# Technological Developments in Nozzle Design for Twin Wire Arc Spraying to Improve the Variety of Application

W. Tillmann, L. Hagen, M. Abdulgader

*Institute of Materials Engineering, Faculty of Mechanical Engineering*

## Abstract

In this study, different approaches are presented to investigate various types of spray nozzle configurations in the twin wire arc spray process. A major emphasis was to investigate nozzle configurations providing different coating properties with respect to the microstructure formation by using increased gas velocities. According to this, the improved flexibility of use due to a focused spray plume and higher particle velocity, were investigated. The flow characteristics and particle behavior were evaluated by using in-flight particle diagnostics and a high speed camera to investigate important interactions, which influence the atomization behavior. In addition, metallographic investigations of the coatings were carried out to assess their suitability. Here, the topography plays an important role in either case to produce smooth coatings to reduce the friction or to minimize post machining processes.

Finally, the results with respect to the flow characteristics, the spray plume characteristics as well as the coating properties are compared to the experiments utilizing commonly parameter settings.

***Keywords:*** *TWAS, nozzle attachment, particle diagnostics, coating properties*

## 1 Introduction

In terms of twin wire arc spraying (TWAS) the coating properties are defined as the sum of the parameters which directly or indirectly influence the particle formation, particle in-flight characteristics, and the flattening behavior of droplets on the surface of the substrate [Wil00, Pou04, Pla04, Jan03, Wan94]. In the field of thermal spraying, in-flight particle characteristics such as the velocity, temperature, and particle size are the controlling factors in splat formation and in the determination of the coating quality. The produced layers

# Near-Net-Shape Coatings Manufactured by Means of Thermal Spraying: Influence of path strategy and robot dynamics

W. Tillmann, P. Hollingsworth, I. Baumann, D. Stangier

*Institute of Materials Engineering, Faculty of Mechanical Engineering*

## Abstract

High Velocity Oxy-Fuel (HVOF) sprayed WC-12Co coatings are used in a wide range of applications to protect tribologically stressed components against wear. In most cases, the parts feature a planar (or almost planar) surface. Hence, the fabrication of high quality coatings with consistent properties mainly depends on the on the characteristics of the feedstock powder, for example the density and the grain size distribution, the spray equipment used and the optimization of the process parameter. These influencing variables were sufficiently investigated by many researchers and are nowadays well known. However, the trend toward smaller component dimensions and higher surface complexities, for example in the forming industry, may cause deviations from optimal values, e.g. the spray angle or the gun velocity. These deviations can affect the mechanical coating properties as well as the deposition rate of the process.

This study presents the manufacturing of near-net-shape coatings on complex geometries by means of thermal spraying, in particular HVOF spraying. It was found, that the key factors to control the deposition process and to achieve specific coating properties are limited robot dynamics (and resulting maximum gun velocities) and an appropriate choice of the path strategy to manufacture near-net-shape coatings.

***Keywords:*** *HVOF, WC-12Co, near-net-shape coatings, robot dynamics, heat input, residual stresses*

# Control of the Material Flow in Deep Drawing by the Use of Rolled Surface Textures

L. Hiegemann, C. Weddeling, N. Ben Khalifa, A. E. Tekkaya

*Institute of Forming Technology and Lightweight Construction*

## Abstract

In this article the possibility of controlling the material flow by rolled surface textures is investigated. For this purpose, textures are rolled in a thermally coated surface by a hydrostatic ball point tool. In this connection, both open as well as closed textures are produced. The friction coefficients of the components with and without textures are determined using a strip drawing test. The obtained results are transferred to a deep drawing process. In this way, the possibility of influencing the material flow and, consequently, the shape of the produced parts is demonstrated.

***Keywords:*** *Ball burnishing, deep drawing, open and closed textures, friction, material flow*

## 1 Introduction

Based on the trend of lightweight construction, high-strength sheet materials are increasingly used in automotive industry. This results in high wear of forming tools due to the higher loads on the tool surfaces. One possibility to counteract this problem is the use of thermally sprayed hard metal coatings on the deep drawing tool surfaces [Tek12]. If these thermally coated tools are used without a post treatment, it results in poor surface qualities and a low drawing ratio of the produced parts due to the high roughness of the thermally sprayed coating. The quality of the produced parts can be improved by a finishing process of the deep drawing tool surfaces, like ball burnishing or grinding [Fra11]. By a smoother surface and, hence, a lower friction between sheet metal and die as well as between sheet metal and blankholder, the drawing ratio and, thus, the process window can be increased [Tek13] [Lan90]. But a control of the material flow only in selected areas of the tools is not possible in this way. A non-uniform material flow can occur in deep drawing,

