Final report
of the cooperation project:

„Development of the process technology and a planning tool for flexible forming of long solid and hollow components with complex geometry“ (FlexFormPro)

sponsored by „BMBF-Fördermaßnahme KMU-innovativ: Produktionsforschung“

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The authors of this publication are responsible for its contents.

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(including 4-month extension)

GEFÖRDERT VOM
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Contents

1 Motivation, objectives and methodology

The research project is assigned to the KMU-innovativ: Produktionsforschung (SME-Innovative/ Production Research) funding program, which focusses on issues relating to the flexibil ization of production of materials with poor formability, its virtualization, and product and process quality. The electroforging process, with which material flow can be flexibly managed by the combination of electrical, thermal and mechanical machine parameters, stands out those categories. It is characterized by a high energy efficiency and allows a one-step, flexible forming even of large cross-sectional volumes. Due to the high complexity of the parameter constellation, the process has been until now empirically configured using time-constant parameters and was, therefore, deemed unsuitable for difficult geometries and small lot sizes. The target of this work is innovating the process and machine technology by contributing to the electro-thermo-mechanical FEM modelling for the electroforging process and determining the parameter functions with which complex geometries can be flexibly electroforged. This requires the development of a methodology for quickly deriving those parameter functions that enable the production of a specific geometry. To fully implement parameter functions mentioned before, state-of-the-art drive system and control system concepts are developed and implemented in cooperation with a machine user.

The project tackles the challenging development of new products by electroforging and exploiting its advantages over current bulk forging techniques. An industrial tool developed in this project enables electroforging of axisymmetric components, both solid and hollow, with reduced energy and force requirements and increased formability in comparison with concurrent closed die forming operations. This process benefits also from better heating performance and lower carbon footprint, coupled with high flexibility of output geometries with relative elementary inexpensive tool designs.

The project is carried out in cooperation between IFUTEC GmbH manufacturing company and the Labor für Umformtechnik und Werkzeugmaschinen (LUW) - Forming Technology and Machine Tools Laboratory of Hochschule Osnabrück - University of Applied Sciences. IFUTEC will lead the acquisition of new business products suitable for electroforging that will be later brought into mass production and implement the machine and process developments conceived with LUW, which also will be responsible for developing a simulation model and a methodology to study and characterize the process that finally will lead to an industrial planning tool for the electroforging process.

Previous work carried out by the project partners involved the development and coupling of an electrical solver with the mechanical and thermal modules of the FEM simulation software FORGE, the focus turned to model validation, analysis of the interdependence between all parameters and construction of a planning tool for electro- forging. Systematic simulations of the process under variation of the boundary conditions have been carried out to build the data pool and quantify the relevance of the parameters in the overall process and schematize the interrelation between them. This determined the necessity and defined the required modifications in machine technology, tool design and control system strategies required to attain the desired flexibility, process stability and profitability. The planning tool is built in a decision-tree like structure, offering guidance in the design of the tooling and billet, and makes use of an analytical model of electroforging to produce an approximate machine configuration. A statistical model derived from such data pool and the analytical model becomes the core of the planning tool, capable of providing a set of time- dependent parameter functions for the precise simulation of electroforging of given geometries. Systematic experimental tests validate the approaches proposed in this work.

2 Plan and execution of the scientific tasks

The project had an initial duration of 24 months, from 01/08/2018 to 31/08/2020. The HS Osnabrück started with a two-month delay, in 10/2018. After a cost neutral extension, the project ended officially in 31/12/2020.

Subproject I – HS Osnabrück:

HS Osnabrück started the project by hiring a M.Sc. Mechanical Engineer (Entgeltgruppe T13 nach TV-L) and making the planned invest in a state-of-the-art Workstation Dell Precision with 22 cores and 64GB RAM that enabled faster FEM simulations needed. Forming/upsetting simulations were carried out with the software FORGE®. CATIA V5 R21 which was required to carry out tooling design. During the project an 8-canal HBM signal amplifier QuantumX MX840B and corresponding sensors was employed in connection with a Dell Latitude portable workstation for recording and processing. Programming task was performed using the object-oriented programming language Python with an open-source integrated development environment. Necessary libraries to fulfill the project objectives were acquired on an as-needed basis.

The scientific tasks performed by HS Osnabrück are outlined here:

- Development of a classification system for the geometry spectrum
- Development of an FEM model as well as its optimization for its application to the process development of new components.
- Development and implementation of a methodology to reduce the development cycle between client request and first prototype.
- Development and implementation of machine and tool technology derived from the knowledge generated with in-depth FEM analysis, especially focussing on thermal management in the process.
- Development of process controlling strategies and corresponding necessary sensor systems derived from the knowledge generated with the in-depth FEM analysis.
- Development and validation of the proposed methodologies with a group of prototype industrial parts.

These correspond to the tasks planed in the workplan for the project. Table 1 references each task (AP) to the section in which it is treated.

Table 1. Fulfilled workplan for Subproject I HS Osnabrück of the original general plan of the FlexFormPro project. Reference to section in which each task package (AP) is addressed in.

Subproject I - HS Osnabrück	Time plan (months)					**Execution of task package (AP) in:**
Simulationsgestützte Konfiguration der Parameter-struktur zur flex. Formgebung durch Elektrostauchen	1-6	7-12	13-18	19-24	25-29	
1.1 Klassifikation des elektrostauchbaren Geometriespek-trums und Zuordnung von Verfahrensrandbedingungen	** ■					Section 3 Section 4 (4.1)
1.2 FEM-Modellbildung und -optimierung sowie simulationsbasierte Prozessvorauslegung	■	■	■			Section 3 Section 4 (4.2, 4.3, 4.4)
1.3 Prozess- und Sensorentwicklung		■	■			Section 5 (5.3, 5.4)
1.4 Optimierungsroutinen für die Simulationsmodelle und Entwicklung der Umformstrategie.			■	■		Section 6
1.5 Verifikation und Validierung der Systematik in Zusammenarbeit mit IFUTEC				■	■	Section 7
1.6 Ergebnisdokumentation					■	Section 8 Section 9

(*) 2-month difference in subprojects start.

All the task of Subproject I - HS Osnabrück were completely and successfully fulfilled. No concurring work by a third party has become known during the project.

In the consecution of the tasks planned following people were involved:

1. Prof. Dr.-Ing. B. Adams, Director of Labor für Umformtechnik und Werkzeugmaschinen (LUW) of Hochschule Osnabrück
2. M.Sc. Sergio Acevedo Rigueras, PhD candidate (TU Chemnitz), researcher at LUW of Hochschule Osnabrück

<u>Subproject II – IFUTEC GmbH</u>:

IFUTEC began to define the financial framework for the modification of the electroforging machine and future shared exploitation. As the costs for a new tempering unit for the tooling could not be covered, an existing cooling system was adapted. The robot and additional elements necessary to execute the planned automation of the chaining between the electroforging machine and subsequent operations in a complex manufacturing cell were tried out on a different, electroforging machine already used for series production.

The tasks performed by IFUTEC are outlined here:

- Market analysis and customer acquisition for small batches of lightweight components that would be technical and economically suitable.
- Analysis of different concepts for servo drives to modify a hydraulic electroforging press. Implementation of the driving system and the developed process control strategies.
- Implementation of fixture designs, focussing on standardization and simplicity. Implementation of a tool tempering-cooling system to improve process stability.
- Development and implementation of a flexible manufacturing cell for series production, consisting in the automated chaining of the modified press with a specifically developed cooling station and a turning station.
- Execution of testing campaigns of series production to validate the implemented solutions along the project in the modified machine.

