive Manufacturing, Influence of Spray Parameters, Industrial Robot

I. INTRODUCTION

Mankind's challenges to reduce resource consumption have to include concepts for sustainable material cycles like circular economy and cradle-to-cradle [1, 2]. Resource-conserving processes for energy saving and production as well as material cycles are in focus of world-wide development and on production side aim for adopted designs of consumer products and industrial goods. For both, refurbishment instead of replacement is a first step into the right direction, but has to tackle all safety measures. Particularly, components in the aerospace industry have to comply with strict regulations to guarantee flight safety. Respective requirements demand structural robustness of the components as well as tight tolerance limits against damage due to corrosion or wear during operation. Moreover, the production of large aerospace components is often complex and cost-intensive. Nevertheless, in aviation industries, even minor defects regularly force components to be taken out of service and replaced. In contrast, suitable repair processes for reconditioning of these components would significantly reduce costs and save production time as well as resources.

FIGURE 1. EXAMPLE OF A ROBOT-GUIDED REPAIR APPLICATION OF COLD SPRAY [3].

In order to obtain an optimum repair result that fulfills the highest requirements regarding material properties, simple geometric shape restoration is not sufficient. Usually in repair, applied additive manufacturing techniques result in particular microstructural features, possible defects and respective – potentially even anisotropic – mechanical properties. Systematical tailoring of microstructures and properties to the specific component and geometry requires complex routines. This work proposes the design of an automated cold spray repair system that facilitates a complete individual repair procedure for aircraft components.

Additive Manufacturing (AM) as a repair method is a step forward towards a more sustainable production economy and enables extending the product life by repair of damaged components [4]. Various processes have demonstrated the suitability in this regard, such as direct energy deposition and gas tungsten arc welding [5, 6]. However, these processes use a direct heat source, e.g. a laser or arc beam, to melt the material to be deposited. Consequently, the substrate component is also subject to a temperature rise, resulting in microstructure modification or phase transformations, potentially even to the liquid state. Also, incorporation of oxides is likely, which are critical for crack initiation and failure. Thus, the challenge of repairing oxidation-sensitive components with low temperature input under ambient conditions remains.

In recent years, cold spraying (CS) has emerged as a promising technology for repair applications, particularly for oxidation-sensitive materials. As compared to other processes, cold spray (CS) has shown advantages in the field of repair due to unique component properties by retaining the phase composition and reaching high deposit strengths. In CS, material is deposited in solid state. Powder material is accelerated in a pressurized and heated process gas stream (e.g. nitrogen or helium) that passes through a de Laval type nozzle. Particles then impact on the substrate with supersonic velocity and deform plastically. This results in a temperature rise localized in the interface area up to temperatures close to the melting point. Thermal softening, and adiabatic shear instabilities in the interface then facilitate metallic bonding without melting. The main advantages of CS concern the high deposition rate, the absence of solidification and comparably low process temperatures, making CS an interesting technology for processing of oxidation-sensitive materials (e.g. aluminum- and titanium-alloys) [7, 8]. However, the properties of the deposited layers are strongly dependent on initial powder conditions, process parameter sets and on geometric influences, such as the deposition angle [9]. Thus, optimum solutions require detailed knowledge about all individual influences and also about possible inter-dependencies.

Current research in the field of CS repair focuses on two distinct topics: repair of the original shape of the component by additive manufacturing (AM) and optimizing the material properties of the component. Nonetheless, the combination of both research topics is necessary to obtain the best repair result and is consequently pursued in this work. In the literature already different attempts are reported for solving the challenges for the use of CS as possible additive manufacturing or repair technique. In [10] the authors investigate the use of CS for restoring parts containing cracks and to analyze the crack resistance of such repaired components. An aluminum alloy plate with a 30° V-notch on its surface is repaired by cold spraying of aluminum alloy powders. The results indicate that the repaired panels have up to sixfold increased crack growth resistance as well as an increased global fatigue life in comparison to the original component containing the defect. However, the proposed process of crack repair might still be enhanced since the existing sharp flank angle of 30° is non-optimum and could result in lower deposit quality. Results of the work in [11] illustrate the influence of the spray angle on the obtained deposition efficiency and porosity. Starting from a spray angle of 90° to the substrate surface, the deposition efficiency is over 95 % and the porosity is 0.13 %. A decrease of the spray angle to 45° results in a drop of the deposition efficiency to 83 % and an increase in porosity to more than 6 %. Thus, optimum repair conditions of defects should also consider pre-processing to adjust the geometry with respect to the ideal process characteristics of CS. The authors of [12] demonstrate the successful application of a portable CS repair system to repair damaged aluminum components. The investigations include pre-processing, CS application, post-processing and performance tests (adhesion, fatigue, and corrosion). The use of the portable system indicates some disadvantages, such as inaccuracies in process repeatability and restrictions to lower process gas temperature and pressure, which results in limited CS deposit qualities than attainable with a stationary repair system. The authors of [13] propose CS of aluminum to repair an internal bore of a navy valve actuator. The defined requirements for the repair are a maximum of 5 % porosity on critical surfaces and a minimum of 68.9 MPa adhesion strength, as attainable in standardized pull-off tests. The results prove the successful repair in accordance with the required properties. An average porosity of 3 % and an average adhesion strength of 71.4 MPa are achieved in this particular case. However, details regarding variations of defect category and respective scatter of the mechanical properties are not provided. More recently, in [14] the authors present a CS repair framework that consists of a 3D scanning system, a defect database and a CS additive repairing system. The 3D scanning system provides information about the component's individual damage, which is then categorized to a typical standard flaw within the database, and a standard repair process is applied accordingly. The CS additive repair system includes programming, simulation and material deposition. Although the work includes the full geometric shape restoration of the damaged area, issues related to respective optimum deposit properties to meet high performance requirements are not considered. In addition, the use of standardized defect layouts in a database cannot provide optimum repair to all sorts of defects with a variety of different, often complex shapes and varying depths.

