RESOURCE EFFICIENT PRODUCTION OF CAR BODY PARTS – IMPLEMENTATION OF DIGITAL TWINS ACROSS PROCESS CHAINS

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ABSTRACT

Sustainable production and environmentally friendly life cycle of every car is a main goal in the automotive industry. But there is a conflict between the rising demands of crash safety, the addition of components due to electric mobility and the reduction of weight. Car body parts can increase the crash safety and have a high lightweight construction potential. Especially tailor welded blanks made of multi-phase steel with a tensile strength of 1000 MPa, which are not established in car body parts, have the potential to improve the crash safety, save resources and lower the weight. The main challenge in the manufacturing of tailor welded blanks made of highest strength steel is the complex and expensive development. Due to the heat input and geometrical changes, the welding process affects the forming properties of the metal sheets. To evaluate the influence from different welding parameters to the forming process, a high number of expensive experiments must be repeated. This includes welding and forming parameter changes as well as adjustments to the forming tool. In order to make the development and manufacturing of tailor welded blanks made of highest strength steels more resource efficient, this work discusses the development and implementation of a digital and bidirectional twin in an industry-oriented environment. The objective is to demonstrate the data management based on the sheet metal properties, the change of properties due to laser welding simulated in Simufact Welding and the final forming process in AutoForm Forming. Additionally, the concept of a life cycle assessment of a tailor welded blank during these steps is developed. As summary the challenges, limitations, and improvements of the digital and bidirectional twin as replacement or, in addition to a consisting development process are discussed.

KEYWORDS: digitalization, industry 4.0, highest strength steel, tailor welded blanks, digital twin

1 INTRODUCTION

A major goal of the European Union is to limit the climate change by reducing the production of greenhouse gases till 2030, in comparison to 1990, by at least 40 % [1] and to become climate-neutral in 2050 [2]. In order to reduce the CO_2-footprint of vehicles during their period of use, the

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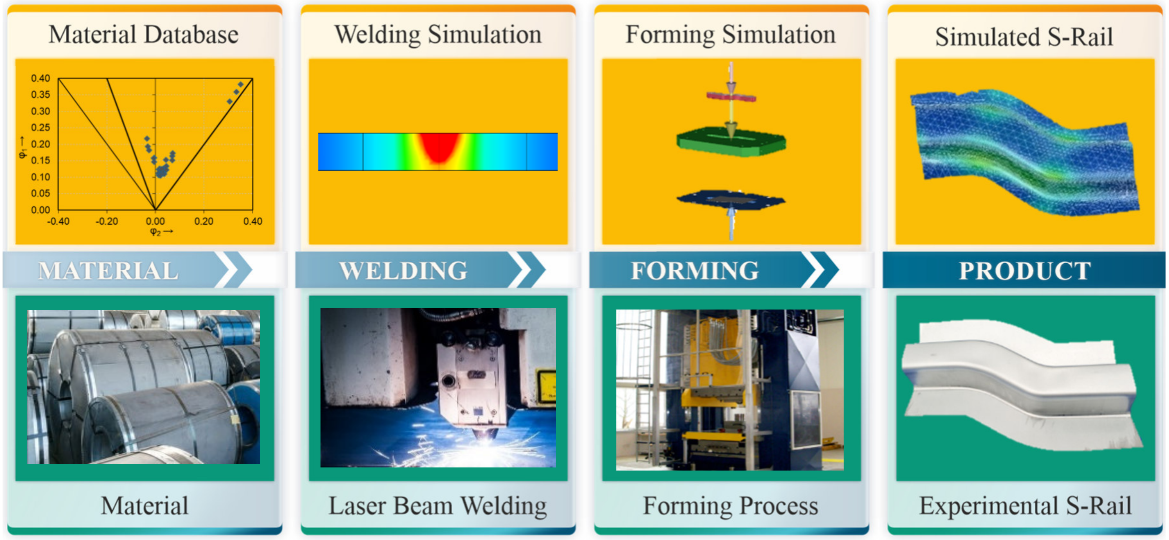

Figure 1: *Scheme of the digital (top) and the conventional (bottom) process chain of tailor welded blanks. The main process steps from the material to a final product are illustrated.*

mobility sectors' strategic focus is the change towards electric mobility. In comparison to fossil fuel vehicles the weight of similar electric vehicles is 200 kg to 700 kg higher. The main reason for the increase of weight are the lithium-ion cells [3]. Due to the energy- and resource-intensive production of electric vehicles on the one hand and the reduction of emissions in their period of use on the other hand, the environmental impact during development and production increases. As shown in Fig. 2, the biggest influence in greenhouse gas pollution is the production of the battery and its periphery with about 46 % and the car body with about 26 % [4]. Through the use of new materials and digitalized development and manufacturing methods, the conventional car body part production has a huge energy-saving potential.