These correspond to the tasks planed in the work plan for the project. Table 2 references each task (AP) to the section in which it is treated.

<u>Table 2.</u> Fulfilled work plan for Subproject II IFUTEC of the original general plan of the FlexFormPro project. Reference to section in which each task package (AP) is addressed in.

<u>Subproject II - IFUTEC</u>	Time plan (months)					**Execution of task package (AP) in:**
Entwicklung Verfahrenstechnologie und Prozessregelung des Elektrostauchens zur flexiblen Formgebung	1-6	7-12	13-18	19-24	25-29	
2.1 Marktanalyse, Akquisition von Einsatzmöglichkeiten und Anwendern. Definition der Versuchsteile						Section 3
2.2 Ausarbeitung v. Konzepten für Servostauchantriebe und Regelung, Aufbau/Implementierung in IFUTEC-Elektrostauchanlage						Section 5 (5.4)
2.3 Entwicklung der Werkzeugtechnologie und Applikation der Heiz- und Kühlsystematik						Section 5 (5.2, 5.3)
2.4 Prozesskettenentwicklung für Serienumformung <u>und</u> spanende Nachbearbeitung						Section 5 (5.5)
2.5 Versuchsreihen zur Verifikation, Validierung und Systemerprobung, Standmengenuntersuchungen						Section 7
2.6 Vergleichende Bewertung der Verfahren, Ergebnisdokumentation						Section 8

All the task of subproject II - IFUTEC were completely and successfully fulfilled with minor deviations.

The investment in a new cooling system could not be covered and an existing cooling device without temperature control was installed instead. The automated process combination (upsetting/turning) was carried out with an older electric upsetting machine as the machine modified was not available in time.

In the consecution of the tasks planned for HS Osnabrück following people were involved:

1. Dr.-Ing. Dirk Odening, Entwicklungsleiter IFUTEC
2. Prof. Dr. Eberhard Rauschnabel

3 Definition of the spectrum of electroforging components

One of the main objectives of the cooperation project focusses on the flexibilization of the production for the electrical forging process. In this manner, a great range of products both solid or hollow will be able to be approached, providing the necessary final quality and corresponding production stability. To assess the strategy proposed, a representative set of industrial parts is chosen by the partners (AP I-1, AP II-1): four hollow and two solid components of different materials with different geometry and different forming requirements. An overview is given in Figure 1 (from left to right):

- Sensor housing of stainless steel (geometry type TE22, according to the classification system later introduced).
- Two anti-roll bars for vehicles (variant 1 and 2) (geometry type TE22).
- Rotor shaft for the electric motor in electric vehicles (geometry type TE42/TE44).
- Drive shaft for the automotive industry (geometry type BE15).
- Turbine blade for gas turbines of nickel-basis alloy (preform stage) (geometry BE14).

Assessment of new electroforging products

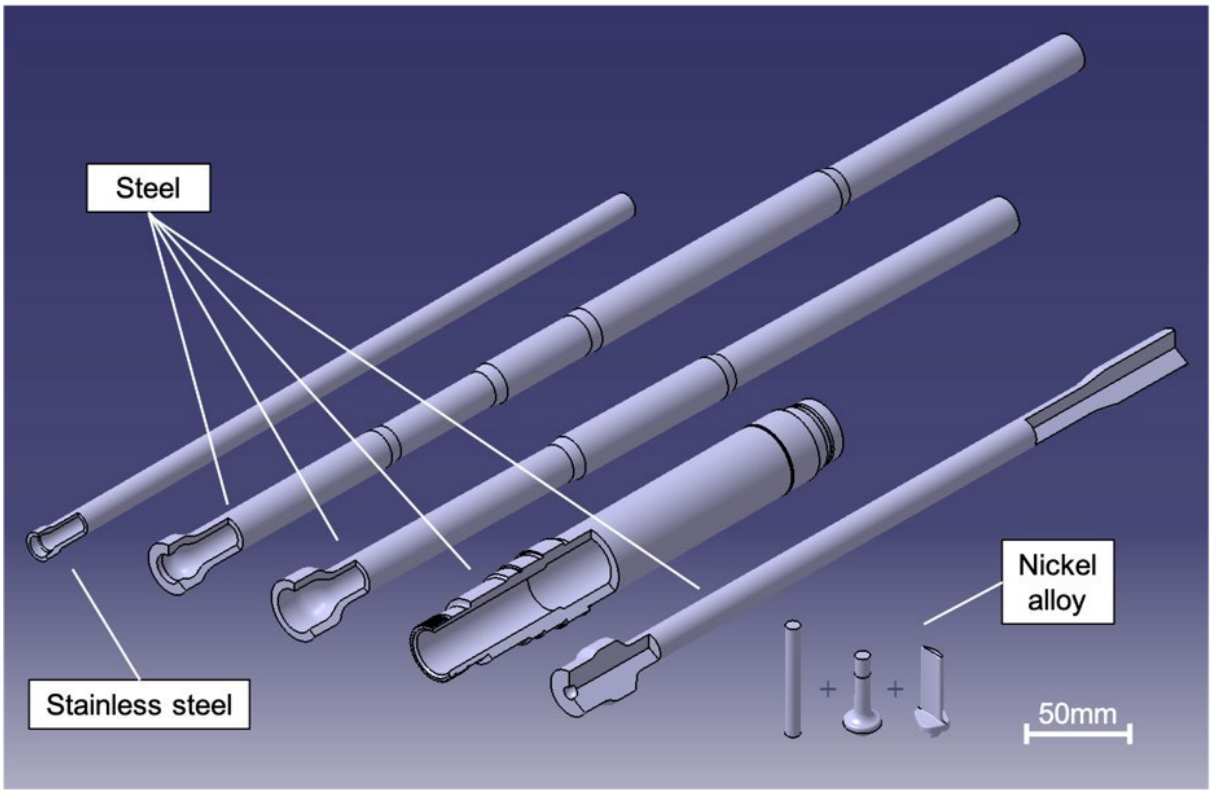


Figure 1. Component prototypes covering the spectrum of geometries objects analyzed in the research project: 4 tubulars and 2 solid industrial parts.

4 Assessment of new electroforging products

Corresponding to the work planned in AP I-1, to assess operational feasibility -technically and economically- of new products it is found necessary to rapidly identify features that would require special considerations if electroforged, like the need for an internal mandrel or electrically isolated dies. To that end, a classification by final electroforged geometry of the product is proposed (Figure 2).