Previous work on the optimization of cold spraying chiefly considered the main parameters given by gas temperature and pressure. However, in reality, the situation is more complex, despite the – in first view – rather simple relation. The performance of a deposit depends on the effective ratio η between particle impact velocity v_p and critical velocity v_{cr}. However, respective effects by (i) particle size on v_p, as well as (ii) mechanical particle properties in as delivered or modified states, (iii) incident deposition angle or even (iv) substrate surface temperature on v_{crit} could have similar influence on deposit properties as primary parameter sets [11, 15–20]. In particular, the surface temperature is further influenced by the gas temperature, the stand-off distance between nozzle exit and substrate, by the robot trajectory and transverse velocity, as well as by the geometry of the component and by the thermal effusivity (i.e. heat capacity and heat conductivity combined) of the substrate material. In addition, peening effects and surface temperatures determine internal stresses [21]. In addition, (iv) surface topographies and properties (roughness and hardness) by respective substrate pre-treatment determine deposit adhesion and thus overall performance of repaired parts. Since CS of high-performance materials like titanium- and aluminum-alloys already operates at upper technical limits, an understanding of all these different influences is needed to reach the thresholds for technical applications. For staying within geometrical boundary conditions like position and angle of the nozzle in relation to the work piece, industrial robots should be used to control the movement with high precision and repeatability to allow for individual repair of complex parts. FIGURE 1 depicts the example of a robot-guided cold spray application, showing the repair of a propeller blade [3].

In order to incorporate all the different, individual dependencies and their complex interplay into one uniform description, an integrated, automated CS concept is needed. In ideal, such should be incorporated into one common digital environment. For following all these parallel paths, the project aims to develop an integrated CS system that includes (i) reverse engineering to analyze, classify and generate digital data of the damaged component, (ii) digital incorporation of thresholds for CS parameter tuning and geometrical boundary conditions, (iii) pre-processing for guarantying needed geometries for the CS process, (iv) adjusting of surface topographies, (v) toolpath planning to optimize robotics for the CS process, (vi) on-line monitoring to ensure process quality, (vii) post-processing and (viii) performance testing of material properties to meet the challenging requirements of aerospace industries. Apart from deposit production, for aerospace repair applications dealing with a batch size of one, also sophisticated methods are needed for non-destructive quality inspection.

Taking Al-and Ti-alloys as examples, the strategies to reach thresholds for aerospace applications by CS repair are given in the following as well as first results on the different paths of development.

II. PARAMETERIZATION OF INFLUENCES ON DEPOSIT PROPERTIES

Most influences on deposit qualities can be expressed in terms of the particle velocity v_p to critical velocity v_{crit} ratio η. This enables to define most suitable parameter sets and particle sizes for reaching high impact velocities. The deposition of Al-and Ti-alloys already operates at upper technical limits of CS. Nevertheless, numerical simulations are under investigation to improve particle velocity and temperature by feedstock specific nozzle designs and alternative nozzle materials that enable better process stability without nozzle clogging. Measures for a more precise definition of the critical velocity concern investigations of powder strengths. Possible powder modifications aim for reducing feedstock strengths to enable better bonding.

Higher effective surface temperatures of the part support bonding and could ensure better deposit qualities. However, a systematic description of respective influences on the critical velocity still needs simulation supported analyses. Moreover, despite locally higher spot temperatures being beneficial for bonding, associated temperature gradients could cause intrinsic deposit stresses. Respective influences are explored by modelling of the temperature distribution for varied heat flux under individual trajectory speeds applied by the robot system and experimentally determined stresses.

Further improvement of deposit qualities can be obtained by thermal or mechanical post treatments. Both is investigated under the view to minimize possible overaging effects of the component under repair.

Thresholds for pre-machining as well as robot toolpath planning are estimated by η roughly scaling with the sine of impact angle. Moreover, the trajectory speeds during deposition then determine local heating time under the spray spot and thus surface temperatures, and therefore should be kept with certain ranges. Both determine thresholds for the robot kinematics used for repair.

All the different influences are validated by experimental analyses of deposit microstructures and properties. These investigations are accomplished by non-destructive tests to derive correlations to direct analyses of material properties. As such, the results of non-destructive analyses like conductivity must be developed into correlation functions to real deposit properties as provided by mechanical tests, and supported by simulations.

To meet all these requirements, an integrated automated cold spray repair has to combine the simulative representation of the process as well as the in-situ process control, both then ensuring a continuous quality.

III. AUTOMATED COLD SPRAY REPAIR SYSTEM

This section provides an overview of an integrated CS repair system. In the project, the automated repair by CS is applied to damaged aircraft components. FIGURE 2 illustrates the setup of the robotic cell exemplary in the state of material deposition. The system contains a powder feeder, a high-pressure gas supply, a gas heater, a spray gun with a de Laval nozzle and the robot framework with the industrial robot, the robot controller as well as the operating computer. The CS gun, the pre-processing tool and the sensors are mounted on the end effector of the industrial robot. Control of the repair process is provided by simulation-based algorithms interfaced with the operating industrial robot.

