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**The Metal Forming Conference MEFORM 2021**
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Preface

Dear colleagues,

For our annual MEFORM conference we invite scientists and engineers from industry and research to present their current developments and advances in the field of “Parameter generation and application” in the context of the current discussion on "Industry 4.0". Even under still valid Corona conditions, we will not stop this good tradition. Thus, we decided, to hold this year’s conference using a virtual format.

Scientific teams are active in developing methods for determining material properties for more than 70 years. Correct and problem-adapted characteristic material data are still a key for the development, control and automation of industrial processes. With the increasing digitalization of industrial production, the generation and interpretation of data is becoming even more important. The continuous process-accompanying generation of material data and the continuous networking of all industrial aggregates and processes along with new methods for automated data analysis by means of artificial intelligence, are the background against which we invite this year to our conference MEFORM 2021. Aiming the motto "Material parameters for smart forming technologies" we want to discuss the role of material parameters and their determination for the development and control of robust and efficient processes or process chains in increasingly digitized forming technologies.

We want to present new results and current trends from the research field "Characteristic values" and focus especially on thermomechanically coupled processes. In addition to the typical use of material models in simulation, control and regulation applications, methods for the automated recording of characteristic values, their opportunities and challenges will also be discussed. One vision is the automated data acquisition from the production process including feedback to the process control. For example, self-learning material databases for self-organizing processes could be developed using fast process models coupled with artificial intelligence and inverse analysis.

Recently, there have been a lot of unprecedented and necessary restrictions on the activity of public life, which also affect the activities of education and science. Acting in accordance with the recommendations of the authorities, we postponed our original MEFORM2020 conference into March 2021. At the same time, we want to avoid the submitted publications to lose their validity and innovation novelty. That is why, together with the organizing committee, we decided to publish all extended abstracts from the original MEFORM 2020 call together with additional abstracts from the recent MEFORM 2021 call in digital form so that they can be cited in upcoming publications.

We hope for your keen interest and we are happy to welcome you to Freiberg in March 2021 for our first virtual MEFORM conference under the special conditions.
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Mobility of the future has to be produced - Materials and technology in digital interaction

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Keywords: Automotive, production, digitization

Introduction

Motorized mobility is becoming increasingly different: multimodal, more flexible, more spontaneous and more situational. However, one thing remains the same: vehicles will still be needed for implementation, which will also have to be produced in the future. Automobile production will increasingly be characterized by diverse dependencies. Diversification, sustainability and ambivalences between mass production and batch size 1 have a massive impact on their competitive implementation.

In order to be able to produce more efficiently, responsively and flexibly, information and communication technologies, internet and cloud technologies, data analysis and artificial intelligence are becoming important enablers. It is also important to implement a continuous virtualization of the real world, which connects planning, production and logistics processes with each other and creates transparency in the supply chain and order processing.

In addition, specific development projects are to be dealt, which show a digital interaction between materials and deformation technologies. It exemplifies how digitization can only be achieved holistically in production if material characteristics are included in an intelligent process right from the start.

Digitization will catapult mobility into the future

Digitization is changing the automotive industry in many ways. With the advent of mobile connectivity, the vehicle itself is becoming a new networked smart product. It serves as a platform for access to using of services and at the same time becomes a supplier of valuable data. This opens up new business models for vehicle manufacturers in addition to mobility options. However, the penetration and increased use of digitization also has an impact on automotive industry. Relationship and cooperation with customers or partners, processes in the company and in particular the value chain of vehicle manufacturing in a digitized, smart factory bring new opportunities as well as a multitude of challenges.

In order to be able to produce more efficiently, more responsively and more flexibly as well as to create a future perspective, companies have to rely on digitization. That means that information and communication technologies, internet and cloud technologies, data analysis and artificial intelligence are becoming increasingly important enablers of this change. With digitalization, automotive production must become modular, scalable and always adaptable. This is the only way to meet the constantly changing capacity requirements in the industry. Complexity, due to an increasing number of model series, can only be mastered by autonomous systems in production and intralogistics. Intelligent modules make it possible to keep the effort for engineering and automation low by having the ability plug and play. It is also important to implement a continuous virtualization of the real world, which efficiently connects planning, production and logistics processes. It creates transparency in the supply chain, production and order processing. Information will therefore be available at any place and at any time. Data can be used to learn from
processes and optimize them. With a systematic collection, integration and evaluation of heterogeneous data along the entire product life cycle from development through production to use phase, important information for the optimization of products and production processes can be obtained. At the same time, this data can be used as a strategic resource to develop digital services.

**Machine 4.0**

Interlinked production with modern information and communication technologies is a broad field of action. While digital infrastructures are increasingly establishing, machine tools, as directly producing elements, still face a multitude of open challenges. They should be intelligent, network with each other, work autonomously, optimize the entire value chain and enable new business models that go beyond the actual production. For these smart features that turn a conventional machine into a Machine 4.0, developments of the specific industrial application are required. In order to realize the necessary basis for this, the Fraunhofer IWU created a special demonstrator for a machine 4.0 with the forming press and integrated it into a holistic digital concept.

*Increase availability, increase lifespan*

In the form of a two-meter-high, fully functional forming press and its virtual twin, components can be punched, deep-drawn and trimmed with a pressing force of 15 tons. In addition to these technological functionalities, digitization ensures complete monitoring of the process or machine, tool and material used. As a result, machine availability can be increased significantly, the service life increased and the training period for the tools can be significantly reduced. In addition, the connection of an optical component inspection offers the possibility to stabilize the production process sustainably.

*Real and virtual sensors*

Comprehensive self-monitoring of the machine is achieved using sensors that are installed at various points and measure forces, paths and strain rates, for example. Since sensors cannot be integrated at every required position of the machine due to difficult access or costly installation, relevant data is often missing. Here virtual sensors were developed that calculate model-based data based on the real sensors and the virtual twin. In this way, stresses can be monitored anywhere in the press structure, which could lead to component failure, particularly at highly stressed points.

All of the data is fed into the newly developed, currently unique, software-based analysis module “Smart Stamp”. This forms the foundation for the generation of the digital image or virtual twin of the press. By purposefully merging the data into substantial key indicators, the meaningfulness of the available data is significantly increased. So, for example the tilting moment initiated by the tool is made visible and the influence on the technology is derived. This avoids manufacturing inaccuracies and increased tool wear.

All information about the forming press and its current status can be displayed at a glance in real time. The basis for this is the “Linked Factory” concept, which was also developed at the Fraunhofer IWU, which among other things makes it possible to reduce the complexity of comprehensive production-relevant data and thus make it usable for employees. Different technologies are used for this. This is done intuitively, for example using augmented / virtual reality, but also via individually configurable key performance indicators that can be configured and put together accordingly.

*Integration - process chain Forming 4.0*

The basis for the holistic effectiveness of “Machine 4.0” is system integration in a future-oriented process chain. In order to achieve this, the concept of “Forming 4.0” was developed. This makes it possible to generate solutions in the field of sheet metal processing and also to synchronize them with existing results.
Inline material test
In order to achieve complete monitoring of the process and machine through digitization, an inline material test is used, which checks the semi-finished product to be used with regard to material characteristics at the beginning of the process (Fig. 1). A solid metal ball hits the sheet with a defined force. Based on the penetration depth of the ball and any material cracks that may arise, an algorithm can be used to infer the properties of the material. Coupling this data with the machine control ensures that the process parameters are influenced in such a way that good parts can be produced even with changing material properties.

Fig. 1: Mini bulge test

Optical component inspection
The manufactured components are processed using Xeidana®, the quality monitoring system developed at the IWU. Xeidana® is software for the detection of defects on component surfaces, which can be used during or after the manufacturing processes. It is beneficial to check each individually produced component in real time. This enables 100% control and traceability to be achieved.

Application in series
Various components of the "Machine 4.0" concept are already in use at OEMs and Tier 1 in the automotive industry. Newly developed networking functionalities are currently being used in the German-Swedish Testbed Industry 4.0 as a solution for the interaction between the three locations Aachen, Chemnitz, Stockholm and thus offer an excellent example of alive Industry 4.0 across borders.
Artificial Intelligence in steel industry – from casting to final product

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Keywords: artificial intelligence, machine learning, basic oxygen furnace, rolling, surface inspection, microstructure analysis

Introduction

Artificial Intelligence (AI) techniques, but especially Machine Learning (ML) methods, are present in everyday life from miniaturized chips to large production devices. The omnipresent AI helps to replace computationally intensive procedures with light and fast metamodels. This work shows applications of ML solutions in heavy industry being a result of the projects realized with various departments of steel mills. The examples start form the casting process based on Basic Oxygen Furnace (BOF), through analysis of the surface of hot rolled products, and finish on classification of final product properties by using automated analysis of micrographs. At first, the common methods applied in this work will be described. Afterwards, the examples mentioned above as well as the obtained results will be shown.

Machine Learning Methodology

Recurrent Neural Networks (RNNs). Prediction of sequential data has always been considered as a key problem in ML field. RNN is one kind of Artificial Neural Networks, widely explored in Deep Learning, developed mainly in the 1980s. The connection between the neurons are in form of directed acyclic graph. The output of the network is connected back again as the input of the same network. As a result, network is able to keep the internal state, which allows it to deal with contextual problem. Neurons need non-linear activation functions which are organised into the layers and learning is supervised with backpropagation technique.

Long Short-Term Memory Networks (LSTMs). Properly handling long term dependencies in sequences may be impossible to achieve using classic RNN networks. One of RNN variations is LSTM, which main feature is ability to learn long-term dependencies. It was introduced by Sepp Hochreiter and Jürgen Schmidhuber in 1997 [1]. Basic LSTM unit is composed from 4 elements: cell state, input gate, output gate and forget gate. Those 4 elements are designed in order to learn when to remember and when to forget. Cell state can be compared to a line which runs straight down the entire network in unfolded form. It is responsible for keeping a state of entire network. Third element, gates, are responsible for updating cell state. They can conditionally let some information through to protect and control the cell state.

Convolutional Neural Networks (CNNs). CNN is a special class of the Deep Neural Networks (DNNs). They are composed of convolutional layers, which base on convolutional filters and activation functions. Convolution layers were firstly presented in [2]. They use weight sharing among different parts of the same layer and exploit spatial relationship between neurons in input, producing spatially related output, which can be used in the next convolutional layer. CNNs achieve significantly better results mostly because they have much more parameters than traditional neural networks but they require huge amounts of data [3]. Big amount of data is mostly difficult to obtain, and sometimes even unavailable. Lack of enough data can be solved using a Transfer Learning procedure [4]. Transfer Learning is a technique that allows to use models trained for one problem to solve another problem. Primary layers of neural networks are not modified during the training, while final layers are trained either from scratch or starting from pretrained model.
ML in Steel Industry

Steelmaking. Basic Oxygen Furnace (BOF), known also as the oxygen converter process, has gained popularity due to its simplicity and efficiency. Main aim of the considered problem was to determine optimal end moment of oxygen blow in BOF. This problem can also be called as a problem of end point control, which is still one of the most challenging problem in BOF steelmaking process. Properly defined end-point is important to achieve final steel with required properties. Currently, such predictions are made by experienced and qualified operators, which mostly results in varying accuracy. The key factor, which is the subject of these predictions, is the temperature of molten steel at the end of blowing. This temperature determines whether the steel is qualified for tapping. As for now, there are many approaches to this problem based on statistical models, which in practice are sometimes characterized by low precision. These models are constructed upon metallurgical knowledge including statistically explored dependencies represented by sets of equations. To solve the end-point problem, LSTM networks were applied, allowing considering various complex dependencies, where conventional mathematical models fail. Two types of models were created. First model, called static model, tries to predict the end point based on chemical composition of batch. In second model, prediction is based upon the data from spectrometer, collecting data in real-time about composition of the off-gas during blowing. Examples of results for the latter model are presented in Fig. 1.

![CO2 prediction compared to real sequence](image)

**Fig. 1:** Models predictions: histogram of static model prediction of oxygen blow (a), dynamic model prediction of CO2 in time vs. measurements of off-gas from spectrometers (b).

Surface Quality Inspection. The products casted in BOF become an input in hot forming processes for manufacturing of flat and long products. The example given in this subsection shows how ML methods can be applied on-line to assess quality of flat products using the Automatic Surface Inspection System (ASIS). The main tasks of ASIS is to take photos during the process to detect defects like scale or holes. The output of ASIS is a map of defects over the surface in form of images. Additional module is responsible for analysis of prepared images. The first approach presented in [5] was based on Decision Trees (DTs), but other approaches using MLPs (Multi-Layer Perceptrons) neural networks and Support Vector Machines (SVMs) were also analyzed. In this work the classifier based on CNNs was also investigated. Two approaches have been chosen: trainings on images containing only defects based on Regions of Interest (ROI) and trainings on the whole images. Main problem of the first approach was related to image resizing, while CNNs need, as the input signals, images of the same size. Defects placed on images have different sizes, and then had to be normalized. Resizing process has generated noises on data, which appear on images with size smaller than output size. On the other hand, shapes and features of some defects have been lost, especially on images with original size much bigger than the output size. Therefore, additional steps were added during data preprocessing. Records with size smaller than output have been
removed. Images with size close to a square were selected to the datasets. However, these steps did not help to improve the result. Accuracy of the best achieved result was at 0.6, while loss was below 1.2. The second approach did not give high quality results as well. Input for this approach was composed of the whole images, which contained the defects, while most of the images contained more than one defect of different type. This is the main problematic issue at the moment. The examples of results obtained by CNN proposed for classification of scales for 10 different classes is presented in Fig. 2.