During the manufacturing of car body parts, the biggest environmental impact has the material production. Producing one kilogram steel takes 25 megajoule of direct energy input [5]. Other reasons to lower the material use are the positive impact on the weight and the power consumption during the period of use [6]. In summary, a material reduction has a positive influence on the energy consumption during the whole life cycle.

One approach to reduce the material use is the application of tailor welded blanks (TWBs) made of highest strength steels. By inserting highest strength steel in car body parts, the thickness of the used metal sheets can be reduced, and additional reinforcements can be disclaimed without lowering the crash safety.

A tailor welded blank is made of two or more metal sheets laser welded together with different material properties, thicknesses, or coatings [7]. Due to the combination of different steel grades, properties can be selected and adjusted to local requirements. Crash relevant areas can be made of steel with higher strength, while areas with lower requirements are made of steel with other characteristics.

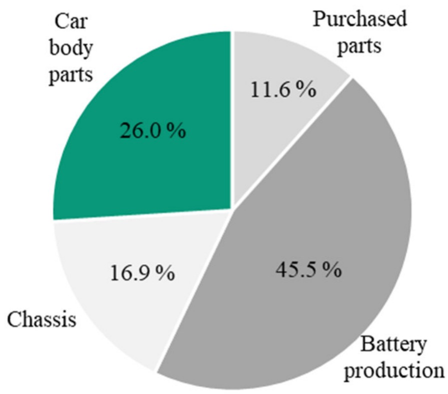

Figure 2: *Greenhouse gas emissions as CO_2-equivalent in percent during the manufacturing of an electric vehicle [based on 4].*

The development of components made of highest strength steels TWBs` takes time, money and material.

A digital bidirectional twin is generated to digitalize the manufacturing steps and enable the use of car body parts in the automotive industry made of highest strength steel tailor welded blanks. The manufacturing of components made of TWBs as a model, this work explains the concept of compiling a digital twin in an industry-oriented environment.

2 PREPARATORY WORK

The final digital twin is supposed to be a virtual tool for representing and passing the complete manufacturing process with connected simulations and intermediate steps. The general process chain of the TWB manufacturing is shown in Fig. 1. Additional to the conventional process chain, a digital process chain is created. This means in the future all manufacturing steps as well as the material properties will be digitalized.

The initial point of the digital twin is the digitalization of the material properties. The material properties are implemented into the subsequent simulations with the help of material cards. The content of the material card and the following steps including the data management are depending on the selected simulation software. In an industry-oriented environment the choice of the simulation programs is limited in terms of existing licenses and the know-how of the operator. Other selection criteria are shown in Table 1. As the two decisive manufacturing steps of TWBs are welding and forming, the welding simulation Simufact Welding 2021.1 and the forming simulation AutoForm Forming R8 are chosen.

Table 1: *Selection criteria for simulation software. (1 - most important to 5 - least important)*

Computing time	1
Operator convenience	2
Programmability	3
Accuracy	4
Automation potential	5

The selection of the data interfaces and the data storage devices depend particularly on the future application. Important criteria for the selection are data security, data integrity and operator convenience. Additionally, the interfaces must be flexible and expandable to be able to react to changing requirements and subsequent needed add-ons.

2.1 DIGITAL MATERIAL IMAGE

For a detailed and valid simulation, it is essential to generate specific material cards. For steel sheet materials like the used multi-phase steel with a tensile strength of 1000 MPa it is necessary for precise simulation results to analyze the material in detail. A material card for the forming simulation software AutoForm contains for cold forming information from the following material tests.