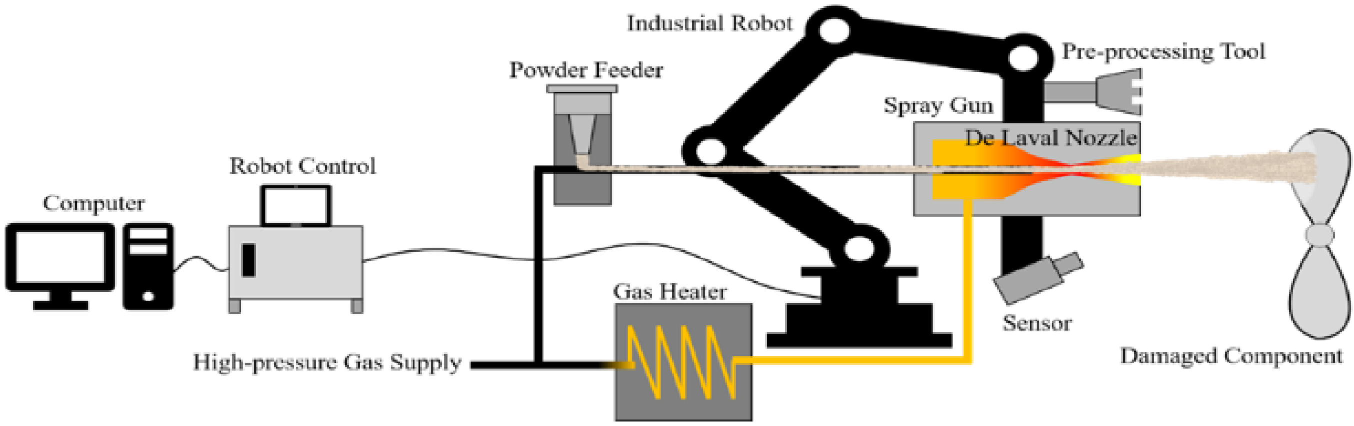


FIGURE 2: SETUP OF THE ROBOTIC COLD SPRAY CELL [22].

The general workflow is schematically illustrated in FIGURE 3 for the example of a propeller with a corrosion damage. Based on the existing corrosion damage, the component and the damaged area are analyzed using sensors. The simulation-based algorithms determine the pre-machining to be applied and the optimum spray toolpath. Here, the suitable material removal for the existing geometry volume and the subsequent optimal spray toolpath (including the optimized process conditions for CS) are determined. Beginning with the realization of pre-machining by milling, the complete removal of damaged material is ensured, as well as the creation of conditions for the subsequent material deposition. Afterwards, the machined damage is refilled by applying the optimized spray toolpath via CS so that the material properties meet the required specifications. To successfully complete the repair process, post-processing by e.g. milling is performed.

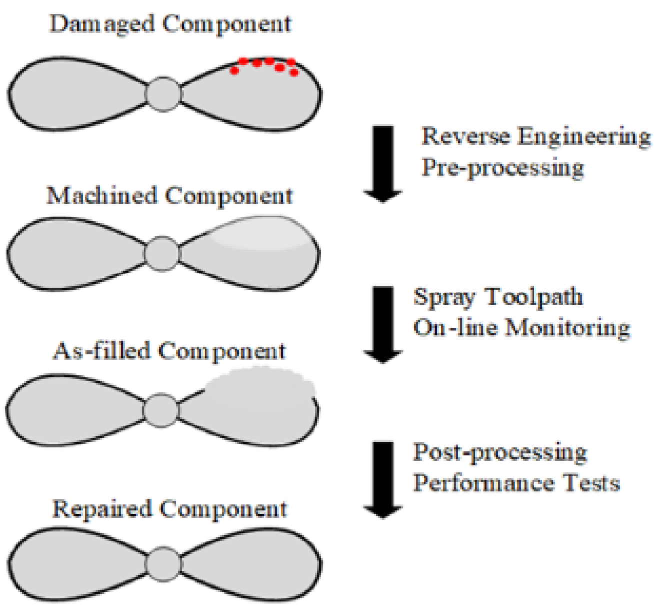


FIGURE 3: REALIZATION OF THE REPAIR PROCESS FOR AN EXEMPLARY CORRODED PROPELLER COMPONENT [22].

The complete repair process flow for developing automated repair by CS is illustrated in FIGURE 4. For a given deposit material, the parameterization of cold spray parameter sets and boundary conditions are supplied as input data (data base, sub-routines). Starting from a damaged component, the first process step concerns analyzing and classifying the damage and the component via reverse engineering using sensors (e.g. optical sensors). This provides information about the component geometry and the damage size, here serving as input data on part and damage characteristics. In addition, the obtained data are utilized for subsequent simulations of the repair process. From this information, needed requirements for the repair can be derived that then define the setting of the necessary process parameters. These include settings of the primary parameters (CS parameters like process gas temperature, pressure etc.) and secondary parameters (robotic parameters like stand-off distance, transverse velocity etc.). The definition of knowledge-based thresholds for maximum deviation from ideal impact angle and other boundary conditions, should then allow to deduce a suitable repair geometry and conditions for pre-processing for individual component defects. This serves as a starting point for the simulative optimization procedure of the actual repair. Within the fixed framework of part and robot coordinates, the damaged area of the component will be pre-processed by milling. This should ensure removing of possibly damaged material and prepare the needed geometrical conditions for CS with respect to needed impact angles for optimum deposit qualities [23]. Component geometry, defect size and tolerance limits define the working area and the damaged areas to be machined by milling and subsequently repaired by CS.

An essential part of the integrated cell concerns the possible coupling of simulative optimization procedures for the individual component besides the real process. In ideal, fast computation and parameterization in databases should allow to develop an automated process that operates on basis of all key data of the respective component. This concerns assigning of toolpaths for machining as well as the simulation of the toolpath planning for the following deposition. For the selected start-geometry, tools and conditions for milling and possibly other pre-processing can be derived by simulation. The once set repair geometry is also the basis for planning and simulation of the spray toolpath, in ideal running in parallel. The holistic models in the background should combine domains of materials science for CS and automation technology for robotics. This includes the use of individually determined, material dependent parameterization of optimum cold spray parameter sets and respective thresholds for toolpath planning in machining and deposition to achieve the desired design requirements.

The planning of the pre-processing is optimized for meeting all requirements for optimum preparation of surface geometries to safely enable needed spray path and trajectories. The illustrated simulation workflow is designed to determine optimized pre-processing and spray toolpaths at any time by coupling respective adjustments. Calculated conditions according to the simulations are transferred to the real repair system after sufficient convergence within defined boundary conditions. The suggested combination of primary and secondary parameters should enable an overall optimum result to restore the original shape, while ensuring the needed material properties.