![Fig. 2: Example of results obtained by CNN for 10 different classes of scale.](image)

**Microstructure Analysis.** The main objective of presented research was an attempt of application of ML techniques in classification of steel microstructures, which can be used to assess final product properties automatically. The research focused on development and implementation of CNN for classification of different types of steel micrographs received from the light microscopy. To get image datasets for this task, a heat treatment was performed in dilatometer for different chemical compositions of steel. Dilatometer samples with a diameter of 5 mm and a length of 10 mm were manufactured from the wire, and dilatometric investigations were carried out on a DIL 805 dilatometer. The samples were austenized at the temperature of 1000 °C, then heated and cooled according to various scenarios. Examples of micrographs used as an input are presented in Fig. 3.

![Fig. 3: Example of micrographs submitted as a part of learning dataset.](image)

Created data set of numerous micrographs of different types of microstructure (33283 photographs) gave the opportunity to develop high precision classification systems and segmentation routines, reaching the accuracy of 99.8%. The tests of developed classification system were performed on 8 different classes of microstructures: C15, C45, C60, C80, V33, X70 and carbide free steel. Presented results confirmed, that CNN can be successfully a useful tool in microstructure classification [6].

**Industry 4.0 in Steel Industry**

Research has shown that ML, having good predictive capabilities, can often replace numerical modeling in monitoring the quality of the process [7]. Industry 4.0, which is a concept of a modern approach to production, in a closed loop of cyber-physical systems, requires the creation of a virtual model of the entire production process - from the furnace to the final product. The virtual model is to allow continuous monitoring of ongoing operations and control with the model to detect irregularities. Hence, virtual models are often called the digital twins. Creating a digital twin on such a large, mega-scale is neither simple nor efficient. The calculation costs of such powerful models would be unprofitable. Hence there is a need of using metamodels and data-driven models. Such models can be successfully used to predict process and product quality [8]. Often, data-driven models are sufficiently precise and many times less computationally expensive than numerical models, so they can be used for real-time prediction [9, 10]. Machine Learning becomes
Artificial Intelligence in steel industry – from casting to final product

one of the main Industry 4.0 instruments and as such is used more and more widely in both scientific research and in industry development.

Summary
The work presents review of ML approaches applied in heavy industry at various stages of a production process. At first application at the very beginning was shown, describing application of LSTM networks in prediction of the optimal end of blowing. Afterwards, usage of DTs and CNNs was describe at the stage of surface quality assessment. The example given in this work was focused on classification of scale defects and holes in hot rolled metal sheet. Finally, the application of CNNs to analysis of micrographs was presented. This solution can be used as a method of automated classification of microstructures and for prediction of mechanical properties. The future research in this area will focus on development of new models at different stages of production processes and models which will be able to classify wider range of microstructure types.

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References
Characterization of phase transformations during graded thermo-mechanical treatment of steel 22MnB5 by means of optical methods

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Keywords: phase transformations, thermal imaging, digital image correlation, flat specimen, steel.

Introduction

The application of car body parts with tailored properties offers a wide range of possibilities to reduce the weight of vehicles. This can be reached by a graded microstructure or a gradation in components thickness. Different austenitization or cooling strategies in combination with varying forming conditions within a part not only enable to adjust graded microstructure mixes but also to vary grain size [1], which influences the material behavior decisively. For an exact characterization of the resulting phase fractions and properties for all areas of a component with a graded microstructure, a high number of tests and specimens are required [2]. The goal of the recent study is the development of a contactless method for the characterization of local phase transformations in inhomogeneous thermo-mechanically treated flat steel specimens.

Experimental procedure

Digital image correlation (DIC) was used for the detection of local strains and a thermal imaging camera was utilized to record the temperature change. A principal scheme of the experimental setup for the high temperature DIC tests is shown in Fig. 1. The tests were performed using a hydraulic universal testing machine from MTS. A high frequency generator with a maximum power of 10 kW and a frequency of 250 kHz in combination with a frontal inductor equipped with a surrounding U-shaped flux concentrator enable rapid heating of flat steel specimens to temperatures of about 900 °C.

The specimens were covered with a black and white (speckle pattern) high temperature varnish. For the high temperature DIC tests, specimens of uncoated 22MnB5 steel with a thickness of 2 mm were used. The dog bone shaped flat specimens have a length of 178 mm and a width of 8 mm within the narrow section. In all tests, the specimens were heated up to a temperature of about 900 °C using the inductor installed behind the back specimen surface with a coupling distance of 2 mm and then cooled down to the ambient temperature on free air or quenched by compressed air. The temperature and strain evolution were measured simultaneous during the heating, soaking and cooling on the front specimen surface by means of an infrared thermal imaging camera and a digital camera. The GOM Correlate software was used to compute the local strains changing during cooling of the specimens. An optical bandpass filter was applied to eliminate the influence of specimen radiation at high temperatures. Pictures for the DIC-evaluation were done.

Fig. 1: Experimental setup with chuck jaws of tensile testing machine (1), flat specimen with speckle pattern (2), frontal inductor with flux concentrator (3), thermal imaging camera (4) and digital camera (5)
Characterization of phase transformations during graded thermo-mechanical treatment of steel 22MnB5 by means of optical methods

every second by automatic triggering. A tensile deformation was performed after heating within 60 seconds and soaking of a duration between 10 and 300 seconds with a speed of 1 mm/s until a total elongation of 10%. Then the specimens were immediately cooled on free air or by compressed air. After that, the specimens were sampled for hardness testing and metallographic analysis. With the information about the local strain and temperature evolution during cooling, it is possible to contrast phase transformations. Diagrams like those in Fig. 2 were constructed for phase transformations start and finish identification. The $D\varphi_y/DT$ curve shows the ratio of the change in strain and temperature as a function of time for a local investigated area of the specimen. If this curve indicates a deviation from the usually horizontal course of the graph and additionally small deviations from the otherwise smooth cooling curve are apparent, a phase transformation took place [3].

Results and discussion

In Figure 2 are depicted the results for a thermo-mechanical treated flat specimen after heating with following soaking of 10 seconds and quenching by compressed air. Area B1 (s. Fig. 2) shows one substantial deviation of the $D\varphi_y/DT$ curve and two small deviations. The micrograph of this area demonstrates a mixed microstructure consist of ferrite, pearlite, bainite and martensite (Figure 3a). With a cooling rate of about 18 K/s, which was calculated according to [4], it was below the critical cooling rate of 25 K/s to get a fully martensitic microstructure [5]. If the start and finish point of the first peak were transferred to the cooling curve, a start temperature of about 780 °C and a finish temperature of about 680 °C could be detected according to Figure 2. This temperature range corresponds with ferrite and following pearlite formation. The next was the bainitic transformation with a start temperature of 680 °C and a finish temperature of about 405 °C. The last transformation between 405 °C and 350 °C is the martensitic transformation with a low amount of martensite. A Vickers hardness of about 282 HV1 within this area also proofs the low fraction of martensite and the existence of the mixed microstructure, respectively.

The temperature-time curve for the area B2 (s. Fig. 2) and the $D\varphi_y/DT$ curve showed no significant deviations from horizontal line since the temperature in this area was below the $A_{c1}$ point. A ferritic-pearlitic microstructure related to the initial state can be found within this area. The Vickers hardness is also comparable to the initial state with 148 HV1. With a cooling rate of about 19 K/s, area B2 was cooled similar to the area B1.

![Fig. 2: Investigated areas in GOM Correlate (left); temperature-time curve and ratio of $D\varphi_y/DT$ for a thermo-mechanical treated specimen after soaking of 10 seconds](image)
Characterization of phase transformations during graded thermo-mechanical treatment of steel 22MnB5 by means of optical methods

Summary

A new characterization method for the determination of phase transformations was studied based on thermo-mechanical treatments of flat steel specimens. The detected phase transformations are validated by micrographs and hardness tests. The start and finish temperatures and times for different phase transformations can be determined by identification of peaks on the $\Delta\varphi/DT$-time-curves. Furthermore, evaluations about the relative number of phases can be drawn from the size of their peaks. In further studies, the accuracy of the characterization method will be verified using already existed deformation-CCT diagrams for the steel 22MnB5.

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References


Production-accompanying quality assurance of mechanical properties according to DIN SPEC 4864

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Keywords: production-accompanying, DIN SPEC 4864, indentation method

Introduction

The tensile test is a complex and destructive test method for determining mechanical properties. A precise (local) testing of components, such as in hardness testing, is not possible with the tensile test. The indentation method according to DIN SPEC 4864 offers decisive improvements in the testing of components and semi-finished products.

The indentation method according to DIN SPEC 4864 is able to combine the advantageous properties of tensile testing and hardness testing. The method is based on 3D measurements of indentations and finite element simulations (Figure 1). The geometries of simulation and real test indentation are automatically brought into precise agreement, whereby the material properties are taken from the simulation. The process is fully automatic and takes only a few seconds. No specialist knowledge is required. Only basic knowledge of materials testing comparable to hardness testing is required. Sample preparation is comparable to that for hardness testing and can be omitted if sufficient surface quality is already present. DIN SPEC 4864 [1] was prepared in cooperation with the Federal Institute for Materials Testing (BAM) Berlin, the Materials Testing Office NRW, the Physikalisch-Technische Bundesanstalt (PTB) Braunschweig and industrial partners. The method provides a flow curve and thus the tensile strength $R_m$ and the yield point $R_{p0.2}$ of a material. For certain materials, the elongation at break of a material can also already be determined. Due to the informative value comparable to the tensile test and the simplicity and flexibility of the hardness test, the method combines the benefits of both methods.

Fig. 1: Flow curves, tensile strength $R_m$ and yield point $R_{p0.2}$ are determined by highly accurate 3D measurement and FEM calculations of hardness indentations (indentation method). Stress-strain curves are available after about one minute.

The testing method can be used for the following quality assurance and optimization tasks:
- Real and local testing of components
- For incoming and outgoing goods, as well as for intermediate inspection,
- For detailed analyses of heat treatments, tailored tempering, welded joints, thermomechanical processes etc.
- For monitoring processes (in-line testing) and for 100% control
In the area of production, the following benefits arise depending on the specific application:
- Test times are reduced from hours for tensile testing (days for external testing) to minutes (depending on implementation)
- Small and thin components can be tested
- Anisotropies can be detected by a single test point when viewing the material pile up
- Heat treatments and processes can be optimized, therefore also the quality of the end products
- Reduction of scrap and misdirected parts during in-process testing (compared to conventional hardness testing)
- Continuous testing and data archiving optimizes the internal quality assurance
- Saving resources through low-destructive testing

Quality management during production using the example of thermal printing

Typical applications are in quality assurance, incoming and outgoing goods and intermediate inspections. The tests are operated close to the process as real component tests, 100% tests and also as in-process tests (inline).

With the technology of thermal printing implemented and introduced by schwartz GmbH (52152 Simmerath) two or more different temperature ranges can be generated on one steel sheet. These different areas undergo a specific, locally limited heat treatment and thus a locally changed time-temperature curve. In this way, soft areas can be set in addition to the hard martensitic areas covered by conventional press hardening. In this way, this innovative technology enables extremely narrow transitions between the different ranges of hardness, depending on individual requirements. The different hardness ranges created during the subsequent pressing of the blanks open up new possibilities for the automotive and supplier industry to manufacture safety-relevant body parts. With the help of the thermal printer system, significantly lighter bodies can be produced, so that vehicles can be designed to be more fuel-efficient and environmentally friendly. "With the process according to DIN SPEC 4864, the different hardness values achieved in the hot-formed components could be verified. Thus, the process has proven its worth in the hot forming of safety-relevant body parts". (customer statement schwartz GmbH)

Comparability with the tensile test

The accuracy of the method, i.e. the agreement with the tensile test, varies depending on the material, but for many materials it is good to very good. In order to exclude measurement uncertainties during the tensile test for comparison purposes, referenced sample materials, e.g. from the Institute for Suitability Testing (IFEP, 45770 Marl), are qualified. Four steel grades C45 (IFEP-1610), 40NiCrMo 8-4-7 (IFEP-1609, IFEP-1709) and SAE12L15 were tested.

The difference between the measured values from the indentation method compared to the tensile test is a maximum of 5 %. [2]

Advantages to the tensile test

If DIN SPEC 4864 is used in-house, compared to the execution of tensile tests, distinct material, machine and personnel costs can be avoided. Compared to external performance by a test laboratory, long waiting times can be avoided. The indentation method can also be applied to small and thin components up to layers.

References

[1] DIN SPEC 4864:2019-11, Test method for the determination of flow curves and benchmark characteristic values for

Characterization of cold formability in bulk metal forming: New test method and its validation in practice

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Keywords: bulk metal forming, metallic materials, formability

Introduction

Analogous to other manufacturing processes, the demands on the reproducibility of properties of each individual component are increasing in the field of bulk metal forming. In series production, changing a supplier of semifinished products or processing a different batch of material can have a negative effect on the continuity of the production process. Therefore, the formability of initial semifinished products, to evaluate the failure limit of the material under given deformation conditions, must be carried out faster, more accurately, and more simply than before. Material (chemical composition, degree of purity, crystal structure, phase composition and described by internal defects), as well as the deformation conditions (stress state, deformation temperature, strain rate and friction conditions, caused by a pretreated surface), play an essential role in defining the formability of a specific material. The failure-free and cost-effective production of parts are needed.

Therefore, a simple, reliable, and reproducible test method is needed, which can yield a wide range of factors influencing the formability of a material.