The flow curve, mechanical characteristics, the anisotropy, and strain rate dependency are determined in uniaxial tensile tests for 0°, 45° and 90° in relation to the direction of rolling. To evaluate the formability under biaxial stress conditions the hydraulic bulge test is chosen, because it allows a higher range of deformation than other tests, which is more similar to the metal forming process. The forming limit curve is determined in the Nakajima test with nine different geometries. The forming limit diagram (FLD) together with the forming limit curve is unique for each material and thickness. Once the strains of a forming process are plotted on a FLD, failure through crack formation is considered to be certain if the plotted strain is above the forming limit curve. The gained information from the material characterization is edited with appropriate material models and implemented in the material card.

In addition to the forming simulation the material card of the welding simulation includes not only the physical, but also the thermal material properties. Tensile tests with varying notches are performed. The tests serve to determine material specific properties, such as Young's modulus, breaking characteristics, anisotropy and yield strength in both weld seam and the surrounding heat affected zone (HAZ). Warm tensile tests are used to determine the temperature-dependent plastic deformation. Dilatometer tests are performed to examine phase properties of the material. Metallographic cross sections and hardness scans of the basic metal sheets, weld and HAZ are used to examine the microstructure.

2.2 SETUP - WELDING SIMULATION

Simufact Welding has been chosen due to its powerful input and output possibilities. Both are designed in open and user-friendly ways. Material cards can be edited to a very complex extent. Also, output formats such as the Universal File Format (UNV) make it easy to transfer results at single nodes. These possibilities in post processing are crucial for a subsequent coupling with the forming software. Moreover, Simufact Welding is commonly used in the industry. The setup of the welding simulation in Simufact Welding can be classified into three basic steps:

Step 1: Build-up of the model
The geometry of the two metal sheets, which are welded with butt joint are generated as a CAD-file within the welding software. They are meshed as 3D hex elements (hexahedron).

Step 2: Calibration of the heat source
The metal sheets are welded together in a laser beam welding process without filler material. In thermal simulations, which disregard a mechanical solution at this point, heat input by the phenomenological heat source in comparison to the physical process can be examined. Therefore, cross-sections and temperature cycles near the weld

are compared to the simulation results in compliance with ISO/TS 18166.

Step 3: Validation of the welding simulation
To validate the simulation model, experimental results are compared to the simulation results. In particular, simulated distortion, hardness and phase transformations are compared to results from beforehand executed experiments. Welded blanks are measured with 3D scanning, hardness-mapping and the analysis of the microstructure with the help of welding phase diagrams are compared to the simulated results. Additionally, metallographic cross sections are compared to welding results to confirm the model.

2.3 SETUP - FORMING SIMULATION

The forming simulation software AutoForm Forming was chosen because of the fast computing time, the user-friendliness and because it is often applied in the automotive industry.

The setup of the forming simulation in AutoForm can be classified into four steps:

Step 1: Build-up of the model
The geometries of punch, die-plate and binder are digitised with the help of a 3D scanner and simplified in AutoForm to reduce the programming time. The advantage of using 3D measured data is a more detailed model, which considers the present state of the tool. For the beginning of the buildup a perfect plate geometrie is assumed. The mesh is generated with elasto-plastic shell elements. During the simulation AutoForm automatically refines the mesh in the areas of interest to get a more detailed result by a short computing time.

Step 2: Implementation of the process parameters
Process parameters like the lubricant, the friction coefficients, the kinematics and forces of the press components enter into the simulation. Additionally, the material cards are established in this step. Especially for TWBs and a high number of iterations of the digital bidirectional twin, it is important to have an automated or semi-automated possibility to integrate the different material cards.

Step 3: Plausibility check
The first verification of the simulation is made with a kinematical comparison. Therefore the press process parameters are recorded by a plugged Raspberry Pi, which can save, show, edit and send the measured information in real-time. This information can be compared to the simulated information. With this comparision the executability, the plausibility and stability of the simulation is verified.

Step 4: Validation of the forming simulation
The final validation of the simulation is a comparison of the simulated part and the manufactured part with regard to the metal sheet thickness and occuring defects. The manufactured geometry is measured with a 3D scanner and a CAD-file is generated. The two digital parts are unrolled and the thickness of the two unrolled geometries is compared in several areas.

2.4 SETUP DATA MANAGEMENT

The data management must be secure, location-independent, easy to handle and adjusted to the simulations. In this case, a data exchange platform based on open-source components is used for the data management. The centerpiece of the platform are distributed data storages for recording and classification of results and administration of access authorizations.