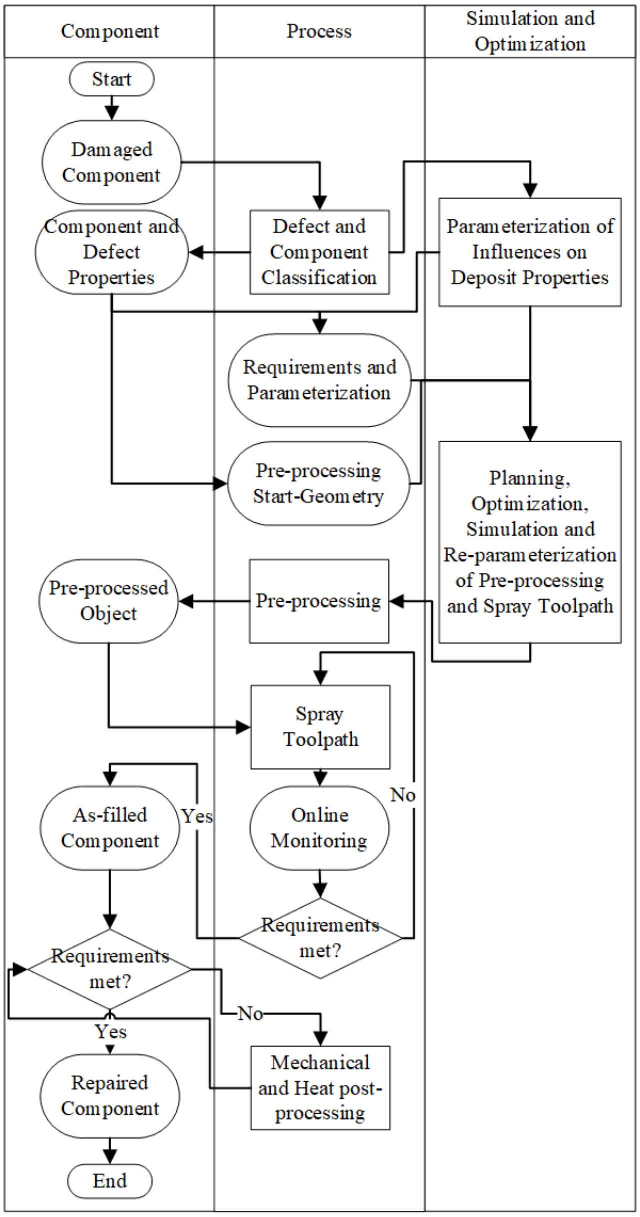


FIGURE 4: FLOW CHART OF THE AUTOMATED COLD SPRAY REPAIR.

In real system performance, disturbances can occur during the spray process. To detect and ideally compensate these disturbances, on-line monitoring can be performed. Here, sensors can be used for on-line control of the built-up layer geometry and quality in comparison to the target values from the simulation. After CS deposition, the as-filled component gets subject to post-processing. This could include further property enhancement, and in any case the final shape adjustment. The application of post treatments and post-machining allows the application of a precisely targeted repair workflow. In order to guarantee the required material properties of the repaired component, non-destructive performance tests must be performed.

IV. DEVELOPMENT OF DEPOSIT PROPERTY DESCRIPTION

A. Deposit Optimization - Primary Influences

In first sets of optimization, Al6061 powder were ordered in different, defined particle size distributions to reveal possible differences in deformation and bonding. The particle strengths were determined by single powder particle compression tests [17].

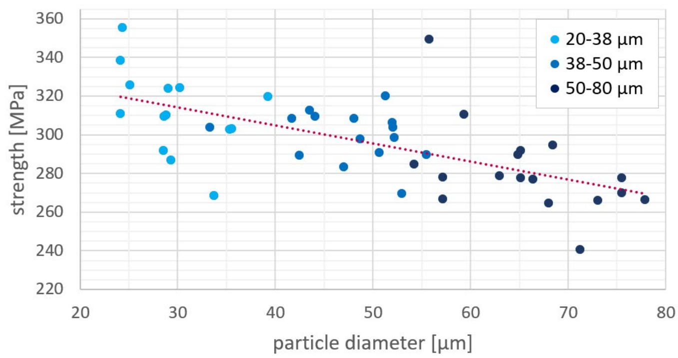


FIGURE 5: STRENGTHS OF AL6061 POWDER PARTICLES OF DIFFERENT SIZE BATCHES IN AS DELIVERED STATES.

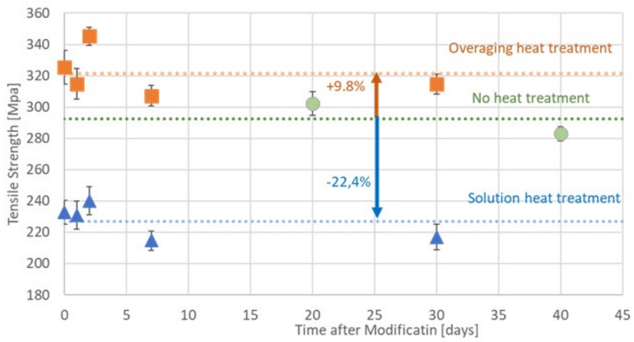
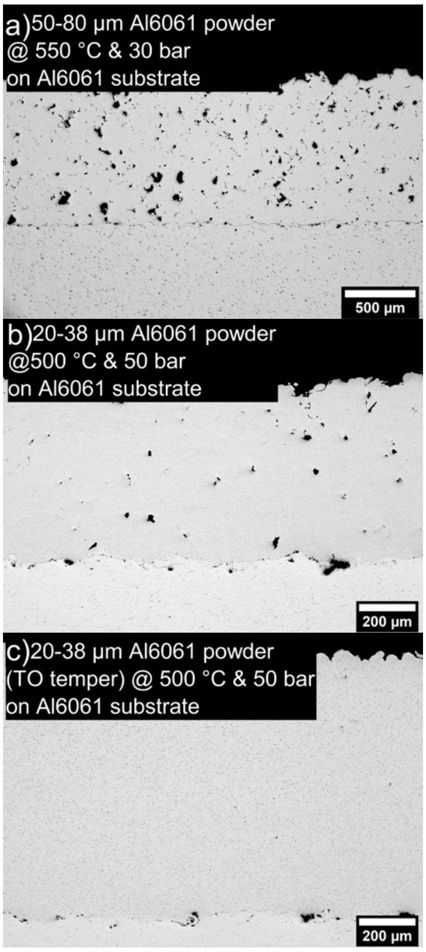