Deficiencies in the current state of the art

Tensile [1], compression [2], and torsion [3] tests are widely carried out to experimentally determine the formability of rod and wire due to their relatively quick and easy application in a wide range of deformation temperatures and strain rates. However, the material characteristics determined in the tensile and torsion tests, due to clearly deviating stress states, only yield qualitative data and do not provide sufficient information about the forming behavior of the material during cold extrusion processes. Specifically, these test methods do not help in identifying inferior material batches. Furthermore, in both methods, the influence of friction and lubrication conditions cannot be taken into account. For this reason, the compression test is often used in bulk metal forming to determine the formability. Although it is a prevalent test method thanks to good usability and low tool investment costs, it has proven to be a less reliable method for the evaluation of materials in case of complex forming operations. In addition, this test method shows a lack of sensitivity for a wide range of materials, i.e., lack of crack initiation even at a 95% deformation degree. Furthermore, in this test method, the time at which the first crack appears cannot be identified by the force or displacement measurement instruments that are usually employed. For other less common technological dependent test methods, special attention must be paid to the conformity of the stress state in the test and the manufacturing case. For this reason, the statements made by such easily reproducible methods that do not represent the process-specific boundary conditions of bulk metal forming, such as bending, folding tests [4] or expansion tests [5, 6], can only be used for cold extrusion processes to a limited extent.
Device for the evaluation of formability

An example of the tool layout of an alternative test method is shown in Fig. 1. The test specimen is inserted into Guide after any lubrication that may be necessary (similar to the manufacturing case) and is deformed with the Punch until the first visible drop in compression force by a translatory movement of the Punch in the direction of the Counterpunch is observed. During the deformation process, part of the sample material enters the Cavity. During testing, the values of acting compressive force and the displacement and/or the time of the displacement movement of the Punch are recorded using standard measuring devices, i.e., load cell and LVDT.

The displacement and/or the time of the displacement movement of the punch corresponding to the first visible drop in compression force represents a material-specific quantitative characteristic value of formability and corresponds to the first crack formation at the flange edge of the specimen under specified forming conditions such as friction conditions and strain rate. The magnitude of the maximum force before the second and subsequent compression force drops is different due to the different material flow after the primary material failure and should, therefore, not be used to evaluate formability.

![Fig. 1: Schematic drawing of the new test method tool](image)

Validation in practice

Within the context of an IGF project (IGF 18925 BG) "Experimental investigation and material-specific description of process-relevant mechanical properties of wire rod from cold extrusion steels as a function of technological parameters of spheroidization annealing," the new test method was successfully applied on laboratory and industrial scales [7].

The aim of this project was a reduction of annealing times for an intercritical spheroidization annealing cycle of cold extrusion steels with regard to their sufficient mechanical and technological properties in the laboratory scale and industrially validation. From a large number of technological annealing, parameters applied for the four different cold extrusion steels 23MnB3, 32CrB4, C35B, and 42CrMo4, and the crucial parameters were selected based on classical characteristic values from tensile test and microstructure analyses. Afterward, these material states were investigated using the new test method in order to classify them in further classes.

The tests were carried out with specimen dimensions of Ø10.6×18.0 mm, with a constant strain rate of 0.1 s⁻¹ and at room temperature. The force-displacement curves were measured, and from these, the force drop to determine the punch displacement until crack initiation was evaluated. All material states were tested four times with a minimal deviation of results in each case.

Afterward, the steel 23MnB3 was subjected to a continuous industrial validation from a shortened spheroidization annealing step of wire bundles in a bell furnace for the series production of a fastener. The optimized parameters of a shortened spheroidization annealing determined in the laboratory scale were nicely adapted by the industrial feasibility for the annealing of wire bundles. After employing the novel spheroidization method, samples were again tested with the new test method under similar conditions. The punch displacement up to 6.2 mm was observed, which is slightly higher than that for the laboratory condition of 6.0 mm. A probable reason for this difference is the slightly increased total annealing time in the industry due to the slower heating and cooling of a wire bundle compared to laboratory conditions. During the industrial manufacturing of approx. 120,000 fastener sufficient formability of steel...
for was confirmed. All components were manufactured without any defects, and the forming tool life remained the same when compared with the tool used by the deformation of the material with the conventional extended annealing time.

**Summary**

In this paper, a new test method for the evaluation of formability and its application advantages was presented. The examples given relate to the area of the cold forging of common steel materials but can also be adopted in the area of high deformation temperatures. Due to its numerous advantages, the test method is predestined for application in the ongoing production process, such as in a wire rolling mill or during the incoming material quality control in further processing plants.

**References**


Materials data for through process multiscale simulation of hot forging and heat treatment of automotive parts

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Keywords: Hot forging, heat treatment, phase transformations, material models.

Introduction
Due to its limitations, the heat treatment of hot forged parts with the use of the heat of forging is still a challenge \cite{1}. It is expected that design of this process will become more efficient when advanced numerical models are used. These models should reliably describe microstructure evolution and phase transformations. Numerous models for steels have been developed, see review in \cite{2}, but reliability of this models depends, to a large extent, on the correctness of material parameters. The objective of the present work was to perform various experimental tests for the selected steels and to determine parameters in the models using inverse analysis for these tests.

Models
The finite element (FE) thermal-mechanical code Forge was combined with microstructure evolution model describing recrystallization and grain growth, as shown in \cite{3}. The FE model predicts distribution of temperature and grain size in the forging, which are used as a starting point for further simulations of phase transformations during cooling. The upgrade of the JMAK equation was used to calculate kinetics of transformation and phase composition after cooling. Full coupling between FE code and phase transformations model was introduced.

Identification
Identification of the material parameters was the general objective of the work. Uniaxial compression tests and stress relaxation tests at various temperatures supplied data for identification of the flow stress and microstructure evolution models and dilatometric tests supplied data for identification of the phase transformation model. The latter tests were performed for various austenitization temperature and grain size prior to phase transformations was in a wide range. The relation of the kinetics of transformation on the grain size was introduced into the model. In consequence, kinetics of the phase transformation was dependent on the state of the austenite microstructure after hot forging.

Inverse algorithm developed by the authors and described in \cite{2} was applied in the identification procedure. Coefficients in all material models for three steels investigated in the project were determined and the database for the computer system was created. This database was attached to the FE code. Thermal-mechanical-metallurgical model with optimal material parameters was verified and validated. A selected example of comparison of measured and calculated start and end temperatures for various cooling rates is shown in Fig. 1.

The validated model was used for simulations of hot forging and controlled cooling in one of the forging shops in Poland.
Materials data for through process multiscale simulation of hot forging and heat treatment of automotive parts

Simulations

Selected steel grades were subjected to different heat treatment processes: i) isothermal annealing, ii) normalization, iii) quenching and tempering. Simulations of the whole manufacturing chain composed of hot forging and controlled cooling were performed. The adapter, which was investigated, is shown in Fig. 2a, while distributions of the austenite grain size at the beginning of transformations and distribution of the bainite volume fraction after isothermal annealing at 560°C for 1 hour are presented in Fig. 2b and Fig. 2c respectively.

Conclusions

Integration of commercial software together with dedicated micro scale models allowed to create reliable solution for modelling of complex production processes with various configuration of materials and their heat treatment. Database implemented for these solution facilitates exchange of material data for these configurations. The results obtained in calculations were verified in physical tests.

Acknowledgements

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References


Computational analysis of deformation maps

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Keywords: Dislocation glide; Dislocation climb; Diffusional creep; Deformation maps

Introduction
A fundamental understanding of the underlying deformation mechanisms is essential to simulate macroscopic stress-strain relations. Plastic strain is caused either by dislocation glide and climb or a stress-directed flow of vacancies. Since diffusion is a thermally activated process, the creep behavior of polycrystalline materials strongly depends on the applied stresses and temperatures. For simulating secondary creep rates, microstructural characterization is mandatory. The steady-state microstructure during secondary creep provides barriers for ongoing dislocation movement on the one hand, and the acceleration of diffusion along grain boundaries and dislocations on the other hand. In the present manuscript, various creep mechanisms are discussed. Implementation of the mechanical threshold concept, as well as the power law and diffusional flow regimes, which are dominant at lower applied stresses, are introduced. Deformation maps of pure aluminum are plotted for different grain sizes, including dislocation glide, low temperature creep (L.T. creep), high temperature creep (H.T. creep), Coble creep (C. creep), Nabarro Herring creep (N.H. creep) and Harper Dorn creep (H.D. creep). Furthermore, power law breakdown at high stresses is phenomenologically described and is included within the simulations.

Model implementation
Dislocation glide is facilitated if the applied stress σ and thermal activation exceed the energy barrier ΔF. Therefore, the stress-strain relation is described by mechanical threshold concept as [1]

\[ \sigma = \bar{\sigma} \cdot \exp \left( \frac{k_B \cdot T \cdot \ln \left( \frac{\dot{\epsilon}_0}{\dot{\epsilon}} \right)}{\Delta F} \right). \] (1)

\( \bar{\sigma} \) is the mechanical threshold, which is needed to overcome an obstacle without thermal activation at 0 K. \( k_B \) is the Boltzmann’s constant, \( T \) the temperature, \( \Delta F \) the Helmholtz free energy, \( \dot{\epsilon}_0 \) is a constant and \( \dot{\epsilon} \) is the applied strain rate. Time-dependent creep behavior of aluminum has often been investigated in literature [2-6]. The following phenomenological equation describes all deformation mechanisms within this framework [7]

\[ \sigma_i = \left( \frac{k_B \cdot T \cdot \dot{\epsilon} \cdot \sinh^{-1} \left( \frac{A_i \cdot D_j \cdot \mu \cdot b}{A_i \cdot D_j \cdot \mu \cdot b} \right) \right)^{n_i} \cdot \mu. \] (2)

\( \mu \) is the shear modulus and \( b \) the Burgers vector. The calculated stress \( \sigma_i \), the constant \( A_i \), the diffusion coefficient \( D_i \) and the exponent \( n_i \) are associated with the prevailing deformation mechanism. The slope of the double-logarithmic stress-strain rate plot is 3 – 10 [7] for power law creep, while Nabarro Herring creep [8], Coble creep [9] and Harper Dorn creep are characterized by \( n = 1 \). The combination of power law breakdown, L.T. creep and H.T. creep at higher stresses is included in following equation [7]

\[ \sigma_j = \frac{\mu}{\bar{\sigma}} \cdot \sinh^{-1} \left( \frac{k_B \cdot T \cdot \dot{\epsilon} \cdot \sinh^{-1} \left( \frac{A_i \cdot D_j \cdot \mu \cdot b}{A_i \cdot D_j \cdot \mu \cdot b} \right) \right)^{n_i} \cdot \mu. \] (3)

The constant \( \bar{\sigma} = 1000 \). The settings for all simulations are summarized in Tab. 1.
**Computational analysis of deformation maps**

**Tab. 1:** Simulation settings for N.H. creep, C. creep, H.D. creep, H.T. creep and L.T. creep. The effective grain boundary thickness $\delta$ is 1 nm and the grain sizes $d$ are 100 $\mu$m and 300 $\mu$m.

<table>
<thead>
<tr>
<th>Creep mechanism</th>
<th>Eq.</th>
<th>$A_i$</th>
<th>$n_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>N.H. creep</td>
<td>2</td>
<td>$42\cdot\frac{b^2}{d^2}$</td>
<td>1</td>
</tr>
<tr>
<td>C. creep</td>
<td>2</td>
<td>$42\cdot\frac{b^2}{d^2}\cdot\pi\cdot\delta/d^3$</td>
<td>1</td>
</tr>
<tr>
<td>H.D. creep</td>
<td>2</td>
<td>$5\cdot10^{-11}$</td>
<td>1</td>
</tr>
<tr>
<td>H.T. creep</td>
<td>3</td>
<td>$2.15\cdot10^{-13}$</td>
<td>6.4</td>
</tr>
<tr>
<td>L.T. creep</td>
<td>3</td>
<td>$2.15\cdot10^{-11}$</td>
<td>4.4</td>
</tr>
</tbody>
</table>

Fig. 1 shows the calculated normalized stresses of Eq. (2) and Eq. (3) for different strain rates and temperatures in dependence of the grain diameter (100 $\mu$m (a), 300 $\mu$m (b)). The numbers in Fig. 1 (a) and Fig. 1 (b) denote the corresponding deformation mechanisms and the black, bold lines indicate the transitions between the deformation regimes.

Fig. 1: Normalized stress [-] for different temperatures and strain rates for 100 $\mu$m (a) and 300 $\mu$m (b). The black, bold lines indicate the transitions between the deformation regimes. The numbers indicate the deformation mechanisms: 1 - dislocation glide; 2 - L.T. creep; 3 - H.T. creep; 4 - C. creep; 5 - N.H. creep; 6 - H.D. creep.

The broken line in Fig. 1 (a) symbolizes the transition from Nabarro Herring creep to Coble creep within the diffusional flow regime. At a grain size of 300 $\mu$m, diffusional flow is replaced by Harper Dorn creep at very high temperature and low stress.

**Summary**

A computational implementation of plastic deformation and different creep mechanisms is introduced. With the model, deformation maps are calculated in dependence of grain size. At higher grain sizes, Harper Dorn creep dominates over Coble creep and Nabarro Herring creep, which is in good agreement with literature [7].

**References**


Towards integration of advanced material models into PLM

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\textbf{Keywords:} Product lifecycle management (PLM), advanced computer aided engineering (CAE), advanced materials tests, inverse analysis, integrated material modelling (IMM), digital image correlation (DIC), infrared camera (IR), business process flow, extended data analysis (EDA), reference processes, master model, child model, JSON data modelling.