# Robot Motion Simulation for Path Optimization

B. Johnen, B. Kuhlenkötter

*Institute of Production Systems, Faculty of Mechanical Engineering*

## Abstract

Industrial robot based thermal spray coating of free form surfaces is a challenging task. It makes high demands on the robot path planning and the dynamic robot motion behavior. This contribution presents a method to integrate robot motion simulation into a path planning and optimization approach for thermal spray coating. The interaction between different path planning and simulation components is outlined and the robot simulation approach is described. During the initial generation and optimization, paths are generated with a high resolution of interpolation points. Simulating the robot motion on these paths results in sampled path data, which are not directly connected. We point out that for the proposed optimization strategy, it is necessary to find corresponding points of the uneven sampled generated and simulated paths and we present an algorithmic solution for this task.

***Keywords:*** *Industrial robots, motion simulation, path interpolation*

## 1 Introduction

Near-net-shape coating with industrial robots of complex free-form surfaces makes high demands on the process control as well as on the associated path planning for the robot system. The robots path defines the important factors of the inclination angle and the surface speed of the coating tool which have significant impact on the process results [Til10].

The Projects A2, A4 and B4 of the SFB 708 develop a corporate approach for the generation of robot trajectories for thermal spray coating. The path planning approach is divided into two main steps. At first an initial surface based path is generated. One example of the applied methods for this path generation uses a family of distance isolines induced by a seed curve on the workpiece surface and an anisotropic distance function in order to find an

# Surface Finish of Wear Resistant Coatings by Grinding – Process, Simulation, and Application

D. Biermann[a], H. Blum[b], P. Kersting[a], A. Rademacher[b], H. Ludwig[b], S. Rausch[a], T. Siebrecht[a]

[a]*Institute of Machining Technology, Faculty of Mechanical Engineering*
[b]*Chair of Scientific Computing LS X, Department of Mathematics*

## Abstract

In this paper the grinding and polishing of wear resistant coatings on machining centers and a simulation based process optimization are presented. In addition to the resulting surface topography, the occurring process forces have been measured and analyzed. By conducting a roughing process with vitrified bonded grinding tools and a subsequent finishing process with elastic bonded polishing tools, the surface roughness can be reduced significantly. A multi-scale simulation system is used to predict the generated surface topography considering individual grains of the grinding tool. In order to accomplish this, a geometric simulation by means of constructive solid geometry modeling and dexel board techniques was developed. Based on detailed engagement situations a finite element analysis is used to calculate the occurring stresses and forces for a single grain. These forces can be used to calibrate the force model of the geometric simulation. Furthermore, a multi-scale finite element method is used to determine macroscopic linear elastic material parameters of the HVOF coating by homogenization.

***Keywords:*** *grinding, polishing, geometric simulation, finite element simulation, homogenization*

# Optimization of Robot Based, Forced Controlled Grinding of Thermal Sprayed Surfaces

C. Krewet, A. Hypki, B. Kuhlenkötter

*Institute of Production Systems, Faculty of Mechanical Engineering*

## Abstract

The goal of the subproject A6 in the Collaborative Research Centre 708 at the Institute of Production Systems (IPS) at TU Dortmund University is the development of a robot based grinding process to optimize the geometry and the surface properties of hard-coated surfaces. One important part of the research work is the development of machining strategies for this setup. In this paper the change of certain machining parameters will be discussed.

***Keywords:*** *Grinding, force control, robot based machining, process control*

## 1 Introduction (Section Heading)

Industrial robots are more and more used for machining tasks. The main reason for this is that the investment costs that are required to purchase these robots are much smaller compared to the costs that are necessary to purchase CNC-controlled machining centers. Other advantages are the relatively small needed footprint of the robot that is needed to build up in relation to the large work space of a machining center and the fact that the robot can easily carry out preceding and subsequent handling processes. Thus it is not necessary to implement additional devices to load and unload the machining centers.

Of course the comparison is not complete without considering the robot's limitations, e. g. a significantly lower stiffness than a machining center. This lack of rigidity, among other, has negative effects on the accuracy of the robot during the machining process [Pan11]. On the other hand, recently developed force control systems for industrial robots have proven very good performance, e.g. high sampling rate and low input-output latency, in a range of different machining applications.