FIGURE 6: DEVELOPMENT OF AL6061 POWDER STRENGTHS AFTER MODIFICATION BY SOFT TEMPER (SOLUTIONIZING, T0) AND OVERAGING OF 38-50µM SIZED AL6061 POWDER.

The data reveal that ultimate powder strengths slightly decrease with size from about 320 to about 260 MPa and are more than twice as high as strengths of soft annealed bulk material. The high powder strength is attributed to fine grained microstructures by rapid solidification in powder production by gas atomization and possibly room temperature aging during storage. In consequence, high critical velocities in cold spraying could restrict attainable deposit properties. As shown in FIGURE 6, powder modification by heat treatments for solutionizing could successfully reduce powder strengths by about 22 %, then not resulting in a strength increase during storage for more than a month.

Comparing the performance in cold spraying under identical conditions, the use of soft annealed instead of as delivered powder could increase the deposition efficiency by about 25 %. Examples for deposit microstructures of Al6061 are shown in FIGURE 7 for using as atomized and soft annealed powders. Applying higher parameter sets for as delivered powder, deposit microstructures could already be significantly improved, reducing the porosity from 3.4 % to about 0.1 %. The use of soft annealed powder at the high spray parameter set results in a rather homogenous deposit microstructures with negligible porosity that in as polished state not allows to reveal any features from particles-particle interfaces. The improvement scales with η ranging from 1,1 to 1,3, and should allow for further optimization. Property analyses of differently prepared deposits are currently under investigation to supply more evidence in respective influences, as well as first sets of experiments with other Al-alloys and Ti as deposit material.



a.

b.

FIGURE 7: DEPOSIT MICROSTRUCTURES AS OBTAINED BY COLD SPRAY OF AS DELIVERED (A, B) AND SOFT ANNEALED POWDERS. COLD SPRAYING WAS PERFORMED WITH PARAMETER SETS OF (A) P_{GAS} = 30 BAR, T_{GAS} = 550°C WITH POWDER SIZED 50-80µM AND (B, C) P_{GAS} = 50 BAR, T_{GAS} = 500°C WITH POWDER SIZED 20-38µM.

B. *Deposit optimization-Secondary influences*

Selected Al6061 deposits were investigated by stress analyses via strain relaxation by hole drilling as well as peak shifts in X-ray diffraction according to the $\sin^2(y)$ correlation. Needed elastic constants for stress calculations were determined by ultrasonic testing. The elastic constants of the deposit are about 5-10 % lower than that of comparable bulk material, which could be attributed to internal defects, most likely non-bonded interfaces. FIGURE 8 shows the example of depth profile of stress distribution for a deposit cold sprayed with the medium size powder (38-50 µm) using a parameter set with p_{gas} = 30 bar, T_{gas} = 500°C.

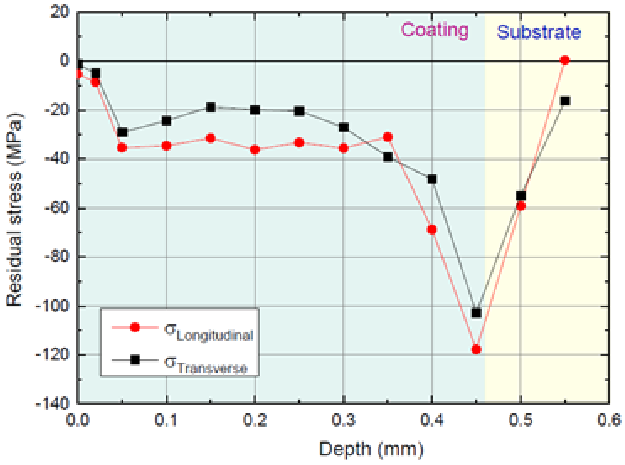


FIGURE 8: DEPTH DISTRIBUTION OF INTRINSIC STRESSES AS OBTAINED BY XRD-ANALYSES OF A AL6061 DEPOSIT, COLD SPRAYED WITH THE MEDIUM SIZE POWDER AT P_{GAS} = 30 BAR, T_{GAS} = 500°C.

Within the deposit, the stresses are rather constant and slightly compressive with about -30 MPa. In contrast, higher compressive stresses of about -120 MPa are obtained at the interface to the substrate, here over a distance of about 100 µm within the substrate then declining to zero. The mainly compressive nature of stresses can be attributed to peening effects under the high velocity particle impact. However, the rather low values within the deposit indicate that other effects might be superimposed. Possible explanations might be given by either i) tensile stresses due to thermal gradients or ii) recrystallization and plastic deformation, or even combinations of both.

Since local stress states could be decisive for repair applications, further investigations are in progress by combining experiments and simulation to distinguish different influences and to derive correlations with spray conditions and used robot kinematics.

For determining the thermal history of a deposit during cold spraying, temperature analyses are coupled with simulation. This combination should allow for calibration of heat flux, means heat input by cold spraying and losses to the environment, as well as heat diffusion over the part. The model setup and a snapshot of temperature distribution for spraying one layer gas only is given in FIGURE 9. The red stripe indicates the high temperatures that are reached within the most upper nozzle scan line out of the set of lines propagating from bottom of the substrate to the top during spraying of one complete layer.