\section*{Introduction}

Simulation of processes, systems and products gain increasing importance within the scope of Industry 4.0. Today, „Product Lifecycle Management“ (PLM) tools support the digital collaboration during the design phase of complex products and cover all aspects of conceptual design, mechanical engineering, and Compliance management. The fields of interest in that context are, the advanced computer aided engineering (CAE) and the product lifecycle management getting into account for simulations, e.g. for crash, distortion and forming requiring advanced material models. The material data have to be material-specific, consistent and complete. Providing consistency and traceability to the raw data sources is challenging the possibility to extract relevant information from databases for models under investigation. A joint German and Czech research project AMMICAL, outlined in this paper builds a framework for an exhaustive extraction of meta- and aggregated data. This ensures the traceability along the entire process chain. Especially with the focus on advanced new materials tests utilizing digital image correlation (DIC) and involving generation and further processing of large volumes of data, which are currently not supported by any materials database or PLM system. This includes integration of advanced materials tests, inverse analysis and derived models into PLM and CAE environments. For the derivation of such kind of database, transparency is one of the pivotal aspects needed for the derivation of a business process flow, fulfilling usable data compression and consolidation. This paper gives an overview of the main ideas starting with the elaboration of business process flows, documenting such processes using BPMN representations and the JSON data model. Furthermore, the processing of data is shown by starting point tensile testing, which is still one of the sources of data for modelling the elasto-plastic behavior of materials. The technical infrastructure provided by EDA materials data system is used as the materials engineering backbone [3,4].

\section*{Business Process Flows}

The processes from testing to application of a model in CAE systems are usually not straightforward and need to be traceable along the entire flow. Modelling of processes is accompanied by data modelling, such that consistency and traceability of data is reached and media breaks can be avoided.
Towards Integration of Advanced Material Models into PLM

Interdisciplinary work of staff from different groups, e.g. materials production, materials testing, CAE calculations are essential for this purpose. The so called EDA task flow (ETF) is a technical infrastructure of the EDA data system which is used to establish the specific task flow for the entire chain of activities from materials tests to engineering tasks depending on the needed objectives. This application ensures entering the whole process starting with the receipt of a project order through the performance and ending with completion of the order generating different kind of reports for customers. However, a link or even integration to enterprise workflow management systems, like PLM- and ERP-Systems still is a future task.

Business Process Model and Notation. Business process flows are documented and visualized by the business process model and notation (BPMN), which maps all pivotal actions and communications on several levels within a process. BPMN components are used in EDA for an illustration of the implemented business process flows in the data system. Any parts of this task flow can be linked to the corresponding object in EDA for a specific description of the functionalities in each process step like shown in Fig.1.

![BPMN diagram](image)

**Fig. 1: BPMN describing a general task flow.**

Data Modelling and Representation

Data structures using the EDA architecture are elaborated to achieve a consistent data model for comparing and analyzing different data form different sources. The object oriented data model of the EDA system utilizes the flexibility of a document centric data model. Objects will be handled by a python middleware, meaning every object is defined by a class that defines how the object operates.

**JSON Data Model.** JSON (JavaScript Object Notation) is the native data format of the underlying MongoDB database system. There are several reasons to use a JSON database, among them performance and sustainability. All data are stored internally in a format which include their metadata and are therefore suitable for long term readability and archiving [2,3].

Master and Child Models. In the context of data modelling for CAE applications, the AMMCAL project uses a concept of master and child models. The main focus is defining a universal master data model, defining all required properties and attributes depending on validated standards, and beyond. All available property definitions of the project consortium are able to derive their own attribute mappings from a common master model. These child models are mapped to the standard definitions used in the master model. By that, a Master Modell contains a consistent set of data which is capable to describe the entire elasto-plastic behavior of a material together with damage models and thermo-physical data. Child models are specific subsets of the master model, which are tailored to meet specific demands of the CAE-systems used. Crash and impact simulation for example, depend on such kind of data systems to ensure the reliability of results. Fig. 2 shows an example modelled by Nordmetall GmbH regarding ballistic tests [1]. The here presented concept helps to assure consistency of results from CAE-calculation performed by different tools and solvers as the underlying material models rely on the same master model. The material properties are also depending on the manufacturing history and can so also vary over a simulated part. This new opportunity avoids lacks of information and inconsistency due to the universal validated standards and opens a gate for efficient and transparent results. [2,3].
Towards Integration of Advanced Material Models into PLM

Processing of Data

The post processing of test data is also performed in EDA. Among others, existing raw data from testing or modelling can be evaluated with all necessary tools as resampling, smoothing and curve fitting with predefined functions. In the context of tensile tests for example, the evaluation of the elastic and plastic deformations are given, as well as the calculation of material specific properties regarding the executed test as the modulus of elasticity, true stress, true strain, engineering stress and engineering strain of the specimen’s cross-section area. In addition to the processing, comparison views of evaluated tests are enabled as graphs and tables. The output of the post processing can be reported in the EDA documentation, where any type of template is available, e.g. for example scientific reports and reports containing raw and processed data as graphs and tables [3,4]. Further on, the project is working on the support for more advanced evaluations, like inverse analysis of material models. Interfaces to specific tools will be created to allow a seamless integration. Fig. 3 presents graphs as comparisons of mechanical characteristics regarding conventionally produced steel alloys depending on different temperatures. Applying curve fitting functions as Hensel-Spittel or Zerilli-Armstrong models, enable the derivation of a parametric master model. The parametrization of such models go together with high flexibility for different views of testing and comparison of results.

Fig. 2: Temperature distribution of a ballistic test – NORDMETALL GmbH.

Fig. 3: Tensile test of conventionally produced steel alloy regarding different temperatures – COMTES F.H.T.
Summary
This paper gives a brief overview of AMMICAL, which is an ongoing project for the integration of advanced materials tests, inverse analysis and derived models into PLM and CAE environments. Among other possibilities, the software application EDA is used for evaluating, processing and reporting any kind of tests and models. With the mapping to a created master model the transparency and traceability of data sources is enabled. Such kinds of models are implemented by the definition of JSON data models with the use of JSON dictionaries. AMMICAL builds a clear and structured chain for all process parts within a project order. Challenging factors are removed by the focus on a master model representing universal standards for the definition of properties and attributes according to leading international standards (ISO, SEP, ASTM). With these developments, a new era is coming up for closing the gaps between material science and material modelling.

References


Physical based microstructure development model for fast calculation

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Keywords: thermomechanical forming, microstructure development, grain size, dislocation density

Introduction

Thermomechanical forging (forging in the temperature range between 800 °C and 1000 °C called “warm”) is a complex multistep process, which aims for high material yield, good product quality and cost efficiency, preferably with complex tools. The process chain is fully automatically controlled and needs to be robust over a long production term. Because of deviation of the steel properties obtained from recycled material, it is challenging for the process stability. Even for standardized grades, mechanical properties and chemical composition differ by different suppliers. Frequently, numerical simulations (which are established design tools) are used to set up first parameters of the production chain by new deliveries and also need to support the variation of primary material. Therefore, the simulation of the process chain needs to be dependent on material flow properties. To get better control of material flow in deformation processes, calculation strategies require changes.

In this paper, new material a new material model is presented, which strongly depended on chemical composition, material microstructure and deformation conditions. In addition, the internal variable of dislocation density, which is the recrystallization control parameter for hardening and softening processes and controls the microstructure evolution. Thus, for this model the dislocation density is a basic quantity for each calculated step and each grain size class in model. Grain size classes are characterized by individual properties such as grain diameter ($D$), dislocation density ($ρ$), geometric elongation, average volume of secretions and their average radius as well as a fraction of the volume ($ν$) in microstructure (Figure 1).

Model description and Methodology

To get a better control of the material flow as a main control factor, in high quality forging processes, changes in the calculation strategies of the material flow are necessary. In this case, material constitutive models which was developed as open source code and implemented in a commercial FEM simulation tool [1], strongly depends the material microstructure [2], especially on the internal variable dislocation density. The dislocation density as the control parameter for recrystallization triggers hardening and softening processes and controls the microstructure evolution. Thus, for this model the dislocation density is a basic quantity for each calculated step and each grain size class in model. Grain size classes are characterized by individual properties such as grain diameter ($D$), dislocation density ($ρ$), geometric elongation, average volume of secretions and their average radius as well as a fraction of the volume ($ν$) in microstructure (Figure 1).

Fig. 1: Schematic influence of microstructure phenomenon on grain size development ($D$: grain size, $ρ$: dislocation density)

With all these sizes in mind, it is possible to calculate a pressure occurring between two grain size classes according to [3] coming from surface energy ($P_D$) stored deformation energy ($P_{RX}$) and precipitation ($P_Z$).

Fig. 2: Grain boundary’s movement and calculation of volume change of each class in the microstructure
From their volume in the microstructure, the probability of occurrence of such pairs for each class can be calculated. Information from the grain boundary mobility derived from the estimation of the iron atom mobility in steel allows calculating the grain boundary movement speed and volume flow from one grain to another (statistical description). From these calculations, new volumes as well as new grain diameters are obtained. During the growth of grains with simultaneous deformation, nuclei (Equation 1 for nucleation rate) of new non-deformed grains in the real microstructure can be observed. This phenomenon is implemented by generating new classes with a given initial constant fraction of 0.001.

\[
\frac{dN}{dt} = \nu \cdot \frac{k \cdot T}{h} \cdot e^{-\frac{Q}{RT}} \tag{1}
\]

Were \( \nu \) nucleation frequency per grain surface, \( k \) Boltzmann constant, \( h \) Planck constant, \( Q \) activation energy for nucleation, \( R \) gas constant and \( T \) absolute temperature.

Model was implemented as standalone program and dynamic library based on C# language and tested for plausibility of results. The results were generated using mobility data for C45 steel from Dictra-Software® and for various thermomechanical conditions (Temperature: 1000; 1100; 1200 °C and strain rate: 0.01; 10; 20 s\(^{-1}\)). By low strain rate 0.01 s\(^{-1}\) a cyclic recrystallization profile of flow curve can be seen (Figure 3). This phenomenon is typically for BCC-materials deformed by low speed. Due to the fact that the material recrystallizes faster than the dislocations reach the critical density, the stored work hardening energy is discharged cyclically depend on temperature.

![Flow curve for 0.01 s\(^{-1}\)](image)

**Fig. 3:** Flow curve for 0.01 s\(^{-1}\)

**Summary**

In this paper a new microstructure-based model for flow curve description is presented, which can describe the cyclic recrystallization in metallic material. The sinus-like curve is controlled by growth of new undeformed grains. The recrystallization phenomenon can be calculated with this model using mobility data from commercial databases.

**References**


Kinematic hardening influence prediction in deep drawing

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Keywords: mixed hardening, sheet metal forming, hardening indicator

Introduction

A large number of complex material hardening models have been developed in the past with the sole aim of accurately predicting the material behavior during forming processes [1]. Some forming processes such as deep drawing involve nonlinear strain paths, and consequently typical isotropic hardening models are inadequate for deep drawing simulation, especially in predicting the springback phenomenon. Therefore, a combination of isotropic and kinematic hardening models [2] must be employed to accurately predict this mechanism. To limit cost, these mixed hardening models should only be employed for materials exhibiting a considerable Bauschinger-effect and in situations involving highly nonlinear strain paths. This current research is focused on further investigating the performance of the kinematic hardening indicator proposed by Lafarge et al. [3] and implementing it with deep drawing simulations in LS-DYNA.

State of the Art:

To predict the influence of kinematic hardening in mixed models, different indicators have been proposed. In Schmitt et al. [4] the dot product of two successive plastic strain tensors was used to quantify strain direction change. Then Van Riel [5], aiming at discretizing this indicator, proposed to use the strain increment. In order to solve the convergence issue of the indicator for increasing sampling frequencies, Van Riel proposed to use the dot product of a strain increment and a reference representing the strain history and using a first order differential equation. The main issue with this solution is the need of a parameter controlling the accumulation of strain in the strain history. Further efforts in this regard were made by Oliveria et al. [6] as they developed an indicator based on plastic strain direction and a fixed reference. Moreover, another indicator was developed by Tekkaya et al. [7] who used the angle between consecutive strain increments for each time step instead of a dot product. This value is then weighted using plastic work and summed up over all increments. An evolution of this last indicator has been presented by Lafarge et al. [3], defined by the following equation:

\[ I_{kin} = \sum \frac{\angle(\alpha, \Delta \varphi_p) \cdot \Delta W_p}{\pi \cdot W_{p,max}} \] (1)

Where:
- \( \alpha \) is a reference for calculating the angle and is estimated as:
  \[ \dot{\alpha} = \frac{d\sigma_0}{d\varepsilon_{ep}} \cdot \dot{\varphi}_p \]
- \( \Delta W_p \) is the variation of the specific plastic work for the given timestep
- \( W_{p,max} \) is the maximum of the specific plastic work in the part
- \( \varphi_p \) is the plastic strain and \( \sigma_0 \) the equivalent yield stress

Simulation input parameters

To analyze the performance of the indicator, two material models are taken into account: a purely isotropic and a mixed hardening model. For better evaluation, a variety of strain paths are used, that are typical for deep drawing processes. In this paper, a T-cup is used as testing geometry, see Fig. 1. The deep drawing process is simulated in LS-DYNA module 11.1.0 using MPP mode for parallel computation. The sheet blank is discretized
Kinematic hardening influence prediction in deep drawing

with around 4800 fully integrated shell elements, whereas the blank and die are modeled as rigid bodies.