Hyperledger-Fabric is the technology base for the distributed data storage. This framework authorizes specific content to the involved companies, to identify these companies through verified identities and to share the content with the approved partners. Additionally, Hyperledger-Fabric allows to use energy- and computing time saving consensus-algorithms. On the platform itself, process flows can be controlled programmatically.

3 SETUP OF THE DIGITAL TWIN

A digital twin can be an extended image of real objects or processes. In the industrial context, these are materials used, semi-finished and finished products, as well as production and manufacturing processes in series production. The integration between physical and virtual spaces is becoming increasingly relevant due to the potential to improve operational steps in manufacturing, design, and service.

The aim of the digital twin in this work is to digitally reproduce the design process of components made of highest strength tailor welded blanks in order to achieve the best properties in terms of process optimization. It mainly reflects two major physical processes: joining of the two sheets of a TWB and the following forming process. The twin imitates this physical process chain to define optimized process parameters which will be applied afterwards during final manufacturing. In this way, it allows saving time, resources, and costs. One crucial characteristic of the presented digital twin is, that data is bi-directionally exchanged between the welding simulation and the forming simulation. The output data after successfully performed welding simulation is supposed to be used as input data for the following forming simulation process. Forming simulations output data gets then evaluated. This sequence is illustrated in simplified form in Fig. 3.

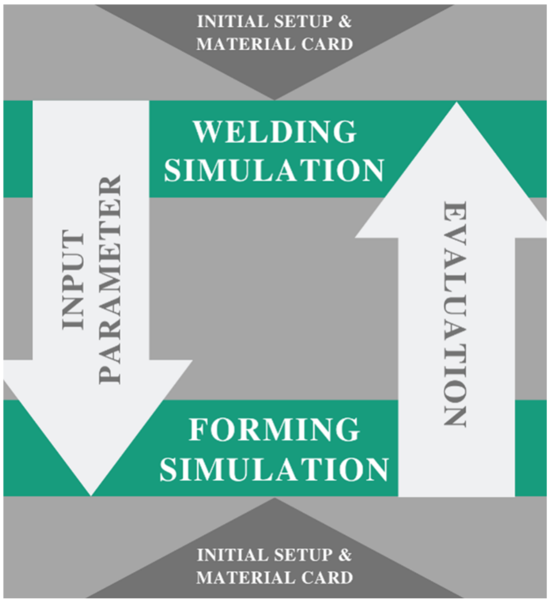

Figure 3: *Simplified sequence of one iteration of the digital bidirectional twin.*

After every sequence of the bidirectional digital twin the results are automatically saved, marked and the next parameters can be examined.

If the simulation results cannot be proven as sufficiently satisfactory as defined by specific parameters that have been defined beforehand, the welding simulations parameters will be adapted. For this, the evaluation of the forming result is considered. This process is described by the bi-directional part of the digital twin. This back-and-forth route can be driven several times, until the forming result is sufficiently satisfying. With slight adaptation of the tool created in this way, this procedure can be able to simulate TWBs of other geometries.

3.1 COMPARISON OF THE INITIAL DATA

The first step towards an operating digital bidirectional twin is the comparison of the initial data of each simulation. The main subjects of the comparison in this digital twin are the material properties of the initial metal sheet. During a semi-automatic parameter study, while the size of the materials zones or the material properties are changing throughout the process chain a backstop, which ensures, that all simulations work with the same parameters must be involved. Otherwise, the simulated results are not viable.

As the most FE-simulations get the data in different display types, every value, which influences the simulation result must be examined, converted, and compared before every iteration of the digital bidirectional twin. There are three different types of data:

- Data used in just one simulation like thermal properties of the heat source. *No comparison necessary.*
- Transferred data, which change during the previous simulation step and must be transferred like the plate geometry or the material properties near the weld seam. *Comparison of the initial data and transfer of the changed data.*
- Data used in both simulations like the hardening curve or the Young´s modulus. *Comparison and synchronization of the data before every iteration of the digital bidirectional twin.*

3.2 DETECTION OF THE INTERFACES AND DATA TRANSFER

One main purpose of the digital twin – to run cost-effective simulations in a virtual environment – allows improvements in quality and performance of manufacturing processes and products. Moreover, it shows the possibility of optimizing steps and predicting failures. This capability is used to reduce risk and cost, enhance production reliability and operational efficiency [8].