# Acquisition and Application of Three Dimensional Spray Footprints in Coating Simulations

T. Wiederkehr, H. Müller

*Department of Computer Science VII – Computer Graphics*

## Abstract

For the planning of robot-guided spray processes the prediction of the coating thickness resulting from a given spray path is essential. We present an efficient, GPU-based approach for thermal spray coating simulation on complex workpieces based on footprints, which are used to describe the mass flow characteristic of the simulated process. In particular, problems arising in the experimental acquisition of the required footprint data are discussed and an optimization approach overcoming most of them is presented.

***Keywords:*** *spray simulation, GPGPU, coating thickness, footprints*

## 1 Introduction

The offline path planning for robot-guided thermal spray processes is an important tool to generate paths for complex workpieces that cannot be teached manually [Kou09, Heg13]. To achieve a desired coating thickness distribution a simulation system can be used to avoid cost- and time-consuming trial and error experiments. Any kind of simulation that aims at predicting the coating distribution needs to model the mass- or volume flow emitted from the spray gun – however, retrieving an accurate model for a given process is a complicated task and in this contribution the acquisition process is discussed. This includes the identification of common problems and the presentation of an optimization approach to overcome most of them.

As a background, in the following a coating simulation system is presented at first. It uses experimentally created and scanned footprint profiles, also known as spray spots, as a basis to model the coating deposition. In contrast to the common approach to use fitted Gaussian distributions it is able to model

# Modeling of the Boundary Regions Between a Spreading Droplet and a Rough Surface of Solid

T. Theis, A. Ouazzi, O. Mierka, S. Turek

*Chair of Applied Mathematics & Numerics (LS3), Department of Mathematics*

## Abstract

Drop impact onto a solid surface is a complex phenomenon, which is depending on a variety of factors. To describe the fluid motion, the incompressible Navier-Stokes equations will be used. It is known that the inertial effects and the viscous and surface tension forces affect the evolution of the drop spreading and accordingly of the receding. The arising singularity in the solution for the stresses at the contact line requires special treatment. The interface is divided into three regions with different length scales. At the inner region, the local viscous drag near the moving contact line determines the value of the microscopic dynamic contact angle. Due to numerical difficulties to resolve a mesh of the order of the slip length, which is comparable with the molecular size, the inner region is removed from the computational domain. We substitute the interplay between the microscopic angle and the macroscopic hydrodynamics by an additional force applied to the contact line. The Navier slip boundary conditions appear on the intermediate region. At the outer region the inertial effects become significant. This region is characterized by the no-slip boundary condition. Both fluids are assumed to be incompressible and Newtonian with constant properties (density, viscosity and surface tension). Some preliminary numerical results for an axisymmetric problem are presented.

***Keywords:*** *Contact line speed, macroscopic and microscopic dynamic contact angle, slip length, drop spreading, Navier-Stokes equations*

# Efficient Analysis of Milling Processes for the Manufacturing of Forming Tools Using a Multi-Scale Simulation System

A. Zabel, S. Odendahl, A. Peuker

*Institute of Machining Technology, Faculty of Mechanical Engineering*

## Abstract

In order to evaluate the process stability and safety of NC milling process for the manufacturing of forming tools during the process planning phase and, thereby, prevent extensive experimental investigations, a preceding simulative analysis of the process is advisable. For a comprehensive analysis and optimization of the milling process, the simulation system should, on the one hand, be able to provide as much information as possible, but it should, on the other hand, also allow multiple simulation runs with varying process parameters in a reasonable time frame. This can be achieved by applying a multi-scale modeling concept with different levels of detail, which offers different optimization options with regard to the run-time of the simulation without limiting the prediction capabilities. The ability of the simulation system to calculate stability charts for milling processes is utilized for the process planning of the NC milling of a springback-compensated deep-drawing die in order to ensure process reliability.

**Keywords:** *Milling, simulation, multi-scale modeling, run-time optimization, springback compensation*

## 1 Introduction

For the economic manufacturing of forming dies and molds, an efficient process planning step with high performance and reliability of the machining process is required. Simulation systems are commonly used to predict different aspects of the process, e.g., material removal or collision detection. The results of the simulations can be used for more comprehensive manual or

# Development of a Layer Thickness Measurement System

W. Tillmann[a], H.-G. Rademacher[b]

[a]*Institute of Materials Engineering, Faculty of Mechanical Engineering*
[b]*RIF e.V. Institute for research and transfer, Dortmund*

## Abstract

At the Institute of Materials Engineering segments for deep-drawing dies are plated with wear-resistant coatings. These are applied by using thermal spray processes. These layers must have a minimal thickness, so that their functionality can be guaranteed. On the other hand it should be coated near net shape, because the excess material must be removed with great effort later. The knowledge of the layer thickness is therefore a very important factor for the coating process as well as for the subsequent processing process. Usually, this value is determined metallographically at discrete locations. The component cannot be longer used, because the examination works destructively. Therefore the process and the conditions must be stable enough, that the next components can be coated in the same way. In the following, alternative methods as well as an optical thickness measurement system are presented, with which this coating thickness can be determined nondestructively.