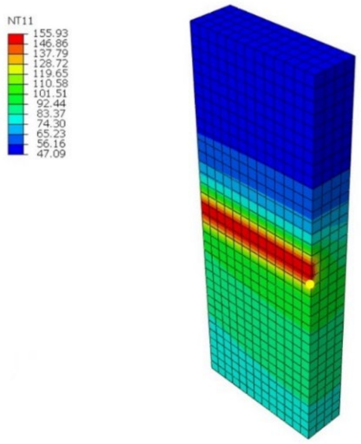


FIGURE 9: SIMULATION MODEL SET-UP AND TEMPERATURE DISTRIBUTION FOR APPLYING ONE LAYER GAS JET IN CS.

FIGURE 10 compares the simulation results of such one layer scan with the experimentally determined surface temperature of a four-layer scan, as measured by a thermocouple, here just applying the cold spray gas jet without powder feeding at p_{gas} = 30 bar, T_{gas} = 500°C. The inserted graph focuses only on the first layer of experimental results and compares the temperature developments with one-layer simulation results. By calibrating the heat flux, the modelled surface temperature could be tuned to experimentally obtained ranges, then allowing to derive more details. The observed surface temperature of more than 100°C in case of Al-alloys should already allow for thermal recrystallization, and thus associated stress relaxation. In next steps, the models should be extended to study possible influences of temperature gradients on internal stress distributions. The results should be used to forecast the thermal history under real process conditions and to define boundary conditions for the most favorable kinetics in robot path generation.

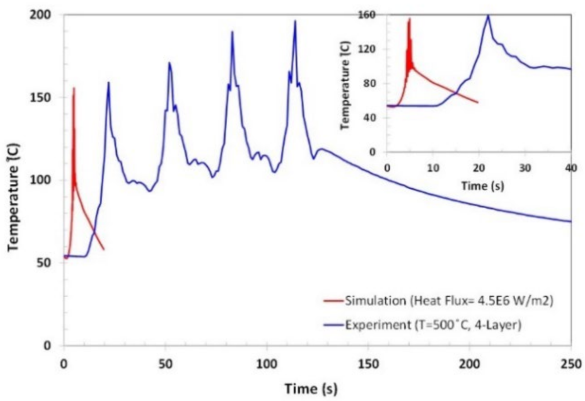


FIGURE 10: COMPARISON OF MODELLING THE SURFACE TEMPERATURE FOR APPLYING ONE-LAYER GAS JET SPRAYING AND THE EXPERIMENTALLY DETERMINED TEMPERATURE FOR FOUR-LAYERS WITH COLD SPRAY PARAMETER SETS OF P_{GAS} = 30 BAR, T_{GAS} = 500°C ONTO AN AL6061 SUBSTRATE IN A STAND-OFF DISTANCE OF 30 MM. THE INSERT COMPARES RESULTS ON TEMPERATURE DEVELOPMENT FROM SIMULATION WITH EXPERIMENTAL ONES DURING THE FIRST LAYER PASS.

C. Single line tracks and 3-D deposits

In cold spraying, the deposit is build-up by the powder distribution in the free jet after passing usually axisymmetric de-laval nozzles. Particle numbers and velocities can be described by peak functions, and thus, in consequence, also the associated material build-up under the spray jet, similar to use of an air-brush. The respective 3-D lines are then assembled to needed 3D-shapes. Solutions of this task are not straight forward and have to consider influences by stand-off distances to the substrate surface and impact angles on single line track shapes. Thus, the development of track shapes has been experimentally investigated and modelled for a range of possible situations that might be given in real processes. FIGURE 11 illustrates the material deposition in single line tracks by an experimental example of a cross section through an Al6061 deposit line orthogonally cold sprayed and the modelled deposit distribution under the spray jet. The comparison shows that peaks functions can be used to describe deposition. FIGURE 12 summarizes the profile shapes and skewness as obtained by using different spray angles. The increasing deviation in symmetry with decreasing spray angle is used for calibrating peak functions. Similar has was done for using different stand distances to the substrate (not shown here). The above description has been developed into a model for shape build-up including the main parameters for cold spraying. First results are shown in FIGURE 13, here demonstrating how line distance could influence surface pattern. This already indicates how line distances and impact angle influence the deposit shape and topography. Next refinements of the model concern the angular situation due to already build-up spray layers and influences on skewness and local deposition efficiency.

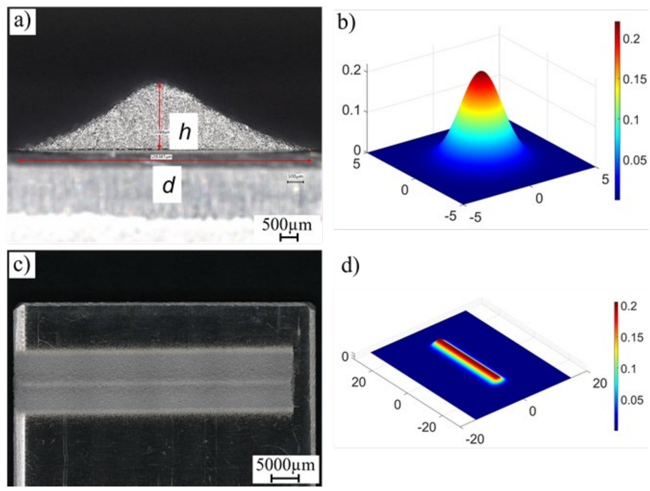


FIGURE 11: MATERIAL DEPOSITION IN SINGLE LINE TRACKS. A) CROSS SECTION THROUGH A AL6061 DEPOSIT LINE ORTHOGONALLY COLD SPRAYED WITH P_{GAS} = 30 BAR, T_{GAS} = 500°C ONTO A ALMG3 SUBSTRATE IN A STAND-OFF DISTANCE OF 30 MM, B) MODELLED DEPOSIT DISTRIBUTION UNDER THE SPRAY JET, C) DEPOSIT DISTRIBUTION IN THE SINGLE LINE AS DETERMINED BY MICROCOPY AND D) MODELLED SINGLE LINE TRACK UNDER THE SPRAY JET