The core of the bidirectional digital twin are the used simulations as well as the data transfer between those. The main challenge is to connect the simulations, which use different physical models, data formats and have different input and output parameters. In order to find the transferable parameters, the following steps can be made.

In the first step the reasonable data must be selected. Knowledge about the processes and changes during every manufacturing step must be available to examine the influenced properties. In the production of tailor welded blanks the changing parameters during the welding process are the geometry of the plate and changes because of the heat input like phase transformation, material property changes and plastic deformation.

In the next step the possibility to transfer the reasonable parameters between the simulations must be checked. The data type and the output format from the examined parameters must be figured out and compared to the input options from the next simulation in the digital process chain. An example for the intersection of Simufact Welding and Autoform Forming for the manufacturing of TWBs is shown in Fig. 4.

Due to the different element types and data formats the chosen output data from Simufact Welding must be converted before being implemented in AutoForm Forming. For the conversion the data

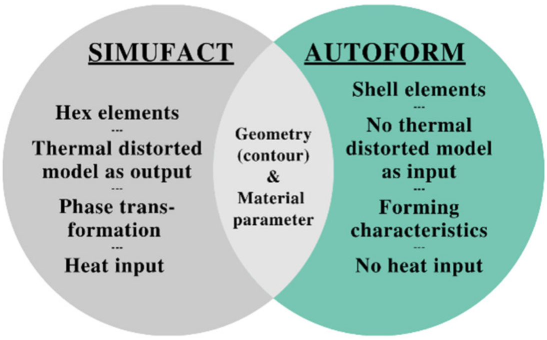

Figure 4: *Different parameters covered by the used simulation software Simufact Welding and AutoForm Forming to simulate the production of tailor welded blanks: features and differences.*

exchange platform is used. The welded plate geometry with hex elements is exported and uploaded to the converter, that selects the needed information like the phase transformation, the hardness, and geometrical changes due to the heat input and transforms this information into CAD-data, that can be imported in Autoform. Because of the physical models AutoForm is running with, not all data, that is transferred and converted can be implemented. Examples therefore are the microstructure or the distortion due to the heat input.

3.3 TRANSFER OF THE GEOMETRICAL DATA

The heat input during the welding process influences the geometry, the residual stresses, and the microstructure of both blanks. The transformations due to the heat input could be crucial for the subsequent forming simulation. As the blank in Simufact Welding is meshed with hexahedron elements and in AutoForm Forming with elasto-plastic shell elements, the geometry and the information about the influence of the heat input cannot be transferred directly. To address this, information regarding the positions of weld seam and HAZ are converted. Data from Simufact Welding is exported as UNV-file.

The exported files contain information about the positions of individual nodes of the deformed mesh as well as values of selected physical result properties of the nodes. The selected physical values are shown in table 2.

Table 2: *Data, that is used to transfer the geometry from Simufact Welding to AutoForm Forming. Yes/no explains, if the import of the parameter in AutoForm is possible (yes) or if the parameter is only considered for the conversion for further geometrical information (no).*

Deformation in x and y-direction	yes
Deformation in z-direction	no
Outline of the blank	yes
Position of the weld seam	yes
Position of the heat-affected zone	yes
Phase ratio	no

The UNV-file with selected information is uploaded to the data exchange platform. The original TWB geometry after the welding simulation is illustrated in Fig. 5.

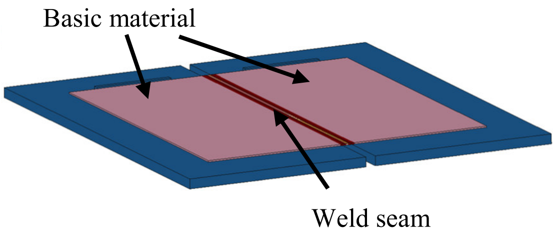

Figure 5: *TWB simulated in Simufact Welding with weld seam, heat-affected zone, and basic material.*

On the data exchange platform, the uploaded data are processed in the following steps.