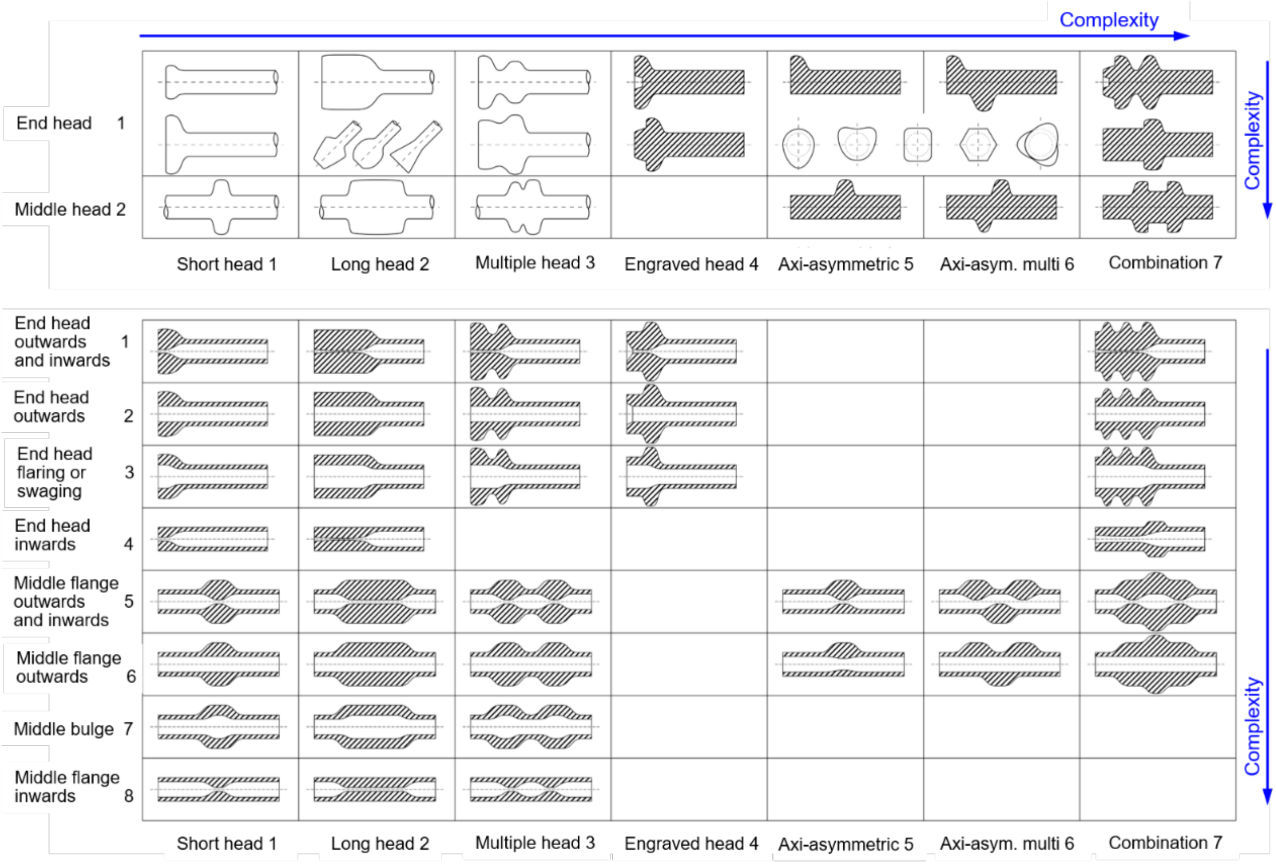


Figure 2. Classification chart for electroforging products

4.1 Development of a classification system for electroforging products according to their geometry after forming

First, the outer shape of blanks is divided in two families: round or non-round. Into this last category fall any blanks whose cross-section is not round or annular. Typically, but not exclusively, squared or hexagonal. Complex profiles could be demanding, though. For instance, non-regular parallelogram-shaped sections would most probably require custom electrodes with associated higher tool development and manufacturing expenses. Note that the non-round shape group is not explicitly depicted in the chart since it is analogous to round shapes. Some small specific variations do not justify including them here or attaching a new chart. Secondly, solid and hollow (tubular) billets are treated separately. The main reason is the tremendous contrast in process technology requirements not only by electroforging, but also with many forming techniques. Round solid bars are the most common billet shape in electroforging. They are characterized by their sturdiness in comparison with tubular shapes, which renders the process straightforward and stable. On the other hand, electroforging of tubes is - per se - challenging and, with decreasing wall-thickness, the instability of the process rises astonishingly.

Thirdly, it can be distinguished between components requiring forging at its end section and components requiring a material gathering in a particular middle section. Among them some types of electro forged heads can be easily spotted. Short head, long head, etc. Of special consideration is “engraving electroforging” at the tip of the part. Depending on the feature, it can be an internal and/or an external engraving. Finally, a combination of one or more of these types is also frequent and as such it is included as a self-type of head with the highest level of complexity.

This classification is based on 3 different material families with characteristic electrical resistivity evolution with temperature. Although material behavior has an effect on the final geometry attainable, billet material impact on this classification is relatively low and including small variations to just illustrate that was deemed cumbersome and unnecessarily convoluted. Material behavior will regain its importance later on.

4.2 Analytical model for prediction of process parameters

The first assessment and configuration of new electrically assisted forging products is generally challenging and time-consuming. While trials are resource-intensive, simulation techniques, such as FEM-modelling, demand high numerical know-how and long computational times, even combined with optimization algorithms. Modern Machine Learning techniques employing surrogate models, as the one proposed later on in this work, also require ample competences and extended training times, and rely on a training dataset, either experimental or simulation based. Corresponding to AP I-2, this work proposes an analytical approach for estimating the process parameters in electrically assisted forging, focussing on part quality and cycle time. It does not require pre-existent process data and is more computationally efficient than high-fidelity models. From geometrical data, material properties, and machine characteristics, the model determines a near-optimal heating current time-function for the preheating phase of the process. For the forming phase, the method estimates the time-dependent sequence of tool velocities and heating current that produces the final part shape and minimizes process time. The temperature distribution computation takes into account heat dissipation to the tool-electrodes, key to process stability and final part quality.