***Keywords:*** *non-destructive testing, digital image correlation, thickness measurement*

## 1 Introduction

Tools for sheet metal forming are produced in a complex process and show wear during their use, so that from some point they lose their geometrical accuracy. To reduce this wear and to simplify the whole manufacturing, thermal sprayed, wear resistant, coatings can be used. These are applied to a main body, which has not to be hardened. Ideally, the tool is almost ready for use and only needs some polishing to improve the surface quality. In practice, the required layer thickness is not achieved precisely. In order to achieve a minimum required coating, the component must be coated thicker than

# A Simulation Based Path Optimization System for Robot Guided Thermal Spray

D. Hegels, H. Müller

*Department of Computer Science VII (Computer Graphics)*

## Abstract

Robot path generation for coating of free form surfaces by thermal spraying is a challenging task due to the complexity of spraying process. A flexible way to cope with this problem is simulation based optimization. This contribution presents a software system implementing such an approach. Its core is an optimization module which iteratively improves the robot path using heuristic rules. The rules take the evaluation of the objective function for the current path as input and generate a modification of the parameters of the current path as output. The evaluation of the objective functions uses two further modules, a coating simulation module and a robot dynamics simulation module. The initial path of the iteration is provided by a so-called elementary path generation module. While this module generates paths that are constrained to a fixed path pattern with a low number of degrees of freedom within reasonable computation time, the path optimization module is able to efficiently refine a given path with respect to application depending parameters of the robot and the spray gun configuration. The modules communicate by a network protocol and can be distributed on different computers. They provide graphical user interfaces for control and visualization.

***Keywords:*** *thermal spraying, path planning, simulation, optimization*

## 1 Introduction

In thermal spraying applications a spray gun is moved over a workpiece in order to build a coating of spray material on the surface of the object. The spray material is heated inside the spray gun until it liquefies and is then accelerated onto the surface where it cools down and builds a solid coating. Depending on the material, different surface properties like wear- or corrosion protection can be achieved.

# Multi-Scale Modelling and Simulation of the Material Behaviour of Thermal-Sprayed Coatings

R. Berthelsen, R. Denzer, A. Menzel

*Institute of Mechanics, TU Dortmund, Germany*

## Abstract

A thermo-mechanical computational homogenisation scheme in terms of an FE² framework for coupled thermo-elasticity is presented in this contribution. Using the example of HVOF thermally sprayed tungsten carbide-cobalt coatings, the unknown effective material properties of the considered heterogeneous coating consisting of two different phases are determined. From the fundamental balance equations, a finite element framework for two different scales is derived and implemented. The computational homogenisation is performed by application of two different homogenisation approaches that are compared with each other, and the effective material parameters are compared to experimental values from the literature. Finally, results of the FE² framework are presented which illustrate the mode of operation of the implemented two scale finite element programme.

***Keywords:*** *thermo-mechanics, computational homogenisation, continuum thermodynamics*

## 1 Introduction

In order to create durable sheet metal forming tools, wear resistant coatings are often produced by thermal spraying techniques for economic reasons. In this contribution, hard material coatings of tungsten carbide (WC) and cobalt (Co) produced by a HVOF thermal spraying process are considered. The spraying process itself is a very complex transient fluid and solid mechanical problem which is not covered by this work but, however, even the cooling of the coated substrate represents a complex transient thermo-mechanical coupled problem. During quenching, unpredictable residual stress states occur, due to the fact that the effective material properties of the heterogeneous WC-Co coating are unknown.

# Efficient Simulation and Optimization of Rotationally Symmetric, Converging-Diverging de Laval Nozzles for Twin Wire Arc Spraying

S. Turek, M. Möller, M. Razzaq, L. Rivkind

*Chair of Applied Mathematics & Numerics (LS 3), Department of Mathematics*

## Abstract

Recent developments in the design of rotationally symmetric, converging-diverging de Laval nozzles for the use in twin wire arc spraying processes are discussed. Various aspects of an efficient implementation of the proposed gas dynamics solution algorithm on modern multi- and many-core architectures are addressed. Finally, a general framework for the application of massively parallel, derivative-free optimization methods on cluster systems is presented.