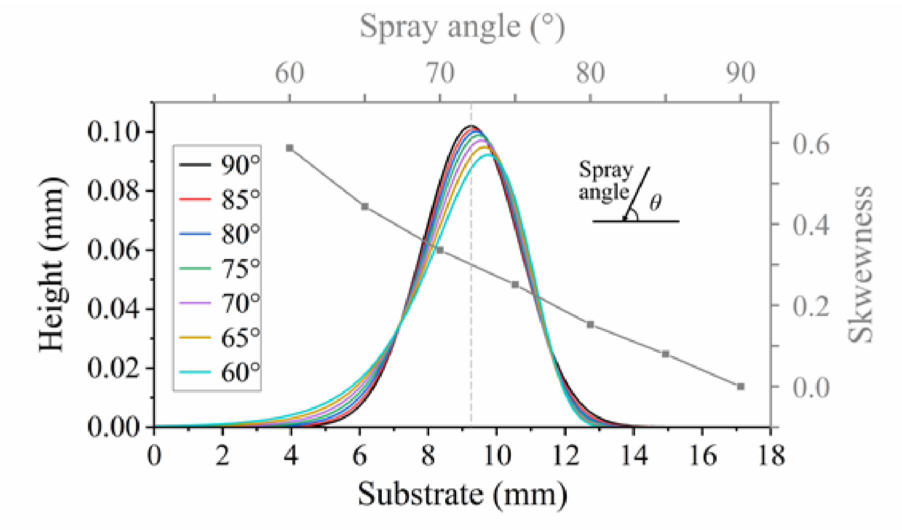


FIGURE 12: PROFILES SHAPES AND SKEWNESS OF SINGLE LINE TRACKS AT DIFFERENT SPRAY ANGLES.

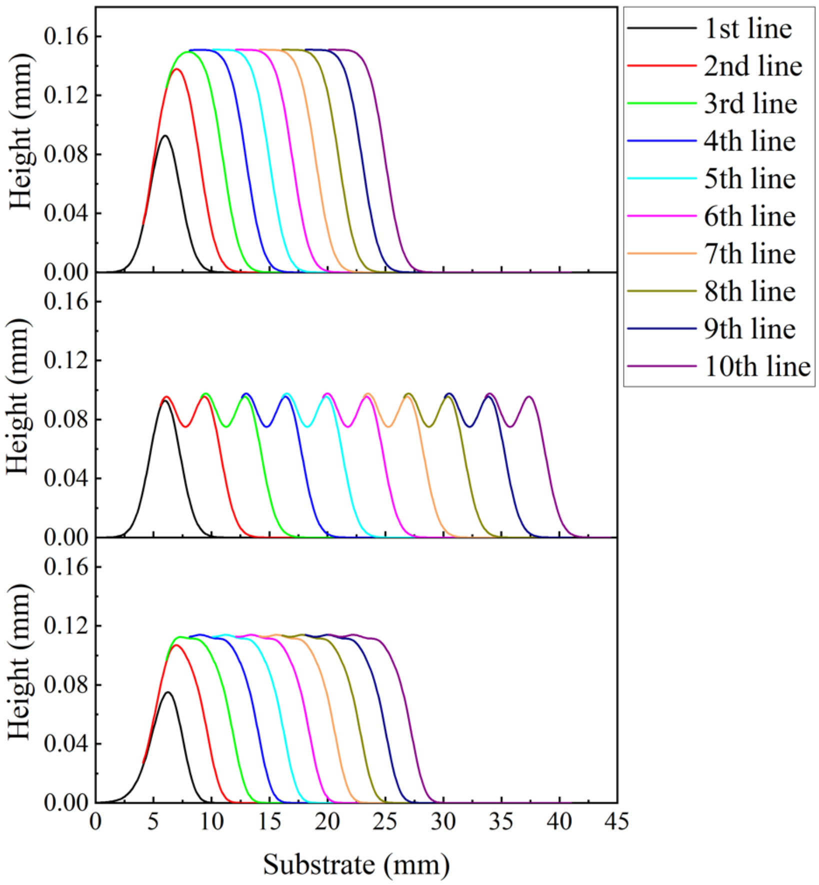


FIGURE 13: MODEL RESULTS FOR ASSEMBLING SPRAY LINES TO A DEPOSIT FOR REPAIR IN COLD SPRAY, WITH A) LINE DISTANCE OF 2 MM AND SPRAY ANGLE OF 90°, B) LINE DISTANCE OF 3.5 MM AND SPRAY ANGLE OF 90°, C) LINE DISTANCE OF 2 MM AND SPRAY ANGLE OF 75°.