**Fig. 1:** Deep drawing die geometry

To enable the calculation of the indicator, no mesh refinement is used. Barlat_YLD2000 (Mat_133) is used as the material model where the material parameters are identified by means of tensile, compression and bulge tests for DP600, DC4 and AA5182. This material card (Mat_133) implements Barlat 2002d Yield curve [8], an exponential hardening law for isotropic hardening and a Chaboche model [9] for kinematic hardening. The material parameters are given in table 1.

Table. 1 DP600 parameters for simulation

<table>
<thead>
<tr>
<th>Parameter description</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young’s Modulus [MPa]</td>
<td>$E$</td>
<td>185</td>
</tr>
<tr>
<td>Mass density [Kg$^{-3}$]</td>
<td>$\rho$</td>
<td>7850</td>
</tr>
<tr>
<td>Poisson coefficient</td>
<td>$\nu$</td>
<td>0.3</td>
</tr>
<tr>
<td>Swift parameter</td>
<td>$\epsilon_0$</td>
<td>$1.8 \times 10^{-3}$</td>
</tr>
<tr>
<td>Swift parameter [MPa]</td>
<td>$k$</td>
<td>1060</td>
</tr>
<tr>
<td>Swift parameter</td>
<td>$n$</td>
<td>0.174</td>
</tr>
<tr>
<td>Chaboche modified parameter [MPa]</td>
<td>$a_f$</td>
<td>379</td>
</tr>
<tr>
<td>Chaboche modified parameter</td>
<td>$c_f$</td>
<td>11.40</td>
</tr>
</tbody>
</table>

The friction coefficient is set to 0.1 using Coulomb friction law. The computational time for simulation with mixed hardening model is around 7 hours using 16 CPU cores. Post-processing occurs in a similar manner as in [3] and is schematized in Fig. 2.

**Fig. 2:** Post processing as in Lafarge et al. [3]

**Results and conclusion**

The numerical results obtained from DP600 deep drawing simulation are shown in Fig. 3. Fig. 3(a) represents the indicator values at the last time step of the simulation. The difference in von Mises equivalent stress between the isotropic and isotropic-kinematic hardening model is depicted in Fig. 3(b). Finally, the difference in accumulated specific plastic energy between the two hardening models is shown in Fig. 3(c).

**Fig. 3:** Values of difference between Von Mises stress and accumulated specific plastic energy

As mentioned earlier, kinematic hardening influences the process when bending and unbending occurs. Therefore, the elements exhibiting nonlinear behavior and undergoing strain paths reversal are more prone to being influenced by the mixed hardening model than those exhibiting linear strain paths.
As explained in the original publication, the indicator's ability to quantify non-accumulative variables, such as Von-Mises stress is limited. The simulation results show that the indicator is correlated with accumulative plastic energy for both simulations: purely isotropic and using a mixed hardening model. The hypothesis that the strain path can be used to calculate kinematic hardening influence is not valid when strain paths are dissimilar. Consequently, high values of the indicator do correspond to significant differences between both simulations. Small values of the indicator, however, do not necessarily correspond to small differences between simulations.

To conclude, the indicator can be used as a global variable: when the indicator reaches high values anywhere in the mesh, the kinematic hardening plays a significant role. The ability to conclude which elements are affected is slightly limited.

Acknowledgement

The authors are grateful to the German Federation of Industrial Research Associations (AiF) for supporting the research project “Relevance analysis for the kinematic hardening in deep drawing processes with closed profiles” (IGF 19973BG). The computations were performed on a PC-Cluster at the Center for Information Services and High Performance Computing (ZIH) at TU Dresden.

References


Image segmentation algorithm for steel microstructure analyses

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Keywords: segmentation of microstructures, metallographic preparation, Deep Convolutional Neural Networks, artificial intelligence.

Introduction

The main task of forming technology is the tailored alteration of the form and properties of metallic materials. Changes of the form are imposed on the material by tension, compression or combined tension-compression strains. This significantly alters the microstructure while usually retaining the lattice structure. While microstructural characterization is very important and pretty well recognized, its classification is not a trivial task. Despite the dynamic development of digital photography and computer systems, classification of the steel microstructure remains the task of experts who "manually" classify a given microstructure image. Classification appears extremely difficult especially in the cases, when there are mixtures of different phases with various substructures. There is no evidence of a computer systems which allow the automatic classification of microstructure, so any attempt in that direction can be valuable.

Therefore, the main objective of the present work is an attempt of application of techniques taken from a dynamically developing field of image analysis based on Deep Convolutional Neural Networks (DCNNs) in segmentation of different types of microstructure, which can be considered as the continuation of research presented in [1, 2].

Methodology

The construction and operation, as well as the training of DCNN with data set of microstructures, which was spatially generated for training and not manually assembled, was presented in [2]. The main step in our research was to evaluate methods of generation of complex microstructure images, from single microstructure type for DCNN based system microstructure analysis. The microstructure data were collected from specially prepared samples by massive imaging. Microstructure classes were generated in samples of 5 mm diameter and length of 10 mm after machining from hot rolled steel wire in dilatometer as the result of a thermomechanical (TM-) treatment cycle. The samples were austenitized at the temperature of 1000 °C for 5 min to dissolve all carbidates and to complete homogenize austenite grain size, next TM-treated by defined conditions (listed in Table 1). All samples were metallographically prepared in several batches with variation of etching times, which resulted in 10 different homogeneous microstructure classes and recorded in the digital light microscopy. For training of DCNN for microstructure identification, an artificial micrograph (see Figure 1) was generated. The generation was performed with Voronoi grains and filled up with real homogeneous microstructures.

Table 1: Classified microstructures

<table>
<thead>
<tr>
<th>Steel grade</th>
<th>TM-treatment</th>
<th>Microstructure type</th>
</tr>
</thead>
<tbody>
<tr>
<td>C15</td>
<td>10 K/s</td>
<td>acicular ferrite</td>
</tr>
<tr>
<td>C15</td>
<td>75 K/s</td>
<td>lamellar bainite</td>
</tr>
<tr>
<td>C80</td>
<td>1 K/s</td>
<td>pearlite</td>
</tr>
<tr>
<td>C80</td>
<td>30 K/s</td>
<td>martensite</td>
</tr>
<tr>
<td>ARMCO</td>
<td>10 K/s</td>
<td>ferrite</td>
</tr>
<tr>
<td>Bainite from [3]</td>
<td>Isothermal holding 350</td>
<td>bainite with retained austenite</td>
</tr>
<tr>
<td>X70</td>
<td>Def.+10 K/s</td>
<td>plate-like upper bainite</td>
</tr>
<tr>
<td>X70</td>
<td>Def.+40 K/s</td>
<td>lath-like upper bainite</td>
</tr>
<tr>
<td>X70</td>
<td>70 K/s</td>
<td>lath-like lower bainite</td>
</tr>
<tr>
<td>X70</td>
<td>50 K/s</td>
<td>granular bainite</td>
</tr>
</tbody>
</table>
The Pix2Pix architecture [4] of DCNN was built for input images of 1600x1200 pixels size. The elaborated DCNN model was calculated for the microstructure photographs of mosaic of microstructure listed in the Table 1. Each photo represented a multiple microstructure types, some of them are very dissimilar. All the photographs were pre-processed, the blurred images were eliminated. From remaining data, we selected 30000 images for training and the remaining were left as a testing data set (2000).

![Image](https://via.placeholder.com/150)

**Fig. 1:** Input and output for training

**Results**

The developed DCNN based model achieved 98.89 % accuracy (percentage of properly segmented examples) for analyzed training data set and 96.89 % for validation data set. In Figure 2 the analyzed artificial images are with high accuracy segmented.

![Image](https://via.placeholder.com/150)

**Fig. 2:** Artificial microstructure Input and prediction with network

By evaluation of trained network with real microstructure, it was found that the boundaries between the different types were difficult to detect. The accuracy of the segmentation is significantly lower with real samples and still offers optimization potential. There are no identified points with a decent area, so strong uncertainty has been identified within the individual microstructure types.

![Image](https://via.placeholder.com/150)

**Fig. 3:** Real microstructure and prediction with network

**Summary**

For metallographic analysis, big amount of data is mostly difficult to obtain, and sometimes even unavailable. In our case we use artificial generated datasets from images with pure microstructure type. All layers are newly trained with these data without the use of pretrained layers. Presented results confirm that the Deep Convolutional Neural Network based system can be useful in segmentation and identification of different types of microstructure of low alloy steels but the architecture of network needs to be developed for accurate prediction.
References


Experimental determination of ductile damage model parameters for magnesium AZ31 thin sheet

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Keywords: ductile damage, AZ31, continuum damage model, void fraction, GTN.

Introduction

Depending on the forming conditions, magnesium (Mg) and its alloys fail in a ductile manner. As such, the failure mechanisms consist of the nucleation of micro sized voids, which then grow and finally coalesce leading to complete fracture. In [1] in situ X-ray computed micro tomography during tensile tests demonstrated that pure Mg shows the ductile damage mechanisms of void nucleation at twin and grain boundaries, followed by a rapid growth stage leading to final fracture. The nucleation of voids in AZ-alloys is generally understood to take place at grain boundaries, where second phase particles are located, or due to twinning [2, 3]. Further, it is possible that Mg alloys inhabit pre-existing hydrogen micro voids due to casting conditions. Compared to voids on grain boundaries, pre-existing grain interior micro voids grow quite slowly [4].

Non-linear finite element (FE) programs with micromechanics-based damage models have found their way into commercially available FE-software. These include coupled damage models such as the Gurson-Tvergaard-Needleman-Model (GTN), as well. Publications of continuum damage modelling applications in forming of AZ31 sheet with reliable experimental data are quite scarce [5–7], mostly because the determination of reliable and accurate damage development parameters is complex. For instance, geometry-based methods, such as density measurements, scanning electron microscopic (SEM) cross sectional images or X-ray micrographs can be utilised [8]. Furthermore, methods for the determination of local mechanical properties, e.g. indentation hardness or micropillar compression modulus, provide the necessary data [9]. The most important aspect is that the determined damage values can be coupled with the local strain distribution.

The GTN-model is based on the flow potential by Gurson [10]. As the void volume fraction increases, the yield surface contracts to express the loss of load bearing capacity. The authors Tvergaard, Chu and Needleman [11–13] have proven more accuracy by replacing the void volume fraction f by a modified damage parameter f* to reflect void coalescence processes after a critical void volume fraction f_c is reached. Depending on the manufacturing process a material exhibits an initial void volume fraction f_0. Once macroscopic failure occurs, a critical void fraction f_k has been reached. In this study, a method to determine these GTN-model based ductile damage parameters is proposed. Forming of AZ31 thin sheet at 250 °C serves as an exemplary test material.

Methods and Experimental Setup

Material. Twin-roll cast, hot rolled and annealed 1.0 mm thin Mg-AZ31 sheet, manufactured at the Institute of Metal Forming (TU Bergakademie Freiberg), was used.

Tensile Tests. Notched tensile specimen, as shown in Fig. 1, were deformed with a traverse velocity of 5 µm/s in a tension module for the SEM at the Technion (Israel Institute of...
Experimental determination of ductile damage model parameters for magnesium

AZ31 thin sheet

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Technology), which resulted in an equivalent strain rate of 0.01 s\(^{-1}\).

![Geometry of tensile specimen for in situ SEM tests indicated in [mm]](image)

**Fig. 1:** Geometry of tensile specimen for in situ SEM tests indicated in [mm]

The test temperature of 250 °C was realized via a heating plate on the underside of the sample. During the tension tests SEM images of the sample surface were taken at a traverse step size of 50 µm. These were then used to measure the local strains using digital image correlation (DIC) with the Matlab Software Ncorr [14].

**Cross section preparation.** Torn samples have been ground parallel to the sheet plane to half their thickness with P4000 grade SiC abrasive paper. The exposed surface has then been polished with an iron-oxide suspension (0.09 µm) and subsequently immersed in a solution of nitric acid and alcohol for 5 seconds.

**Results**

The determination of the local void volume fraction could be implemented based on the relative area fractions of matrix material and voids visible in the specimen cross section. Fig. a shows that the Mg-matrix could be distinguished by its gray appearance and the voids are visibly darker.

![SEM image of cross section with visible particles, voids including the calculated Voronoi-cells and void centroids (a); resulting local void area fraction per cell (b)](image)

**Fig. 2:** SEM image of cross section with visible particles, voids including the calculated Voronoi-cells and void centroids (a); resulting local void area fraction per cell (b)

Following the methodology in [15], the cross section was divided into subareas using the Voronoi-algorithm, with the geometric centroids of each void as nuclei (see Fig. a). The result is a local void area fraction, shown in Fig. b. By extracting the local void area fraction along the direction of uniaxial tension loading, each row of these measuring points can be averaged to one smooth line profile. As demonstrated in Fig. the DIC analysis reveals the local strains, which can be directly coupled to the local void area fraction profile.

![Local void area fraction as a function of the local strain](image)

**Fig. 3:** Local void area fraction as a function of the local strain

In this way, the damage parameters \( f_0 \) (initial void fraction), \( f_c \) (void fraction at onset of coalescence) and \( f_f \) (void fraction at failure) could be determined. \( f_c \) was established on the base of the abrupt rise of the void fraction, because the void coalescence processes increases void growth rates [1]. \( f_f \) is determined to be the maximum void fraction, which has lead to macroscopic failure. It should be noted that these GTN-model based parameters were determined within a two-dimensional cross section, but it is common practice to assume that they are equivalent in volume.