Outline of the blank:

- Import data from the UNV-file in Python.
- Option 1: Construct a mesh object of the welded blanks in a CAD software (e.g., FreeCAD) based on the deformed geometrical positions of the nodes. Even though this option is characterized by a potentially lower development effort, its level of flexibility is assessed as more limited.
- Option 2: In Python, determine a specific layer in z-direction, derive a 2D outline of the deformed blanks based on the positions of the nodes within the layer and build a file in a CAD-file format containing the outline. As this option is conducted directly in Python and is independent of a CAD software, its level of flexibility is considered to be higher.

This 2D-outline takes the deformation in x- and y-direction during the welding process into account, but the deformation in z-direction is neglected. While AutoForm Forming neglects deformations in z-direction, this is likely to be inconsequential as the loads during the deep drawing process smooth out those deformations. The positions of the weld seam and the heat-affected zone are extracted differently than the outline of the blank.

Weld seam:

- Option 1: Get weld seam from process information in Simufact Welding.
- Option 2: Extract weld seam from properties such as phase information.

Heat-affected zone:

- Extract volume fraction of martensite from the UNV-file.
- Determine phase ratio diagrams along several equidistant lines perpendicular to the weld seam.
- When the phase ration crosses a certain threshold value, a border point is defined.
- The border points define a line, which separates different head-affected areas and the base material.

Due to this approach the heat-affected zone can be divided from the basic material. The converted data can be exported as a file in a CAD-file format. The generated 2D-lines can be imported into AutoForm and a blank, as shown in Fig. 6, can be generated.

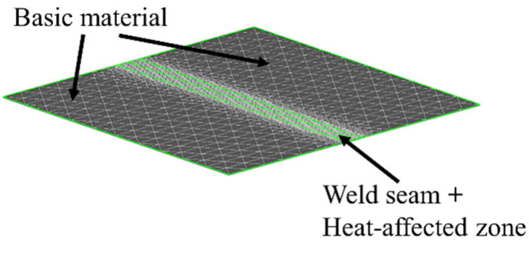

Figure 6: *TWB imported in AutoForm Forming with weld seam, heat-affected zone, and basic material corresponding to the geometry from the welding simulation.*

3.4 SUSTAINABILITY POTENTIAL

Through the usage of components made of TWBs with higher strength, the metal sheet thickness can be reduced, and material is saved as well as the weight of the component reduced. This lowers the needed energy of the entire life cycle: for production and during the usage of a vehicle.

The application of a digital bidirectional twin in the development phase of a product has huge potential for the contribution of further savings. Due to the high number of parameter tests, that can be investigated in a short period of time with a small amount of resources used, the digital twin can give detailed predictions about the final component. With this information the real process chain can be built with a lower risk of errors and optimized process steps. This means for the manufacturing of components made of TWBs, that less expensive adjustments to the pressing tools and the welding process must be executed.

Because of the flexibility of the data interfaces and the data platform, additional features like a life-cycle-analysis (LCA) tool can be added to the existing digital twin. The information gained from the LCA of each production step can be provided across the whole process chain and the information is always available.

The life cycle of a vehicle component is subdivided into the raw material mining, the production phase, the period of use and the end of life. For every step the CO_2-footprint can be determined with the help of the GaBi software.

4 SUMMARY

This work discusses the challenges and concepts of creating a digital bidirectional twin for the complete production process of components made of tailor welded blanks. A main point generating a digital bidirectional twin in an industry-oriented environment is the preparatory work. A detailed concept with knowledge about the process and the implementation opportunities must be generated. Depending on the goals of the twin, the simulations and the data interfaces are selected in coordination with every involved partner. For the digital description of the process chain Simufact Welding, AutoForm Forming and an open-source data exchange platform based on Hyperledger-Fabric are chosen. It is shown exemplary, how the geometrical data from Simufact Welding can be transferred to AutoForm, taking the deformation into x- and y-direction and the phase transformation from the welding process into account. But there is also information like the residual stresses and the deformation in z-direction, which cannot be used directly in AutoForm Forming.

The savings potential in terms of time-to-market and sustainability seems remarkable. Especially the time and material savings due to the high number of digital experiments in a short time has a high potential. In regard to the gained information the real process chain can be built with more information and optimized parameters. Another advantage of a digital process chain is the opportunity to change and expand it with less costs and effort than the conventional manufacturing process. This method of establishing a cross-process digital bidirectional twin to produce tailor welded blanks can also be applied for other process chains.

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