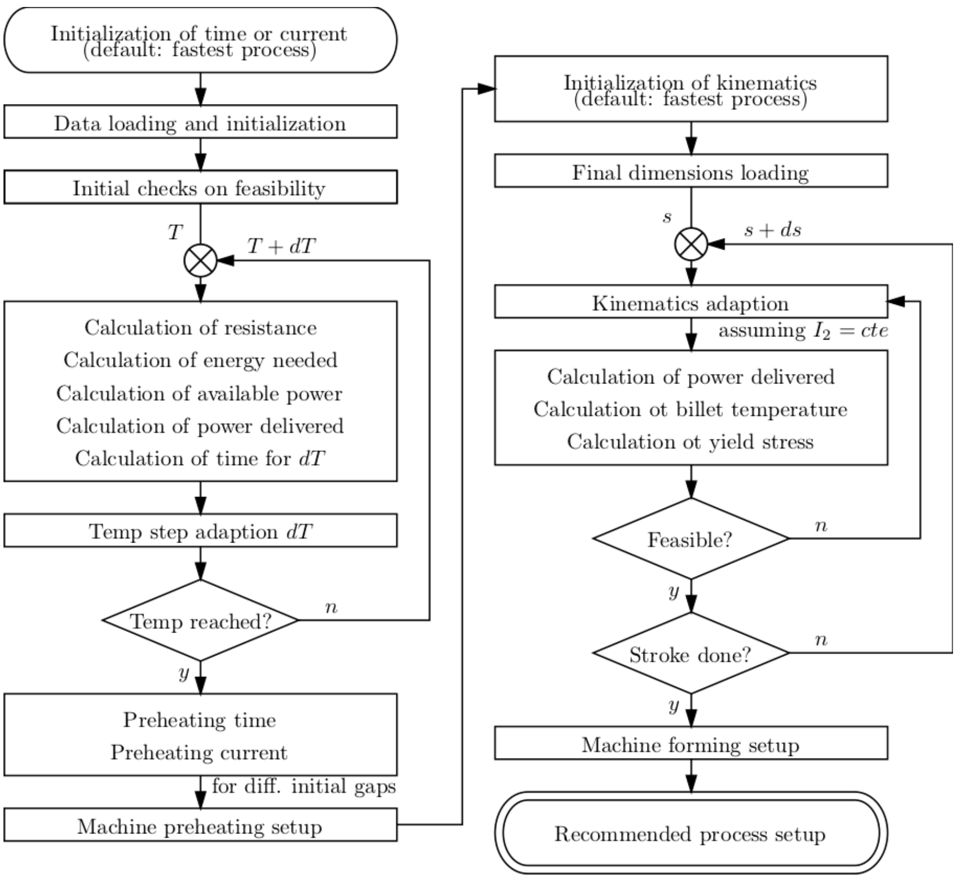


Figure 3. Overview of the proposed analytical model for the prediction of process parameters in electroforging

4.2.1 Preprocessing

Initial process and machine data are loaded and checked, first. Among others, critical buckling force is determined, and skin effect is analyzed. Also, the calculation is in this case set up with the fastest process in mind -process time minimization- or at a constant heating current, which is a constrain present in most machines.

4.2.2 Preheating calculation

The preheating consists of a stationary heating -no movement involved-, so the position of the tools remains constant, ideally. Therefore, the main variable determination needed is the electric energy required from the transformer, which depends on the load to be heated. Equating the energy required per time unit to the available power of the installation, the electric losses of the circuit and the thermal losses in form of conduction to the tooling and convection and radiation to the ambient define the heating of the workpiece. For both scenarios, processtime minimization or constant current, the outcome is a current curve over time and the minimized preheating time for a given workpiece.

4.2.3 Forming calculation

Following, making use of the elementary method to estimate the forming force, the kinematic of the tools are iteratively determined. The calculation is constrained by a set of conditions derived from physical limitations: essentially, the heating current must be high enough to keep the part at working temperature; the forming force cannot exceed a given limit value; and the kinematics must be within the machine capacity. A thermal, electrical and mechanical balance is performed in each iteration. The result are the time dependent functions of tool position, forming force and heating current for a given workpiece.

4.3 Development of a thermal-electrical-mechanical coupled FEM model and a simulation methodology for the electroforging process

In the present section, covering AP I-2, the definition of the FEM model of the process and the optimization thereof are described. The overall process is analyzed by isolating specific smaller problems, which allowed to improve the model to account for some occurring phenomena and determine the optimal model for a more systematic simulation study, possible thanks to the only capital expenditure of this project partner, that is, a professional workstation for high performance computing.

4.3.1 FEM model definition

The model is based on a simplified tool geometry, adapted to some simulative needs (tolerances, radius of edges, small angles), and the workpiece. The assembly consists of a ram that pushes the tube, an anvil that moves away, a static die electrically isolated from the rest of the tooling, and a clamp. A defined current flow is forced from the current input body towards the anvil holder, where a zero potential condition is set. The material data for the tooling and the billet, including electric properties for a wide range of temperatures, was generated with the software JMatPro®. Figure 4 shows the outline of the FEM model in contraposition to the real system.

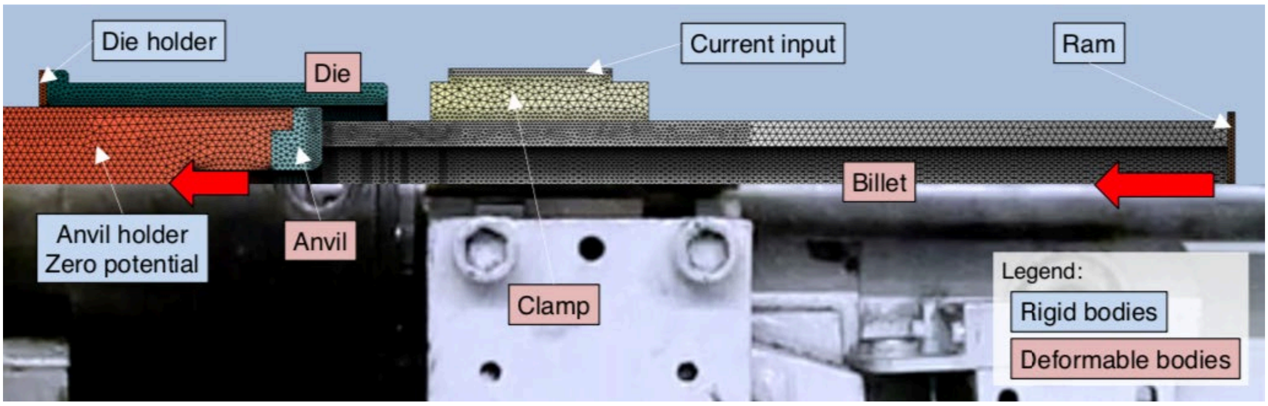


Figure 4. Outline of the FEM model in contraposition to the real system.

4.3.2 Loading and boundary conditions

4.3.2.1 Power supply

The distinctive feature of the electric forming processes resides in the simultaneous heating and forging operations. The desired range of the workpiece is settled between the anvil and the clamping jaws and supplied with current through them. Then, by means of resistance heating, the metal is taken to the required working temperature, above recrystallization temperature of the material, and accordingly forged. This can be achieved by supplying direct (DC) or alternating (AC) electric current, as well as with electromagnetic induction in some specific applications, all of which are electively included in the model.

The utility of the heating current is only achieved with high amperage and reciprocal low voltage, though. Conventional magnitudes of apparent power are between 12 and 315 kW, providing 2 to 8 V and 1 × 8 to 2 × 27, 5 kA at the secondary wirings of the transformer. With aforementioned power is possible to conform pieces with diameter ranging from 3 to 70 mm and the energy efficiency varies between 35% and 80%. However, with growing diameters the losses due to induced and eddy currents worsen the performance to the point of imperatively using direct current for diameters bigger than 70 mm.

4.3.2.2 Electrical resistance

In order to calculate the electrical resistance that the material opposes against the current flow, the skin effect and the proximity effect have to be considered. Both are negative consequences of an AC power supply. The contact resistance in the touching surfaces between tool parts and workpiece have also an influence on the resistance global value.

4.3.2.2.1 Contact electrical resistance

The contribution of the contact resistance must be taken into account to calculate the total resistance. Contact electrical resistivity is closely dependent on the contact pressure, the contact surface temperature, and the surface quality of the bodies.

4.3.2.2.2 Skin effect

Although the current density distribution along the workpiece diameter can be approximated by an exponential function, for simplification, the current density can be supposed to be concentrated within an outer layer, the depth of which can be expressed as: $\delta = \pi f \sigma \mu$, where f is the frequency, σ is the electrical conductivity, and μ is the magnetic permeability. It is important to note that both conductivity and permeability are strong dependent on the temperature. For further simplification, the skin effect in neglected in the simulation, given that most machines work with relatively small enough diameters, which means the skin depth is bigger or at least similar to the workpiece radius. Inclusion of an electromagnetic calculation to actually calculate the skin effect evolution would greatly complicate the model and increase computation time.