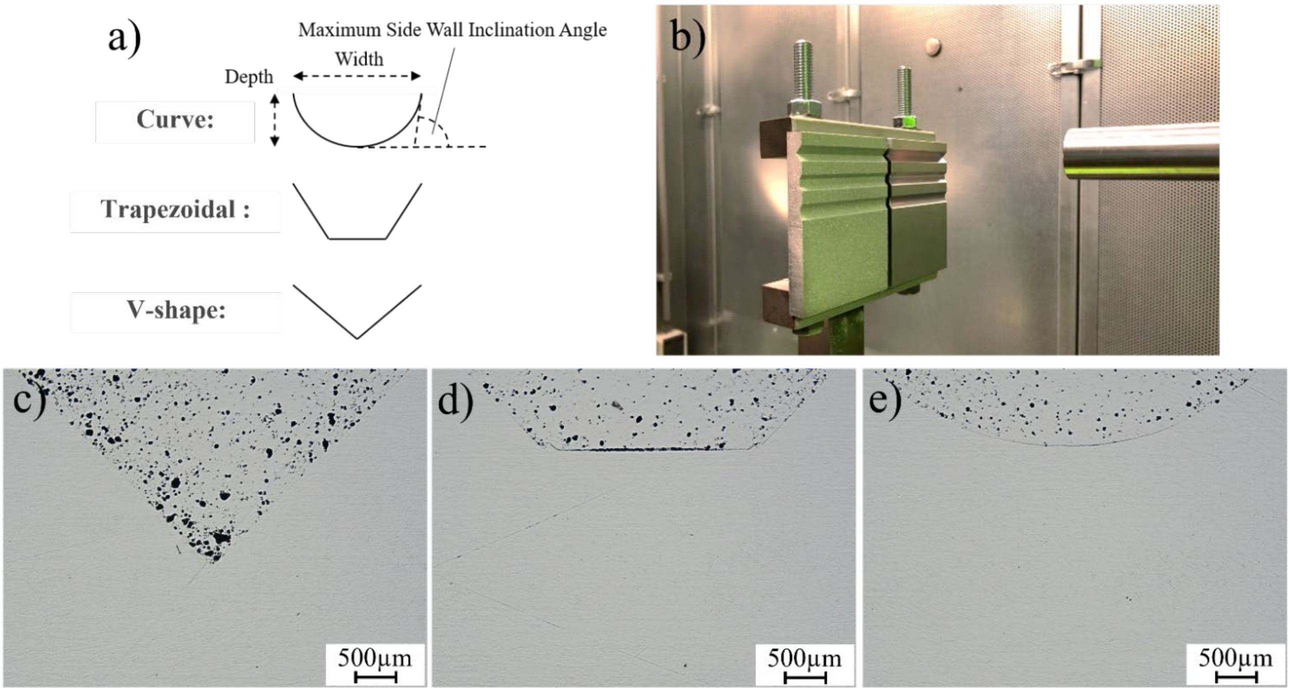


FIGURE 14: EXAMPLES FOR FILLING OF CAVITIES WITH A) SCHEMATIC OF DIFFERENT GROOVE GEOMETRIES, B) THE EXPERIMENTAL SET-UP AND C), D) E) EXAMPLES OF DEPOSIT MICROSTRUCTURES WITHIN FILLED CAVITIES.

D. Filling of Cavities

Success of by cold spray deposition and associated deposit qualities depends on local impact angles. In filling of cavities, the situation gets more difficult by particle deceleration under more pronounced bow-shock effects. As case study for cavity filling, several artificial groove types were prepared and filled by cold spraying by an orthogonal pass. Dimensions, set-up and examples of deposits are given in FIGURE 14. The deposit microstructures, in detail porosities confirm the manifold influence of cavity shapes on deposit qualities. Particularly layer build-up onto sharp edges and shape transitions seems to cause problems. Despite similar side angles, the microstructures with the cavity with a flat base shows less porosity at the side than the one with the sharp groove. However, the flat base suffers from problems with adhesion. In contrast, the microstructure within the smooth cavity is showing a rather homogenous porosity and overall a uniform interface appearance to the base material. More investigations are on the way to describe boundary conditions for general cavity shapes, tolerable deposit angles and transitions in shape.

E. Toolpath programming

The successful restoration of a specified damaged part to the needed shape and size by cold spraying requires the implementation of an accurate toolpath, which is also essential to meet the basic performance requirements. The planning, programming and subsequent implementation of the paths need to consider the various boundary conditions of the deposition, robot kinematics and the physical environment and layout. For each segment of the damage area, a high precision of spray path tracks and applied parameters is needed. Apart from spray angle, stand-off distance, as well as scanning speed and scanning step width, issues related to local heating and possible thermal stresses also should be considered. FIGURE 15 shows an example of cold spray toolpath planning, programming and implementation using robotic offline programming technology. This method enables the set toolpath to be exactly applied to each spraying target point. Process simulation in a virtual workstation allows for robot kinematics analysis, toolpath optimization and physical collision detection. As a result, the calibrated robot program is transferred to the real robot controller for execution. Future work will further investigate more strategies and analysis for robot trajectory planning and optimization in complex geometry reconstruction to achieve the expected cold-spray material deposition and desired repair quality.

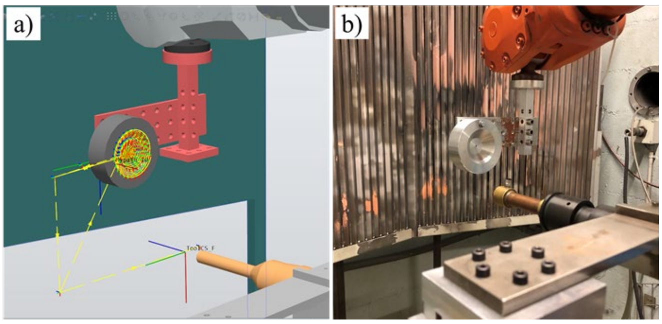


FIGURE 15: A) TOOLPATH SIMULATION IN THE VIRTUAL WORKSTATION, AND B) PROCESS IN A REAL SPRAY ENVIRONMENT.

V. SUMMARY AND CONCLUSIONS

To provide sophisticated repair solutions for aerospace applications, the suggested concept uses an interdisciplinary approach ranging from basic materials science of CS deposition by experiments and modelling to computer supported automation technologies and practical engineering applications. Within the limited frame of this project overview, only some snapshots and selected results of the different subtopics could be presented. So far, the results within the different topics already demonstrate the variety of influences on deposit qualities for possible repair and provide first correlations for the holistic concept of a general, digital description.

In order to successfully transfer the entire framework, methods and results to the real part repair applications in the future, further work is under progress for optimizing CS deposition techniques and thus deposit properties. Linking approaches of fluid mechanics, pre- and post-processing as well as non-destructive testing into the sketched framework aims for an integrated, digital concept. This concept does not only allow implementation as repair process under enhanced process and quality control. Apart from that, the suggested strategies can furthermore provide a more advanced theoretical basis for cold spray additive manufacturing in general, and for easy transfer to other engineering applications.

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