**Summary and Outlook**

The present study has shown, that local strain measurements via DIC during simple tension testing can be correlated to local damage values. Based on the GTN-model, damage parameters for AZ31 thin sheet have been established at 250 °C. For extensive parameterization as an outlook, these
examinations should also be tested for different temperatures, strain rates and sample geometries. These can then be validated by comparing FE simulations to real forming experiments.

Acknowledgments

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References


Set up of the RVE for properties simulation in multiphase steels

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**Keywords:** RVE, phase transformations, multiphase steels, mechanical properties.

**Introduction**

The AHSSs have been developed to improve the balance between strength and formability for deep drawing applications. Dual phase (DP) and complex phase (CP) steels are widely used in the industry. The hardness difference between the ferrite and martensite in DP steels leads to the poor local formability, which is crucial in the hole expansion and stretch elongation tests [1]. The fraction of hard phases in CP steels is higher, which gives higher strength. On the other hand, the hardness gradients are smoother which make CP steels suitable for stretch-forming. It is expected that further improvement of properties can be obtained by control of gradients of microstructure features [2]. It was assumed that numerical simulations should supply data for better description of the microstructure. Development of the RVE (representative volume element) for properties simulation by direct digitization from microstructure characterization results was the general objective of the paper.

**Models**

Three models, all based on the RVE, were used in the present work. The first was phase transformation model and the second was dislocation density model. The third was the model, which predicts gradients of mechanical properties on the basis of results from the previous models.

General idea of the diffusion based phase transformation model is described in [3]. The mathematical formulation uses the solution of the 2nd Fick law:

\[
\frac{\partial c}{\partial t} = \nabla \cdot D \nabla c
\]

where: \( c \) – carbon concentration, \( D \) – diffusion coefficient, \( t \) – time.

Solution is performed in the RVE using finite element (FE) method. Determination of the position of the interface, which varies in time, is defined as the Stefan problem. Evolution of grain boundary was done using Level Set Method (LSM) described in [4]. In the LSM merging and splitting of regions comes naturally and the grid does not have to be changed when the interface moves. In such an approach each grain has its own assigned individual level set function (\( \phi \)) (multiple level set approach) initialized with the distance function. The equation of motion governing grain boundaries is:

\[
\frac{\partial \phi}{\partial t} + \nabla | \nabla \phi | = 0
\]

In equation (2) the velocity field \( \nu \) is a function of the carbon diffusion. Each level set function is solved on the same grid and the coupled level set functions are corrected as:

\[
\phi^c = \bigwedge_{x \in \Omega} \max (\phi_i)
\]

where: \( \phi^c \) - the corrector of \( \phi^p \) level set function.

Solution of equations (1) and (2) accounting for (3) allows to predict growth of the ferrite and to calculate carbon distribution in the remaining austenite. When the temperature drops below \( B_s \) (bainite start), bainite transformation is simulated. Following this, martensite fraction is calculated below \( M_s \) (martensite start) temperature. Conventional models described in [5] were used for bainite and martensite transformations.
Distribution of the dislocation density $\rho$ was calculated by the solution of the evolution equation [6]:

$$\rho'(t) = a \dot{\epsilon} - b \rho \dot{\epsilon}$$  \hspace{1cm} (4)

where: $\dot{\epsilon}$ - strain rate, $a, b$ - coefficients.

Results of simulations using FE + LSM approach in the bainite and martensite and equation (4) in the ferrite were used as input data for calculation of gradients of mechanical properties. Hardness of the bainite and martensite was calculated as a function of the carbon concentration [7]. Hardness of the ferrite was a function of the dislocation density.

Calculations of gradients of mechanical properties were based on the sensitivity analysis methods [8]. In the Morris Design [9] estimation of the main effect of the parameter, local measures (elementary effects) at different points in the input space are computed as:

$$\xi_i = \frac{y(x_1, \ldots, x_{i-1}, x_i + \Delta_i, x_{i+1}, \ldots, x_n) - y(x)}{\Delta_i}$$ \hspace{1cm} (5)

where: $y(x)$ - model output, in the present work it was hardness, $x = (x_1, \ldots, x_n)^T$ - vector of independent variables, $\Delta_i$ - increment of the variable $i$.

Gradients of the hardness were calculated from equation (5) in several locations in the RVE and distribution of gradients was determined. In the next step, following [8], an average gradient and standard deviation was calculated.

Results

Selected results of simulations are presented below. Calculated progress of the ferritic transformation and changes of the carbon distribution during cooling are shown in Fig. 1. The next set of results shows distribution of hardness and gradients of hardness calculated on the basis of carbon distribution in the martensite and dislocation density distribution in the ferrite (Fig. 2).

Fig. 1: Progress of the ferritic transformation and carbon distribution in the austenite during cooling.

Conclusions

Model based on internal variable was developed and coupled with the FE+LSM approach to predict carbon distribution. Spatial distributions of hardness in the RVE were predicted. The algorithm for gradients of properties was developed.
Set up of the RVE for properties simulation in multiphase steels

Fig. 2: Hardness distribution in the martensite (a), in the ferrite (b) and in the whole RVE (c) and gradients of the hardness (d).

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References


Compressive deformation behavior, structure and properties of biomedical Ti-Ni shape memory alloy

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Keywords: Shape memory alloys, Ti-Ni, structure formation, dynamic softening.

Introduction

Ti-Ni-based shape memory alloys (SMA) are attractive functional materials. One of the most effective ways to control the SMA functional properties (FP) is thermomechanical treatment (TMT), which allows creating a wide spectrum of structures from coarse-grained to nanocrystalline. For further testing of different TMT modes at the temperatures below 400 °C, it is necessary to know the temperature ranges of dynamic processes of hardening and softening. Thus, the optimization of technological processes of production Ti-Ni SMA with high FP requires more detailed knowledge of the structure formation in a wide range of deformation temperatures. The aim of this work was searching for optimal regimes of thermomechanical treatment for manufacturing Ti-Ni SMA with controlled FP.

Experimental

Plastometric compression tests of the Ti-Ni alloy were performed using the hot deformation simulator "WUMSI" using a deformation rate of 1 s\(^{-1}\) in a temperature range from 100 to 900 °C. The samples after the reference treatment (700 °C, 30 min by cooling in water) were used for compression. The structure, substructure and phase composition after deformation by compression at a given temperature with accumulated strain \(e=0.5\), was examined by X-ray diffraction analysis, light and transmission electron microscopies. The mechanical properties were evaluated by Vickers hardness tests. The value of completely recoverable strain was determined by a thermomechanical method, including deformation by bending in liquid nitrogen and heating for the shape recovery.

Results and discussion

Deformation behavior. In the range of deformation temperatures from 900 to 600 °C, the flow curves rapidly reach the steady-state stage. A decrease in the deformation temperature shifts the beginning of the steady-state stage toward higher strains. The flow character changes starting from the temperature of 600 °C, as follows: the flow stress passes through a gentle maximum, then somewhat decreases and reaches a steady-state stage. Reaching the steady-state stage of deformation and therefore the possibility of forming a favorable dynamically polygonized substructure is realized in a wide temperature range from 300 to 600 °C.

Structure formation. Light microscopy study of the structure reveals that the average grain size of B2-austenite measured after deformation at temperatures from 100 to 600 °C increases slightly with the increase in deformation temperature from 16 to 22 μm, while the elongated shape of the grains...
Compressive Deformation Behavior, Structure and Properties of Biomedical Ti-Ni Shape Memory Alloy

is preserved. Deformation at 700 °C leads to the formation of new fine grains due to dynamic recrystallization, while the average grain size does not practically change (23 μm after the reference treatment). An increase in the deformation temperature to 900 °C leads to complete recrystallization and increase in the average grain size to 33 μm.

**X-ray diffraction.** The \{110\} B2-austenite X-ray line width was plotted against the deformation temperature. It decreases as the deformation temperature increases at first slowly (up to 300 °C), then rapidly (from 300 to 600 °C) and then stabilizes. Such line width change indicates a decrease in the degree of crystal lattice defectness due to the successive development of recovery, polygonization, and recrystallization processes (Fig. 1).

As comparative study of Ti-Ni SMA structure, phase formation and changes in hardness in a wide range of deformation temperatures (100–900 °C) allows to determine the borders of the temperature ranges of dynamic softening processes under the definite deformation condition. The dynamic recovery region of the alloy is 100–300 °C, which follows from the observation of a very high dislocation density and a cellular type of substructure due to the prevalence of dynamic strain hardening over softening. The region of dynamic polygonization of the alloy is 300–600 °C, as evidenced by the formation of the polygonized substructure, the accelerated decrease in the width of the X-ray line, and the attainment of the steady-state stage in the flow curves (Fig. 1). The region of dynamic recrystallization lies above 600 °C due to observation of new recrystallized grains and the "return" of the X-ray line width to the level of reference treatment.

Fig. 1: – Dependence of the \{110\} B2-austenite X-ray line width on deformation temperature.

**Mechanical and functional properties.** Lowering the deformation temperature from 900 to 100 °C is accompanied by an increase in hardness from 280 to 350 HV, which indicates an increase in crystal lattice defects concentration. At a deformation temperature of 600 °C and higher, the hardness approaches the level of the reference treatment, which indicates the progress of the recrystallization processes. After all deformation modes the value of the completely recoverable strain was not less than 7 %. The maximum values of $\varepsilon_{rt} = 9 \%$ were obtained after deformation at 400-600 °C.

**Summary**

The temperature ranges of the development of dynamic softening processes in aging Ti-Ni SMA are established as follows: dynamic recovery in the 100-300 °C range; dynamic polygonization in the 300-600 °C range, and dynamic recrystallization above 600 °C. The inhibition of the dynamic softening processes is defined by the development of dynamic strain aging. The highest shape recovery characteristics were obtained after deformation in the temperature range of 400-600 °C.
Formability of WE43 magnesium alloy extruded by KOBO method

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Keywords: cast WE43 magnesium alloy, extrusion by KOBO method, formability, plastometric testing, stress – strain relationships, microstructure

Introduction

Direct extrusion by the KOBO method employs, during the course of the whole process, permanent change of strain travel, realized by a periodical, bilateral, plastic metal torsion. The schema of KOBO direct extrusion is shown on Fig. 1 [1, 2]. The torsion of extruded metal leads to a state characteristic of the fluid state, for example: the viscosity coefficient $\eta$ for aluminium is then about $10^7$ Pa, while solid state is maintained [3]. In such conditions, plastic flow of metal through the die resulting from the extrusion force is extremely easy and requires no special conditions, except the correlation of torsion frequency and extrusion rate.

Fig. 1: Diagram of direct extrusion by KOBO method; 1 – punch, 2 – container, 3 – periodically rotated die with grooves on face, 4 – extruded metal/charge, 5 – product [2]

Magnesium products are commonly manufactured by casting processes, but resultant mechanical properties are not sufficient for the use in many applications. Plastic working obviously improves these properties. Poor ductility at room temperature requires plastic working to be carried out at elevated temperatures. WE43 cast magnesium alloy, used in medicine and aerospace and automotive industries, retains stable properties up to 300°C. Usually the product is cast gravitationally and during cooling cracks can appear, needing repair. Plastic working is carried out at 300°C-500°C. At about 300 °C and strain rate of 0.1 s⁻¹ dynamic recrystallization starts, which forms new grains and increases plasticity. With decreasing strain rate, processes of recrystallization and recovery have more time to prevent material strengthening through an increase of dislocation and their piling up [4].

Specimens taken from a KOBO method processed WE43 magnesium alloy bars were investigated. The influence of temperature and strain rate on material flow, critical deformation and development of the microstructure are considered.

Material and methods

50 mm diameter WE43 cast magnesium alloy bar was extruded by the KOBO process at room temperature in one pass to10 mm diameter. Fig. 2 shows the fine grained microstructure after the KOBO process. After heating at elevated temperatures of 300, 340 or 400 °C, samples were deformed in compression at strain rates of 0.1, 1 and 10 s⁻¹, up to 0.65 logarithmic strain, on a plastometer WUMSI at the Metal Forming Institute TU BA Freiberg. The test specimens were heated up to the elevated temperature in 25 minutes and held for 10 minutes prior to testing.
Results
Microstructure

The microstructure on the longitudinal section in side shown Fig. 3 is for a specimen heated at 400° C and compressed at a strain rate 10 s⁻¹.

Stress – strain relationships

The stress – logarithmic strain relationships for the processing parameters are shown on Figs. 4-5. Strengthening results from processing at 300°C at a strain rate of 0.1-10 s⁻¹. At higher temperatures 340 and 400°C and strain rates 0.1 and 1 s⁻¹ recrystallisation starts and develops up to 0.6 strain. Calculated sensitivity ratio on strain rates during compression at 400°C is 0.24 at start and 0.27 at 0.7 strain. It implies superplasticity conditions.
Formability of WE43 magnesium alloy extruded by KOBO method

**Summary**

WE 43 bar was produced from a cast ingot by the KOBO method at ambient temperature. Specimens taken from this bar were compressed on a plastometer at 300-400 °C. At strain rates 0.1- 10 s⁻¹ the material has good formability up to 0.7 (log strain). Recrystallization during processing appears, except at the strain rate 10 s⁻¹. At 400°C there appears the possibility of superplastic forming of the WE43 KOBO alloy.

**Acknowledgments**

Authors thanks Prof. Bochniak (AGH Krakow) for making the WE43 material and Dr. - Ing. G. Korpala (TU Freiberg) for assisting by plastometric testing.