4.3.2.3 Electroplastic effect

The electroplastic effect, as the effect of the passing current in a metal, can be accounted for in the FEM model by introducing in the material behavior law the variation in yield stress derived from this phenomenon. The lack of electroplastic effect empirical data limits the scope of this addition to the model, that nonetheless was implemented as a user-variable in FORGE® until planned experimental tests are performed.

4.3.2.4 Thermal exchange

The electrodes are water cooled to keep their integrity and prolong their lifetime. The simulation model may include a constant heat exchange coefficient between the bodies or a more complex model if needed. A heat exchange coefficient dependent on normal pressure is a common practice, as well as temperature dependent. The temperature field initialization in the tools has a big impact on the model and the process too, as discussed later.

4.3.2.5 Frictional state

Friction between tooling and the workpiece is considered to be low and usually following a Coulomb-Tresca friction model. Lubricants are rarely needed in electroforging.

4.3.2.6 Kinematics

The project focusses on a new velocity-driven electroforging machine, where the position over time of the ram and the anvil characterizes the forming operation. In the simulation model, the actual behavior of the real system, like elasticities from hydraulics or acceleration, is represented in the velocity over time curve for each moving die as well.

4.3.2.7 FEM related

Time step for the iterative computation is to be handed carefully in electroforging simulation. Mesh size has an impact on the accuracy of the results too, especially in the force results.

5 Advancements in process and machine technology

This stage of the project, addressing the work planned in AP I-3 and AP II-2, aimed to assess new mechanical features of the existing electroforging machine and develop state-of-the-art features to be implemented in the control system to improve process flexibility, stability, reproducibility and final part quality. It helped to further evaluate the accuracy and reliability of the models developed as well. Summarizing, abovementioned new features, successfully implemented, are:

- Substitution of hydraulic elements by modern direct drive servo motors to meet required specifications. This way, previous hydraulic-related issues to process stability and reproducibility were eliminated.
- Independent tempering-cooling systems for the tooling components as well as optical and contact sensors for the workpiece temperature measurement were implemented: FEM analysis proved that heat management is essential for process stability.
- Modified SIMATIC 7 control system with improved management of all forming parameters and including a set of newly developed controlling strategies. Tabulated input of complex time dependent functions of tools position, forming force, heating power, clamping force and current allows for new, more flexible and optimized processes.

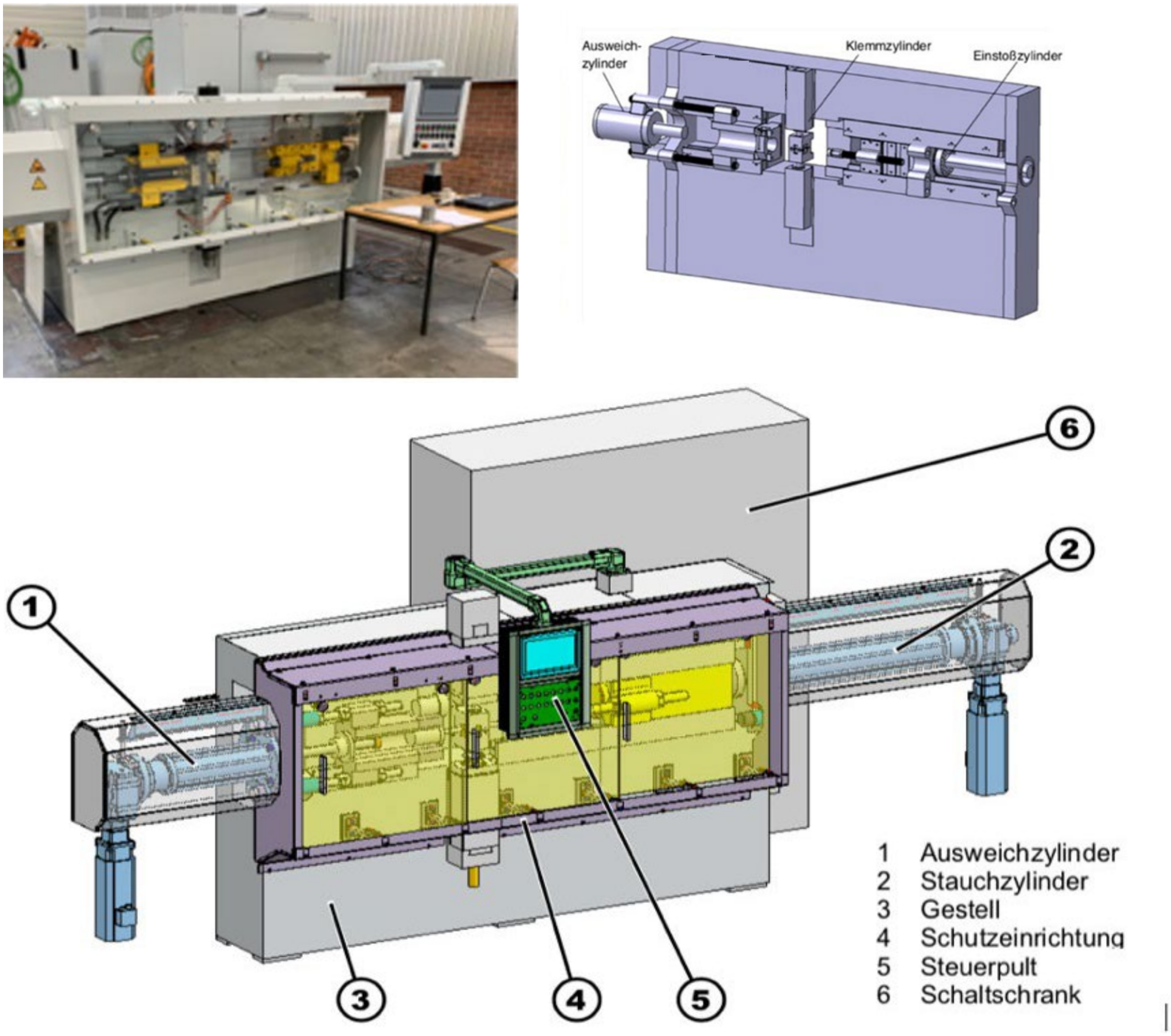


Figure 5. modification of the machine with state-of-the-art direct-drive servo motors and new control system with developed control strategies. Top: final machine (left) and schematic CAD of the original hydraulic machine (right). Bottom: CAD with the implemented systems.

6 Forming methodology for the electrically assisted forging process

In this chapter, corresponding to AP I-4, all methodologies proposed earlier are condensed into a unified strategy, also referred to as assistant system or planning tool for electroforging. The need for a planning tool steams from the complexity of the parameter set encountered in electroforging. More even in regard to a highly flexible manufacturing process that aims at small and medium-to-small production batches of custom products in a wide range of geometries with a virtually universal tooling. FEM simulation characterization of these parameters is time consuming and also inefficient in a way that designers can develop a working -but non-optimal- electroforging processes by suggesting different set of parameters. To amend that, it is proposed a planning methodology devised to provide a close-to-optimal (in terms of process stability and profitability) parametrization with which narrow down and refine a FEM study that will ultimately confirm the best course of action for a certain product.