***Keywords:*** *Converging-diverging nozzle, shape optimization, parallelization, high-resolution scheme, equations of gas dynamics, boundary treatment*

## 1 Introduction

Thermal spraying techniques such as HVOF, plasma and flame spraying are widely used in industrial applications to produce metal coatings on structural materials to protect them against high temperatures, erosion, and wear or to impose a special surface structure which is particularly desirable in sheet metal forming. Amongst the alternative approaches, twin wire arc spraying is quite attractive due to its high deposition rates, the low process temperatures which cause less stress in the coating and the substrate and, from an economical point of view, its moderate operation costs. On the other hand, the resulting coatings usually contain numerous pores due to low particle velocities as compared to other spraying processes with higher kinetic energy.

Encouraged by the measurements and observations pursued by subproject A1 of the SFB 708, the common aim is to modify parts of the commercial spraying system so as to achieve higher particle velocities and to obtain a well focused spray jet at the same time. To reach this goal, different strategies are

# Towards Optimal Control of Elastoplastic Contact Problems with Application to Incremental Rolling

T. Betz, C. Meyer, A. Rademacher, K. Rosin

*Chair X of Scientific Computing, Faculty of Mathematics*

## Abstract

The paper deals with optimal control problems governed by elastic contact problems and elastoplastic deformation processes, respectively. Problems of this type often arise in the optimization of industrial forming processes such as e.g. incremental rolling. The associated mechanical models typically provide a non-smooth behavior, which complicates the application of fast derivative based methods for their optimization. A remedy is the use of regularization methods in combination with an efficient error balancing as preliminary numerical tests indicate.

***Keywords:*** *optimal control, variational inequalities, Signorini problem, elastoplastic deformation, regularization, dual weighted residual error estimator*

## 1 Introduction

Elastoplastic contact problems play a fundamental role in a multitude of industrial production processes. This particularly concerns the production chain for complex, free-formed deep drawing tools as considered in SFB 708. We exemplarily mention the incremental rolling of the coated surface in order to grade the surface texture. The optimization of the overall production chain thus requires to optimize processes which provide elastoplastic deformation and mechanical contact. Such processes are frequently modeled by variational inequalities, which leads to a certain non-smooth behavior of the model. This concerns both aspects, i.e. contact problems as well as elastoplasticity models. To overcome this challenge, tailored regularization approaches have successfully been pursued which are especially well suited to the non-smooth behavior induced by the contact conditions and the elastoplastic material models. Up to now, both phenomena have been investigated separately. The

# The Possibilities of Stiffness Variation in Deep Drawing Tools Made of Polymers

T. Mennecart, A. Güner, A. E. Tekkaya

*Institute of Forming Technology and Lightweight Construction, Faculty of Mechanical Engineering*

## Abstract

As a result of the increase in number of types of cars, the batch sizes become more and more small. Therefore the use of tools with a lifetime of nearly 10,000 parts becomes more attractive. In case of low production volumes as well as in the design process, deep drawing tools can be made of polymers. The main advantage of this polymer tools is the easy way to change or influence its stiffness. The outcome of this is the possibility, by the use of tools with such stiffness varying elements, to decrease the springback and to enhance the forming quality of the final part.

In this research the possibility of the influence of stiffness variation in polymer tool is shown for the deep drawing process of DP 600 high strength steel. A reduction of springback could be reached for two different forming operations. This reduction is affected by ascending tension in those sections via adjusting the stiffness to a suitable level. During the forming process actuators allow consistent modifications of stiffness. The results show better geometrical accuracy in case of using elements like the springs and actuators.

**Keywords:** *sheet metal forming, polymer tools, springback, stiffness variation, geometry accuracy*

# In Situ Wear Test on HVOF Sprayed WC-12Co Coatings in a Large Chamber SEM

U. Selvadurai, W. Tillmann, W. Luo

*Institute of Materials Engineering, Faculty of Mechanical Engineering*

## Abstract

Currently, the determination of the mass loss is usually used for a quantitative evaluation of wear tests, while the analysis of wear tracks is utilized for a qualitative evaluation of wear. Both evaluation methods can only be used after the wear testing process. Their results only present the final outcome of the wear test. However, the changes during the wear test and the time-dependent wear mechanisms are of great interest as well. A running wear test in a large chamber scanning electron microscope (SEM) offers the first opportunity to observe the wear process in situ. Different wear mechanisms, such as the adhesive, abrasive wear, and tribochemical reaction, can be recorded with high magnification.