**References**


Copper-Titanium-Alloys – On the effect of low alloy content in materials with high strength and good conductivity

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Keywords: Copper alloys, electrical conductivity, hardness, precipitation hardening

Introduction

Due to the ever growing and partly contradictory requirements, the demands on the properties of materials in modern day applications are always getting more difficult to achieve. Global trends such as digitization, e-mobility and automation are constantly setting new standards. For copper materials, the pursuit for ever better mechanical properties, while maintaining the highest possible electrical and thermal conductivity, is one of the most important goals of copper material design. There are various possible approaches to increase the strength of copper, which influence the conductivity of the material.

Idea

In the investigation presented it will be shown which opportunities titanium offers as an alloying element for increasing the strength while maintaining the highest possible electrical conductivity. For this purpose, only a few tenth of a percent up to one percent of titanium will be added to the copper. By combining this with a suitable heat treatment, it should be possible to precipitate the titanium, which reduces the conductivity in the dissolved state, from the copper matrix in order to achieve an effective increase in strength. With the addition of these small amounts of titanium, the formation of the intermetallic phase Cu₄Ti is achieved in a very high Volume of precipitation [1], which has already been investigated in earlier studies of alloys with a higher titanium concentration. [3-6] The resulting titanium poorer copper matrix should provide an increased electrical conductivity.

Theory and Simulation

Before experimentally testing different copper titanium compositions a set of different simulations was performed to assess which temperatures for precipitation hardening could be suitable. First the theoretical potential of volume of the precipitation phase Cu₄Ti for different compositions in equilibrium was calculated (Fig. 1).

![Fig. 1: Theoretical phase fraction of Cu₄Ti in different copper titanium alloys in equilibrium](image)

The figure shows a high potential for the volume of the precipitable phase. Since equilibrium considerations are not of high value for choosing parameters for a precipitation treatment a simulation of the precipitation behaviour was conducted. Fig. 2 shows the simulated development the volume fraction and particle size of Cu₄Ti in CuTi1 at different temperatures.
Copper-Titanium-Alloys – On the effect of low alloy content in materials with high strength and good conductivity

The simulation suggests that a temperature between 350 °C and 550 °C will be suitable for a heat treatment to develop a high volume of precipitation phase. While the lower temperatures will provide a higher volume of precipitation phase, the higher temperatures will lead to a faster growth to a bigger size of precipitations. Most likely there will be a compromise between a high volume of precipitation phase and particle size which will lead to a high strengthening effect.

To combine the theoretical behaviour from the simulation with real material properties experiments were carried out.

Experimental
Five different compositions of CuTi were melted and cast in a vacuum induction casting machine from high purity Copper and a CuTi8 master alloy. The chemical composition were verified by x-ray fluorescence analysis. The samples (CuTi1, CuTi0.8, CuTi0.6, CuTi0.4 and CuTi0.2) were afterwards homogenized at 850 °C for 48 h as suggested by the literature. The specimens were heat treated at 350 °C, 450 °C and 550 °C for 24 h. Vickers hardness was measured by low load hardness testing and the electrical conductivity was measured by eddy current testing.

Results
Fig. 3 shows that 450 °C is the most suitable temperature for increasing the hardness and the electrical conductivity by isothermal heat treatment in CuTi1. The biggest increase of properties happens in the first few hours of heat treatment. The hardness was more than doubled and the electrical conductivity almost tripled due to the precipitation hardening over 24 h at 450 °C. While the heat treatment at 550 °C lead to a fast increase in hardness and electrical conductivity it wasn’t possible to maintain the increase of properties over a longer duration. The reason for this is most likely the lower volume of precipitation phase combined with too coarse precipitations, due to a considerably higher growth rate. The development of properties of the other compositions showed a similar behaviour in respect to the influence of the temperature. A comparison of the different compositions is shown in Figure 4 and Figure 5.

The figures show that a considerable effect of precipitation hardening was only measurable to a titanium content of 0.6 Ma.-%. The highest conductivity is reached by CuTi0.2 due to the low amount of solved titanium in the copper matrix. This also leads to the lowest hardness that couldn’t be increased by heat treatment. For strengthening the alloy the contents of 1 Ma.-% and 0.8 Ma.-% titanium showed to be most effective, which makes sense due to the
high possible volume of precipitation phase. Interestingly the highest increase of electrical conductivity due to precipitation are observed in CuTi0.8, not in CuTi0.6.

Fig. 4: Development of the electrical conductivity of CuTi-alloys over time at isothermal heat treatment at 450 °C

Fig. 5: Development of the hardness of CuTi-alloys over time at isothermal heat treatment at 450 °C

A reason for this behaviour could be a higher titanium content the remains solved in the copper matrix due to the overall lower titanium content that reduces the potential of the development of precipitations.

To improve the precipitation behaviour and mechanical properties of the alloy cold work will be applied to different CuTi alloys. The cold working itself should increase the hardness considerably, while the electrical conductivity should only be slightly decreased. The increased dislocation density should make it easier for precipitations to form as they serve as nuclei and provide energy that promotes precipitation formation.

Summary
This study shows that titanium is a suitable element for precipitation hardening, even in lower alloy contents. It was shown that:
1. Precipitation hardening was possible with down to 0.6 Ma.-% titanium
2. it is possible to more than double the hardness of the alloys (from 80 HV0.1 to 184 HV0.1 in CuTi1 at 450 °C over 24 h)
3. it is possible to almost triple the electrical conductivity of the alloys (from 5,77 MS/m to 15,88 MS/m in CuTi1 at 450 °C over 24 h)

For further research the use of cold work before heat treatment and the use a third element to increase the amount of precipitated phase could be a promising approach, which would lead to a reduced content of alloying elements in the copper matrix increasing the electrical conductivity further while achieving considerable strengthening effects.

References
Development of rolling technology for H-Beams with large strain intensity

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Keywords: roll pass design, section rolling, plastometric test, numerical modelling, FEM, straightening process.

Introduction

The quality and properties of section profiles must be continuously improved to fulfill increasing industrial requirements and to perform well in the challenging competitions with the other materials, on the other hand [4-5]. Design of rolling processes of section profiles must take into account their performance requirements [6-7]. Many researchers have been carried out works in the field of groove design by using FEM, but there are no complete outcomes for roll pass design, especially for sections rolling. Analytical analysis of shape rolling process can help to design new grooves and rolling schedule without spending much time and money for experiments [1]. The dependence of the rolling process on many variables interfering the results obtained when complex grooves have been applied [2-4]. The aim of the following study was to develop new roll pass design (RPD) of H-Beams and introduce it into industry. The necessity of usage of a charge stock with a greater cross section has caused an applying of the new rolling schedule with a large strain intensities.

Properties of steel used for H-Beams

Series of tests were performed using torsional plastometer. The obtained results in a form of flow stress variations as a function of temperature, strain and strain rate were loaded into computer program as the material database. The obtained flow stresses for S355J2 steel grade are presented in the Fig. 1 - Fig. 2.

New Roll Pass Design for H-Beams

The model is based on the industrial conditions of continuous rolling line in Medium Section Mill. Numerical methods were used to aid roll pass designing for H-Beams. A commercial package ABAQUS was applied for this purpose; ABAQUS Explicit being used for the deformation models, and ABAQUS Standard used for the thermal analysis. Three-dimensional, deformable and linear hexahedral (brick) elements were used to
model the stock, rolls and rolling equipment. The friction between rolls and rolling stock was described by Coulomb law. Heat from the rolled stock into the rolls and the environment was transferred by the convection. The radiation from surfaces of the elements in the contact with the environment has been computed according to the law of Stefan-Boltzmann. 

The following examples demonstrate the results from selected three-dimensional FEM simulations:

- Fig. 3. shows the FEM modelling of rolling in two-high stand (knife pass),
- Fig. 4. shows FEA analysis in the last universal rolling stand.

Fig. 3: Stock shape at the exit from the knife pass during rolling of H-Beams

Fig. 4: Stock shape at the exit from universal mill during rolling of H-Beams in last stand

Straightening process of H-Beams

Complex straightening line consist of horizontal roller unit that is made of ten rollers and a guided roller, Fig. 5.

Fig. 5: FEM modeling of the straightening process of rolled H-Beams

From practice, it is well known that the flange of an H-section flaps towards the roller during straightening. This effect is observed in the research as well.

Fig. 6: Cross-section of HE160A during straightening at upper and bottom rollers

As the example, Fig. 6 shows the shape of the H-Beam geometry during straightening at different rollers. The flange of the beam moves towards the upper roller No. 5 and moves towards bottom roller No. 6. The movement of the flange is restricted by the working rollers and the maximum displacement is reached when the tip of the flange touches the face of the rollers.

Fig. 7: The distribution of von Misses stresses inside of HE160A after straightening process

The presented results simulation proves as well increasing of the web high of the beam during straightening. The measurement of the distance on the mesh nodes show insignificant increasing length of the web caused by the straightening process.

Quality of rolled H-Beams

The mechanical properties of a rolled products are primarily determined by its microstructure. The material of rolled beams was characterized by a highly homogenous and fine microstructure, Fig. 8. As a result of the application of new roll pass design a favourable combination of tensile strength up to 585 MPa and elongation A5 of about 30% were achieved, Table 1. As well, the application of a large strain intensities during rolling process contributes to a good final properties of the beams.
Development of rolling technology for H-Beams with large strain intensity

Fig. 8: Microstructure of HE 160A after rolling and cooling (steel - S355J2)

Table 1. Obtained properties of the H-Beams after hot rolling with large strain intensity

<table>
<thead>
<tr>
<th>Steel grade</th>
<th>R_e, MPa</th>
<th>R_m, MPa</th>
<th>A5, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>S355J2</td>
<td>470,1</td>
<td>584,7</td>
<td>29,8</td>
</tr>
</tbody>
</table>

All hot rolled and straightened H-Beams have been characterized by the surfaces free from scratches, pinholes, scabs and lapping, Fig. 9. Final properties of sections prove that developed new roll pass design with large strain intensity and whole rolling process are well realized. In the consequence the quality standards have been fulfilled for rolled beams.

Fig. 9: Template of HEA160 after industrial rolling with the use of new RPD

Summary

Computer-aided roll pass design of H-Beams enabled to project new grooves and place them properly in the roll assemblies. It also allowed to avoid the stock twisting or bending at the roll exit and to obtain the right product shape. Applying of the new rolling schedule with a large strain intensities has caused that focus was also laid on the rolling forces and torques. The performed analysis of H-Beams straightening process allowed to evaluate the extent of plastic deformation accumulation between a flange and a web. It was very important to behave soundness and straightness of the H-Beams in the corner region.

Acknowledgments

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References


Methods for predicting properties in Times of Industry 4.0 in the steel industry

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Keywords: ANN, XGBoost, steel, mechanical properties

Abstract

As part of Industry 4.0, digital twins are becoming increasingly important in steel production and application, due to the many process stages in the manufacturing process. For example, characteristic value predictions after various process stages are of a major importance for the adaption of subsequent processes regarding an optimized final product. In addition to purely physical approaches for property prediction, methods of data-driven prediction are gaining traction in the steel industry. Which benefits can be expected thereof?

Regarding available methods, on the one hand there are modern methods such as machine learning or artificial intelligence (neural networks, gradient boosted trees), compared to classical regression methods or own approaches using ensemble models on the other hand. We will discuss the application and advantages of different approaches used for the prognosis of mechanical-technological properties of hot-rolled steel strip and hot-dip galvanized cold-rolled strip as produced by Salzgitter Flachstahl GmbH.

Introduction

Salzgitter Flachstahl GmbH produces a wide range of different flat steel grades and dimensions. Their properties vary widely depending on the product stage, the process and their chemical composition. For the property predictions in this publication, steel grades were selected as hot and cold-rolled strip from interstitial-free (IF) steels to modern high-strength steels (HSS) with tensile strengths up to 1100 MPa. In the production process of steel, many mechanical and technological properties are determined in order to ensure a high quality of the finished steel strip. These properties, together with local process parameters from the process stages and the chemical composition, represent the digital twin of the steel strip. These data can be used to create, validate and apply prognosis models for various mechanical-technological parameters. For this purpose, the data for all processes were divided into training, test and validation data sets.

Prediction of Properties

The following methods have been used to predict the mechanical-technological properties: multiple linear regression, regression of clusters, ensemble modeling [1], several artificial neural networks (ANN) of differing complexity and XGBoost regression based on a gradient tree boosting system [2]. The costs in terms of training time vary between these methods from very fast multiple regressions to long lasting ANN.

In the case of hot-rolled wide strip, the data set from 15,000 mechanical tests was divided into 50 different clusters in order to be able to subsequently predict the yield strength of hot-rolled wide strip using regression methods within the clusters. The clusters were determined using the k-nearest neighbors algorithm as a function of chemical composition and selected process parameters, so that newly produced strips are assigned to the clusters. Within the clusters, the yield strength predictions are performed using stored regression models. A good
correlation between measured and predicted yield strengths is observed (see Figure 1).

![Fig. 1: Scatter plot of measured and predicted values for the test data sets with regression of clusters for hot-rolled steel (up) and XGBoost regression for cold-rolled and hot-dip galvanized steel (down)](image)

A higher prediction quality is achieved by an ensemble model, which first searches the training data for similarly produced hot strips. Based on these, different prognosis values are determined, which are combined by an ensemble model to a predicted yield strength. In addition to more accurate predictions of yield strength, this approach shows that the prediction quality of the ensemble model is significantly better, if a higher number of similarly produced hot strips is available for the prediction. The disadvantages are the costly model generation and computing time required to identify similar hot strips.