6.1 Outline of the planning methodology

The methodology proposed consists in a series of calculation and decision-making suggestions that will begin with geometrical and material data from the part and machine characteristics, and finish with an optimized parametrization of the process.

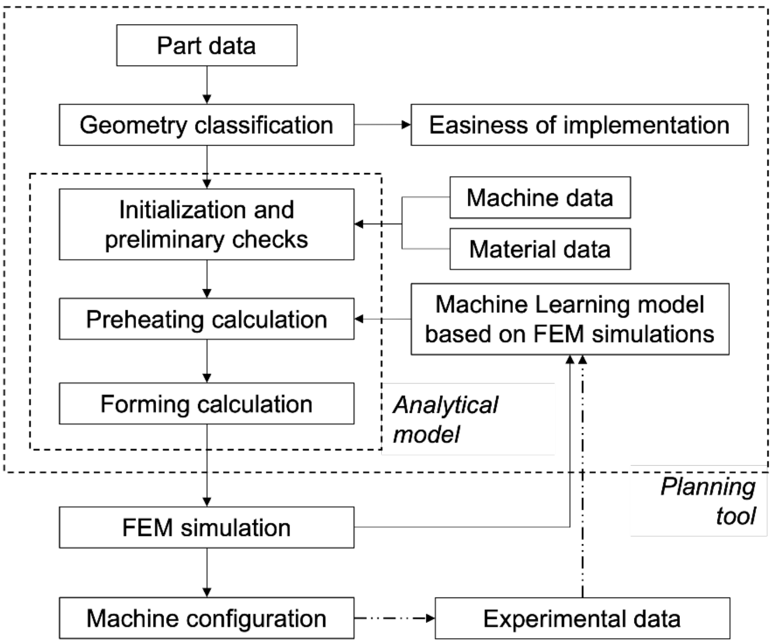
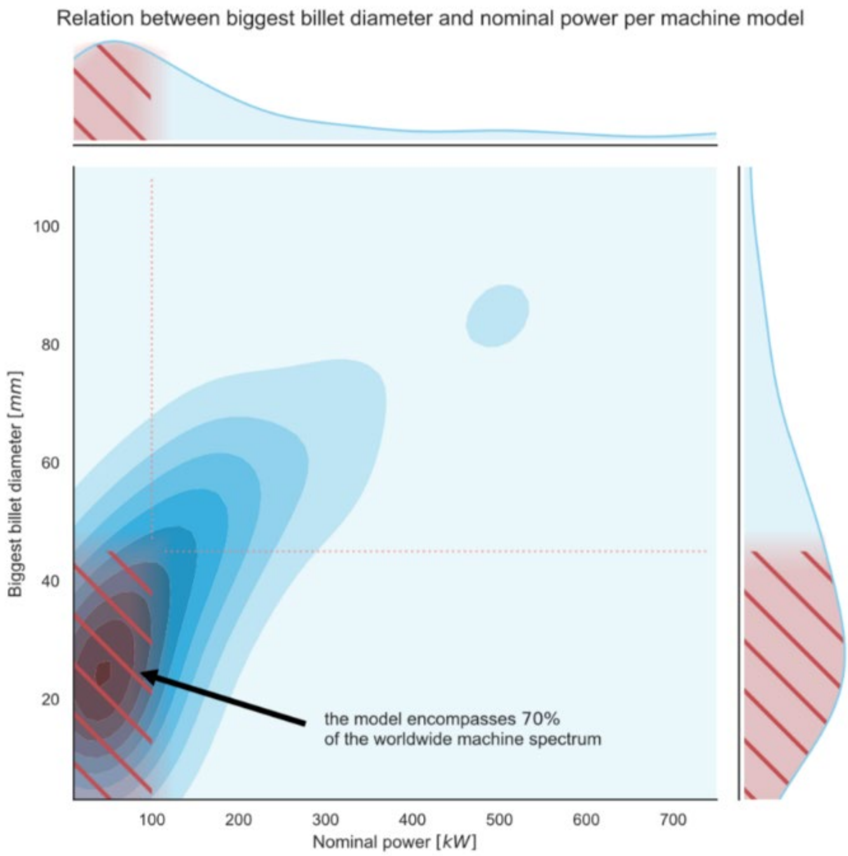


Figure 6. Schema of the planning methodology for electroforging, based on analytical and numerical models.

The proposed strategy is segregated into two main routines. First, new products are classified according to their geometry and checked against current machine capacity and. This is structured in a decision-tree like flowchart and gives a rough estimation on easiness of implementation and feasibility.

The second routine focusses on the preheating phase and then the upsetting combined with simultaneous heating. First, process variables are delimited according to geometrical and dynamical constraints of a specific machine. Some calculation steps are managed by knowledge inferred from electroforging characterization data extracted from a series of FEM studies, enabling the reuse of calculated data from every project to render the model continuously more robust and widen its application range. It might include data either from numerical, experimental or analytical sources as well.



The combination of production-oriented insight with the calculations of the proposed analytical model returns a close-to-optimal pre-heating parametrization for a particular component. The model (Figure 7) provides the approximate time-dependent functions of tools position, forming force and secondary current for the process. Finally, validation and optimization are done with a FEM study with the model explicitly developed.

The model is expected to cover at least approximately 70% of the current worldwide park of electro forging machines focussing on the middle-to-low nominal power range, where manufacturing flexibility is of paramount importance.

Figure 7. Market analysis of current worldwide park of electroforging machines by quantity and the expected coverage of the proposed planning tool for electroforging

6.2 Deduction of an adequate billet geometry for prototype implementation

Read downstream -from top to bottom-, the chart of Figure 2 introduced in Section 4.1 “Development of a classification system for electroforging products according to their geometry after”, focusses on easiness of implementation of new products. Beginning from the end shape of a particular product, it is possible to navigate backwards up to a recommendation for billet’s type and get an easiness of implementation estimation. Sometimes the same final product is obtainable parting from solid or hollow billets. Solid material is in this case preferred for prototyping, since hollow parts usually involve more fine tuning. This means that, at first, optimization is put aside. On the contrary, if read upstream -bottom to top-, the most material-efficient solution can be found first. Working towards a practical prototype is favored on a first approach for new products.

6.2.1 Considerations on tooling design

Having broadly classified the product, the focus turns into what geometries are feasible for each family of billets and which ones require to take special precautions. As a rule of thumb, complexity increases by traveling southeast in the classification chart. More than usual it is required to limit the outward flow of material in some extent. If the workpiece head is relatively short, an anvil with an engraving will be sufficient. Otherwise, an outer die must be implemented. If an indentation is needed on the central axis of the billet, there are generally also two options: a protruding engraving in the anvil -for short features- or a mandrel -either independent from the anvil or dependent on it (Figure 8).

Die, mandrel or anvil with engraving can be simple or present increasing degree of complexity, having an effect on the product’s easiness of implementation and related expenses. Upon the application, a coating or tool hardening might be advantageous. Furthermore, within this work the benefit for electrically isolated tooling was theoretically and experimentally proved and this can be added on top of the different tool requirements.