Within this research, a special pin-on-disc testing device is designed for a vacuum environment. Using this device, WC-12Co coatings generated by means of high-velocity-oxygen-fuel (HVOF) spraying were tested in a large chamber SEM with $Al_2O_3$ ceramic balls as wear counterparts. During the wear testing, different wear mechanisms were determined and the processes were recorded in short video streams.

***Keywords:*** *wear testing, in situ, thermal spray coating, large chamber SEM*

## 1 Introduction

After the thermal spray technique has been invented a hundred years ago, scientists as well as industry have always been interested to use this process as a coating technology to protect components against wear, corrosion, and heat, or to obtain electrical and magnetic properties [Wie00], [Hei02], [Bac05]. To test the wear behavior of the coatings, pin-on-disc [Bol06] and taber-abraser tests [Voo05] are usually employed. In order to evaluate the

# Springback Reduction of Deep Drawn Parts by the Use of Variable Blankholder Force and Tools with Adjustable Stiffness Based on Numerical Simulations

H. ul Hassan[a], J. Fruth[b], M. Ivanov[b], S. Kuhnt[b], A. Güner[a], A.E. Tekkaya[a]

[a]*Institute of Forming Technology and Lightweight Construction, Faculty of Mechanical Engineering*

[b]*Institute for Mathematical Statistics and Applications in Industry, Faculty of Statistics*

## Abstract

This article presents two approaches to reduce the springback induced shape deviation in sheet metal forming. In the first case the blankholder force (BHF) profile is optimized over time (punch travel) for the minimization of springback. In the next case, the stiffness of the deep drawing tool is varied over the punch travel to reduce the shape deviation. Finite element simulations are performed for both of these methods and for both the varying inputs are analysed based on piecewise constant functional designs. In case of the varying BHF a direct minimization based on statistical response surface models is carried out. The effect of time varying tool stiffness on springback is also investigated with the help of statististical design of experiments. It is shown that the strategy of time dependent BHF and tools with time varying stiffness leads to smaller springback.

***Keywords:*** *sheet metal forming, springback, simulation, functional input parameters, response surface optimization*

## 1 Introduction

In sheet metal formed components, springback is one of the main sources of geometrical and dimensional inaccuracy. The final shape of a part depends on the amount of elastic energy stored in the part during the process of sheet metal forming [Nar04]. The stored elastic energy itself is influenced by a number of parameters, making prediction of springback a complicated task. The sensitivity

# Optimization of the Process Chain for the Efficient Manufacturing of Forming Tools With Complex 3D Surfaces

T. Wagner[a], L. Klein[b], D. Hegels[c], T. Wiederkehr[c], A. Peuker[a], S. Odendahl[a], S. Rausch[a], D. Biermann[a], C. Buchheim[b], H. Müller[c]

[a]*Institute of Machining Technology (ISF), Faculty of Mechanical Engineering*

[b]*Chair of Discrete Optimization (LSV), Department of Mathematics*

[c]*Chair Informatik VII, Department of Computer Science*

## Abstract

The manufacturing of wear-resistant forming tools with 3D surfaces requires a sequence of manufacturing operations. First, the basic shape of the forming tool is manufactured by five-axis milling. The tool is then coated by a thermal spray robot. Finally the geometric tolerances and the surface finish are ensured by a free-form grinding operation. In this paper, the efficiency of the process chain is optimized using coupled simulations of all process steps. To accomplish this, the deviations from the target geometry after the spraying process are analyzed and the NC code positions used for machining the basic shape of the forming tool are adjusted. By approximating a parametric free-form deformation, no manual adjustment of the control code is required. The deformation can be automatically derived from an analysis of the form errors after coating. The results of this approach are demonstrated based on geometric simulations of the involved milling and coating processes on a test part of a complex modular 3D forming tool.

***Keywords:*** *Five-axis milling, grinding, thermal spraying, geometric simulation, free-form deformation, form-error compensation, optimization, process chain*

## 1 Introduction

The manufacturing of forming tools is a complex planning task in which different machining operations, such as milling and grinding, have to be performed. In addition, coating processes can improve the wear and surface characteristics of the tool [Til12]. They, however, possess additional