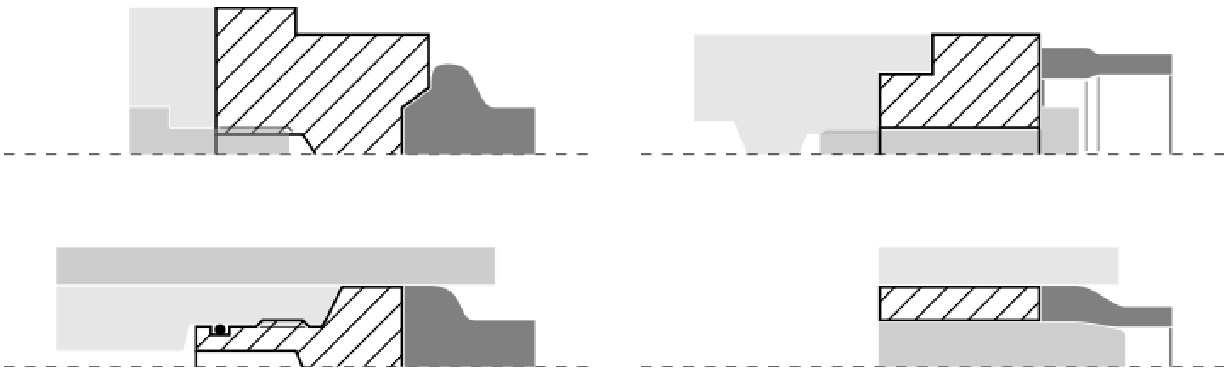


Figure 8. Some anvil designs (dashed) proposed to tackle specific requirements

6.2.2 Considerations on workpiece blank

It is feasible to electrically upset bars with diverse shapes of cross section, such as oval, flat rectangular or angular, that accordingly require special clamp electrode design. The forging of tubes is possible as well, yet the most widely used are rounded cross sections. Regardless of the choice, the raw preform must meet some requirements. Contact interfaces, with their geometrical and surface properties, are a main topic when speaking about repeatability of processes in which the electric flow between components is involved. The contact areas with the workpiece define the way the current flow travels and, consequently, affect the distribution of the Joule heating.

6.2.2.1 Dimensional accuracy

In order to guarantee a reasonable control throughout the procedure, a minimum dimensional accuracy on the blank rod was found necessary. To this end, the desirable diameter tolerance is set at around h11, specially for the outer diameter that comes into contact with the clamping electrodes. Deviation from these values can cause significant differences in heating evolution and result in undesired final geometry of the upset workpiece along a serial production, even process failures. This deviation from standardization becomes especially relevant in the matter of low deformation-to-diameter rates.

6.2.2.2 Surface roughness

Surface conditions of the bar stock have significant impact too. It is recommend utilizing a straight and cylindrical shell surface with surface roughness Rz between 40 and 63 µm. The optimal raw preform is obtained through extrusion followed by a ground rolling process or even burnished. Due to a bad roughness, the contact interface between the clamping electrode and the workpiece can be deteriorated to the point that tool life is affected, and the irregularity of the current flow leads to a distorted head shape.

6.2.2.3 Front face in contact with the anvil

Another aspect is the bar front face that must be flat and normal to the axis of the bar in order to establish a proper contact with the anvil. In the case of deviation from perpendicularity, the initial touch point with the anvil becomes quickly overheated which adversely affects the tool and originates an inhomogeneous temperature field and process failures.

6.3 Calculations with the developed assistant system for process development

After defining machine and product data and importing accurate material data, the calculation is launched. The resulting process parameters are provided in the form of a report. Data files with calculated point-by-point time functions of process parameters are generated and can be directly imported into a FEM simulation project for validation and fine tuning. They are compatible with the new machine control system interface too, so an experimental try-out can be also directly performed. The tool is designed for the next step, that would couple the model directly with the control system of the new machine to adapt the process parameters on the fly by real time calculations. Figure 10 shows a case study calculated with the proposed planning tool.

7 Experimental methodology for validation testing

As planned in AP I-5 and AP II-5, experimental tests were carried out at project partner’s installations.

7.1 Design of a data acquisition system (DAQ) for systematic experimental testing

Two HBM P8AP absolute pressure transducers (half-bridge principle) were employed for the measurement of pressures and two HBM displacement transducers (inductive full-bridge principle) of 500 mm and 200 mm for ram and the anvil, respectively. All four of them were connected to an up-to-date HBM signal amplifier QuantumX MX840B and to a computer for recording and processing.

The pressure in the cylinder driving the clamping is also monitored with another HBM P8AP absolute pressure transducer (half-bridge principle) rated for 200 bar, connected to the signal amplifier too.

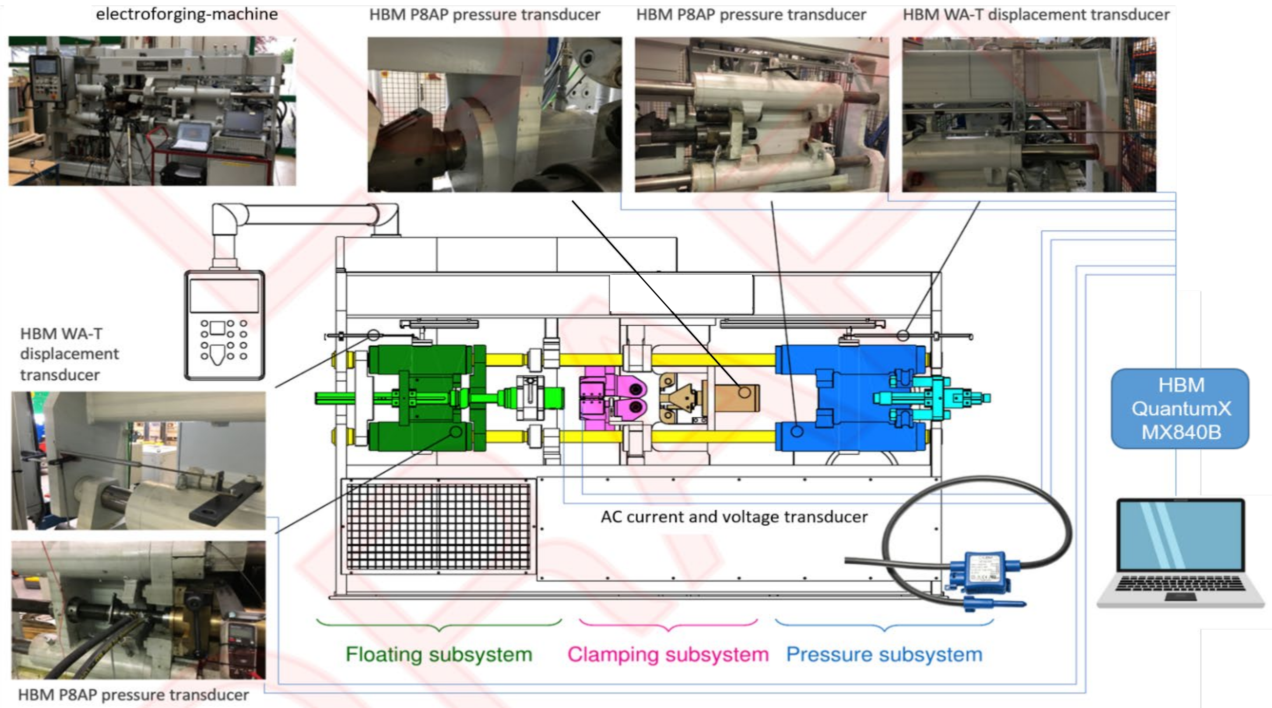


Figure 9. Outline of the DAQ designed for the systematic data acquisition of electroforging experimental tests in the electric upsetter.

The secondary AC voltage, considering as such the difference in potential between electrodes, is measured with a multimeter with its probes attached to the anvil fastener and to the clamping fixing. The materials of both electrodes are, by necessity, highly conductive, which means the voltage drop over each one of them is small. Measurement showed a magnitude of about 0.1 V, respectively

Secondary AC current is measured over the output wiring of the transformer with a PEM Rogowski coil Current Waveform Transducer type RCTrms/25000/2.5/700 rated for 25 kA, also connected HBM signal amplifier QuantumX MX840B. The coil is carefully located around the group of copper braided straps that transport the electricity to the electrodes to minimized measurement error.

7.2 Experimental results of forming parameters derived from FEM simulation

The industrial components and corresponding forming parameters derived from FEM analysis following the proposed planning strategy serve a twofold objective:

- First, test every individual addition in machine technology presented in previous chapters, confirming reproducibility provided by the work done.
- Secondly, evaluate the methodology proposed and corresponding tool technology and process control improvements with practical study cases, validating the models and technology developed in an industrial environment, making process stability and production flexibility a reality.

7.2.1 Electroforging of type TE22 component

A double approach is used during the testing phase. The same vehicle anti-roll component of geometry type TE22 was developed and tested in free forming and closed-die configuration according to following reasons:

1. For prototyping and small batch production a free electroforging operation is successfully executed without the need for costly tool development and prolonged time between client request and first try-out.
2. For medium-large series production of several thousand pieces per year a tooling design following the technology developed during the project described above in section 5.3 “Innovation in tool design derived from simulation analysis” is implemented, consisting in a cylindrical shell of a heat resistant metal that is electrically isolated from the rest of the machine. This provides the sufficient material saving to balance out the tooling costs.

The optimized model results were formatted and directly imported into the modified machine with improved drive system, cooling management and controlling strategy, with the result being very close to previously calculated deformations in FORGE®. From the first try- outs the expected output is reached, requiring only minor calibration. Figure 10 summarizes the optimization carried out in FORGE® and the obtained forged workpieces.

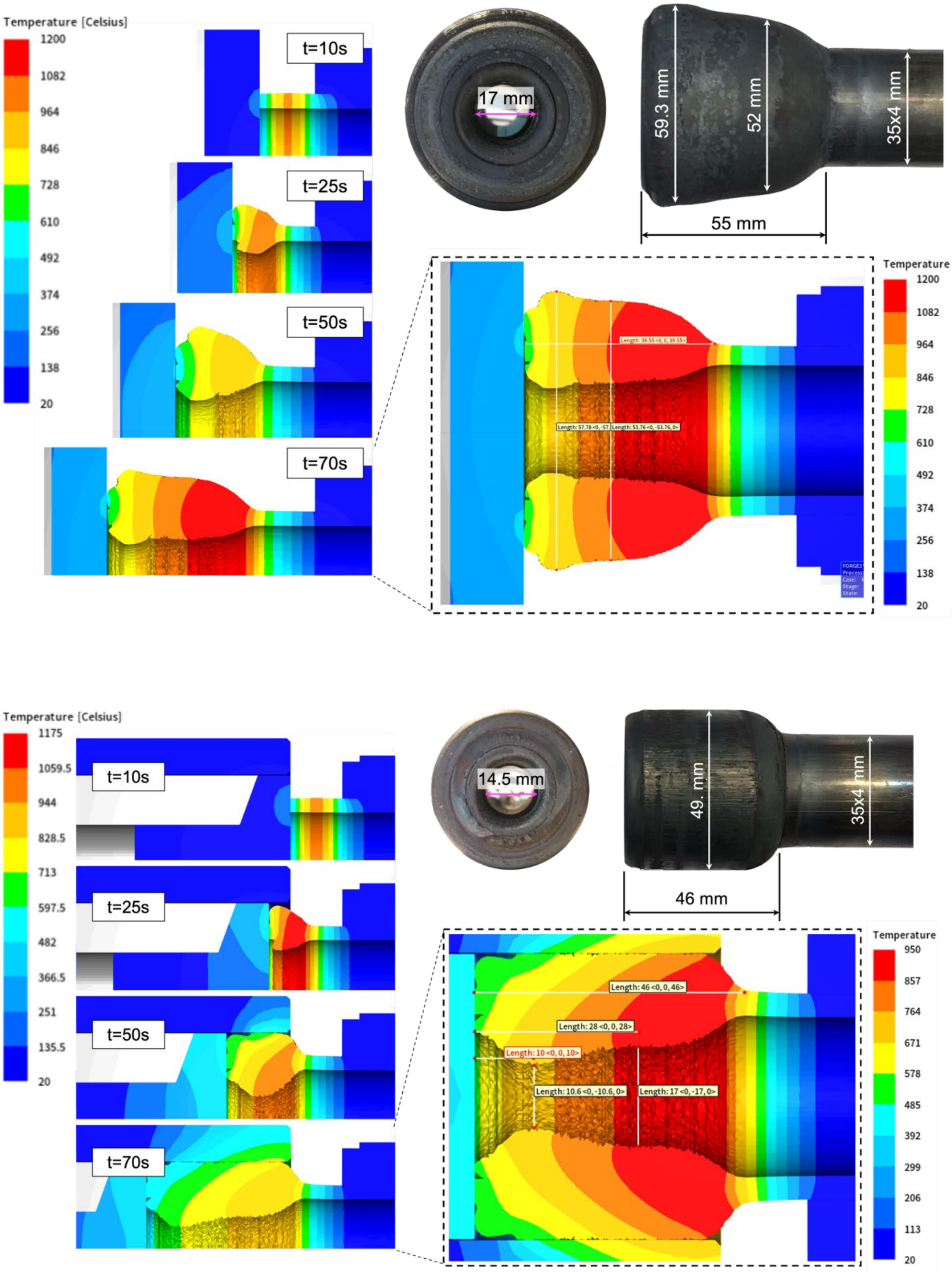


Figure 10. Process configuration using the methodology developed during the project for the free electroforging and closed die electroforging of a tube (geometry type TE22) for a vehicle anti-roll component of low carbon steel. Process evolution is shown in the left, with comparison of final geometry between simulation and forging on the right.

8 Publications

List of publications in the framework of the project:

- Application to Baden-Württemberg Umwelttechnikpreis 2021 that awards outstanding and innovative contributions to resource efficiency and environmental protection in the manufacturing industry.
- Acevedo-Rigueras, S., planned PhD thesis „Entwicklung der Verfahrenstechnologie und eines Planungstools zum Elektrostauchen“, TU Chemnitz, 2021
- Alves, J., Acevedo-Rigueras, S., Marie, S., Rogeon, P., Bay, F., Adams, B. Electrically assisted forming simulation solutions with FORGE®, ESAFORM 2019, Vitoria 05/2019
- Rauschnabel, E., Alves, J., Acevedo-Rigueras, S., Adams, B., Odening, D. Development of an Expert System for Electrical Forging, NEMU 2019, Stuttgart 05/2019
- Planned article in peer-reviewed scientific journal.
- Planned patent registration relating to technologies developed along the project pertaining to tool design for process stability.
- Planned, presentation during the 37th annual cold and hot forming VDI congress from 23rd to 24th February 2022 in Düsseldorf