The second use case deals with cold-rolled galvanized steel. The 30,000 datasets used consist of chemical composition, process data of hot rolling and hot-dip galvanizing lines and five mechanical properties taken from samples from the beginning and the end of the galvanized cold-rolled steel strip: yield strength $R_{p0.2}$, tensile strength $R_m$, fracture elongation $A_{80}$, hardening exponent $n_{90}$ and vertical anisotropy $r_{90}$. The ANN executes the prediction with a single model for all five properties whereas both the linear and XGBoost regression use distinct models for each mechanical property.

![Fig. 2: Deviation curve of measured and predicted values for the test data sets with regression of clusters for hot-rolled steel (up) and XGBoost regression for cold-rolled and hot-dip galvanized steel (down). The deviation curve shows the percentage of strips whose prediction deviation is below a certain deviation. The smaller the area above the curve, the better is the method.](image)
Even though ANN with various complexity have been chosen, the coefficient of determination \( R^2 \) ranges between 0.83 and 0.99 for the five mechanical properties with a small variance. But even the simple linear regression achieves very similar \( R^2 \) values. The best results are attained by the XGBoost regression. The right side of Figure 1 and Figure 2 shows the good quality of the prediction of the tensile strength with a \( R^2 \) of 0.994.

There are very few predictions that exceed the ±10% threshold. Table 1 shows the quality of the prediction.

**Table 1**: Overview of the coefficient of determination for the different use cases and methods

<table>
<thead>
<tr>
<th>Use case</th>
<th>Method</th>
<th>Property</th>
<th>( R^2 ) of predicted property</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hot-rolled steel</td>
<td>regression</td>
<td>Rp0.2</td>
<td>0.94</td>
</tr>
<tr>
<td></td>
<td>regression of clusters</td>
<td></td>
<td>0.96</td>
</tr>
<tr>
<td></td>
<td>ensemble modeling</td>
<td></td>
<td>0.97</td>
</tr>
<tr>
<td>Cold-rolled and hot-dip galvanized steel</td>
<td>XGBoost regression</td>
<td>Rm</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rp0.2</td>
<td>0.95</td>
</tr>
<tr>
<td></td>
<td></td>
<td>A80</td>
<td>0.90</td>
</tr>
<tr>
<td></td>
<td></td>
<td>n90</td>
<td>0.87</td>
</tr>
<tr>
<td></td>
<td></td>
<td>r90</td>
<td>0.91</td>
</tr>
</tbody>
</table>

**Conclusion**

Data-driven predictions show good agreement between measured and predicted mechanical properties. Even simple regression approaches already show good prediction quality for hot-rolled and cold-rolled strips. Only higher modeling and computational effort leads to models such as the shown ensemble model or XGBoost regression with an improved prediction quality. The prediction quality of artificial neural networks is similar to the other methods, despite the significantly longer training times.

Nevertheless, the used input data consists only of samples representing the beginning and end of strips, so that no precise predictions can be made about the properties along the strip length. Nor can data-based predictions replace material tests to document the fulfilment of the sheet specifications for the customer. Useful applications of such methods can be the adaptation of process parameters in subsequent processing steps based on the predictions as well as plausibility checks of properties in order to recognize and avoid sample confusions.

**References**


Improving the methodology for assessing the drawability of high-strength materials

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Keywords: material model data, drawability, high-strength materials, drawability evaluation methodology.

Introduction

The article presents a drawability assessment procedure developed on the basis of many years of experience [1-10]; conducted at the Department of Advanced Materials and Technology of the Silesian University of Technology, Katowice, Poland. The application of the guidelines collected in the elaborate procedure facilitates and organizes research activities, thus enabling the development of comprehensive characteristic pressing properties or technological plasticity.

Application of the developed methodology

The drawability assessment procedure allowed to preparation metallic charge material characteristics complement and make more accurate material model of a given metallic charge. Such material model is applied in numerical simulation and computer-aided design of the production of a selected draw piece, e.g. see Fig. 1. By using FEM numerical simulation software for stamping processes, e.g. Dynaform 5.9 and the extended material model of a given charge sheet; more accurate forecasting of the pressing result is possible. This is especially important for high-strength materials, the pressing of which is limited by numerous phenomena, such as the effect of sheet metal springback. The study presents an example of the use of the developed procedure for the design of pressing technology for a selected axially-symmetrical product of heat-resistant and creep-resistant nickel alloy - Inconel 625 0.45mm thick sheet metal blank. The geometry of selected draw piece is presented on Fig. 1.

Fig. 1: Cone cover draw piece made of Inconel 625 nickel superalloy.

In the Eta / Dynaform 5.9 software it is possible to use complex material models: of tools (matrices, punches, clamps, elastomer membranes and liquids) and of charge material. According to the developed methodology, it is recommended to use the extended material model by strain-stress curve and forming limit curve pointed out experimentally. The result of the simulation in Dynaform 5.9 of cone drawpiece liquid forming process is shown in Fig. 2.

Fig. 2: Result of numerical simulation of axially-symmetrical draw piece forming using Dynaform 5.9 software.
Summary

The proposed procedure for assessing deformability based on extended computer-assisted drawability tests and numerical simulations of the shaping process, provides a practical tool and a proven procedure for preparing deformation characteristics of any type of material used for stamping. It becomes particularly effective when designing the process of forming high-strength materials, for which simplified models do not consider the effect of sheet metal springback effect. Thanks to computer-aided design, the manufacturing design process is significantly streamlined, it becomes easier to predict phenomena limiting sheet metal stamping; and thus, less expensive than movement tests and industrial trials.

References


Production optimisation due to real time information of profile and surface defects on rolling products

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Keywords: Inline measurement gauge, hot rolling mill, long products, SBQ products, pipes, production optimisation, closed loop control, rolling defect detection, surface defect detection

Introduction
The metal industry, especially steel industry, faces challenges regarding delivery time, production costs and product quality driven by high requirements from e.g. the automotive industry [1]. One measure to address these challenges is striving for production automation with comprehensive understanding of material behaviour under certain control action in the rolling production line of long products. Contactless inline measuring systems play a key role in production optimisation.

Laser based systems are the solution for sound information about the product geometry and its surface condition with high accuracy. The detection of deviations of profile and surface, as well as the analysis of its source regarding the calibre is crucial for taking the right control actions in the rolling line. Smart evaluation and data processing allow real time detection of product parameters and the supply of significant details for the process control system and the operator, respectively. In times of digitalisation the minimisation of the time gap between detection and execution of a control action is tangible by automation.

Challenges in Hot Rolling Mills
Hot rolling mills are the last production step to influence the product quality and production costs significantly [2]. Wear, damages, adhesive scale and defects on the rolling calibre as well as production process condition changes like temperature changes, unforeseen production interruptions or strain variation at the calibre influence the quality of the rolled products. The consequences on the rolling product are profile deviations, break-outs, splitting and bursting, dents, scratches and cracks [3].

Tight tolerance demands require shortest reaction time on production condition changes. Manual process control for rolling mills is still common and results in challenges for product quality and production costs [4].

Especially in wire production mills the wire gets turned and twisted by usage of a layer head. This production set-up causes high difficulties to identify distinct calibre information in order to control the finishing block accurately.

Laser Based Solutions
Shadowing Systems. The contactless measuring principle for shadowing systems is the shadowing principle. A laser scan is emitted and received in a single axis measuring range. An object in the measuring range interrupts the scan so that the size of the object can be measured by interruption time. Up to 6 axes can be used in a measuring range of 500mm and more in the LAP shadowing gauges CONTOUR CHECK ROUND & EDGE. This system principle is already established for over 25 years on the market.

Fig. 1: CONTOUR CHECK ROUND & EDGE system
Light Sectioning Systems. The contactless measuring principle for the light sectioning systems is the triangulation principle with a laser line. A laser line is projected and traced by a camera in a certain measuring range. The laser line is distracted by income of an object and is detected as object profile information by the camera. The complete profile is measured by usage of at least 4 sensors in a measuring gauge. Up to 6 sensors in a measuring range of up to 900mm are used in the LAP light sectioning gauge CONTOUR CHECK SHAPE.

In the application of profile measurement including the identification of rolling defects and rolling gap this system principle has been established since 2015. The newest application (2019) is profile measurement in combination with surface defect detection on hot rolling products in one single measurement gauge.

Fig. 2: CONTOUR CHECK SHAPE system

Benefits in Hot Rolling Mills. These systems are mainly used in hot rolling mills for long products, rebars and pipes, especially for valuable materials like SBQ.

The LAP shadowing system CONTOUR CHECK ROUND & EDGE provides profile information at the implemented axes like diameter and ovality for round products.

The LAP light sectioning system CC SHAPE can identify and visualise rolling defects regarding the position of the calibre to each other and its filling factor.

Especially in wire rolling mills with layer heads the identification of the rolling gap and the relation of the measured information to the gap solves a crucial production challenge.

In productions with high material surface requirements the CC SHAPE is additionally used for surface defect detection. Surface defects down to 100µm depth or height and 200µm width can be identified over the length of the material. The surface defect length depends on the production speed. The detectable surface defects can differ between convex and concave shapes as well as steps. The surface defects are evaluated in defect classes based on their length over the rolling product.

The comprehensive LAP measuring software SMART CORE PRO gives the operator the possibility to receive the most important information at one glance by high level of usability to react on certain events. The software displays real time calibre related information via numerical, graphical and 3D elements.

In order to fulfil industrial requirements for tight production tolerances closed loop control systems for rolling mills are becoming more important. Such size control systems require usually a laser light sectioning gauge at the exit of the finishing block for subsequent feedback control [2]. In order to enhance the production tolerance range even more the additional use of a measuring gauge at entry position of the finishing block is needed. The information density for such additional feedforward control can sufficiently be generated by the LAP shadowing gauges.

LAP provides measuring gauges for both feedback and feedforward control with the same real time set-up and defined communication architecture.

Summary

In order to meet the requirements of the industry, rolling mill directors have to gather as much information about their products as possible. LAP systems fulfil current requirements of rolling mills, especially hot rolling mills and SBQ mills. Shadowing systems are used in one or several upstream positions before the finishing block. Light sectioning systems are positioned after the finishing block. These systems provide the necessary information for production optimisation regarding rolling and surface defects as well as tight production tolerances.
References


Characterizing and simulating multi-pass hot roll bonding

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\textbf{Keywords:} roll bonding, materials characterization, materials modelling, FE simulation.

\textbf{Introduction}

Economic and ecological goals are a driving force for innovation. In many engineering applications, this results in special requirements on the material properties, that can often not be met by a single material. Thus, engineers combine multiple materials with different properties \cite{1}. Joining by forming techniques can achieve the required bond between those materials \cite{2}. Roll bonding is one method to achieve bonded work pieces, especially when a high volume is desired. Roll bonding achieves a bond via plastic deformation resulting from compressive and shear stresses in the roll gap \cite{3}. However, the bond has to persist during the tensile and shear stresses near the roll gap exit. The mechanisms governing the bond formation and evolution in the roll gap during a single pass of cold roll bonding are well researched \cite{3–5}. They can be described by various mechanical \cite{6} or semi-empirical \cite{7} models and finite element (FE) simulations \cite{8}. However, hot roll bonding is usually a multi-pass process. This leads to additional influences from a change in temperature as well as having inter-pass times and multiple deformations. In order to account for these influences when determining processing strategies FE simulations are required. Describing the bond behavior in in FE simulations thus is critical for designing efficient processes.

The goal of this paper therefor is the experimental investigation of these effects with regard to the bond strength, especially considering inter-pass times and multiple deformations, using a torsion plastometer STD812 from TA instruments. Utilizing an Abaqus subroutine allows accounting for these results in FE simulations of the industrial process. The subroutine calculates the bond strength evolution and resulting temperature profile, which allows conducting multi-pass hot roll bonding FE simulations. Hence, section 2 details the materials used, experiments conducted and their results. Section 3 explains the subroutine and section 4 provides a summary and outlook.

\textbf{Experiments and materials}

\textbf{Materials}. All experiments apply two aluminum alloys from the AA6000 and AA8000 series.

\textbf{Experiments and results}. The torsion plastometer uses opposing samples, one of each material. All experiments start with inductive heating and homogenization until the desired temperature is achieved. Afterwards a bond is established at the contact area of the opposing samples by compression. Then the bond strength is characterized by applying an increasing tensile load on the samples until they separate (called debonding) \cite{9}.

In the case of investigating multiple deformations, the bond is established in four consecutive deformations of 1 mm to a total of \((\Delta h_{\text{tot}})^4\) mm at temperatures of 400 °C, 450 °C and 500 °C. As a reference, \(\Delta h_{\text{tot}}\) is applied in a single compression step.

Fig. shows the measured forces during bonding and debonding. The measurements reveal three results. Firstly, the debonding force is smaller than the bonding force, as expected. Secondly, lower temperatures result in higher forces due to the increase in flow stress. Thirdly, multiple deformations yield smaller bonding and debonding forces. The cause might be the observed tensile forces (max. 200 N) stemming from unloading after each compression. This may already lead to local debonding thus reducing the bond strength.
Enabling FE simulations

In order to enable the simulation of multi-pass hot roll bonding processes, two aspects are key. Firstly, models describing the bond formation and bond strength correctly. These are derived from the previously mentioned experiments. Secondly, defining the mechanical and thermal interactions. Fig. displays the interactions between the core- and outer-layer, the surroundings and the roll. Abaqus handles the thermal and mechanical interactions with the roll and surroundings while the subroutine defines the interactions between the layers [10].

Without a bond, an oxide layer or thin film is present reducing the heat transfer compared to direct metal-metal contact of bonded material. Thus, in addition to the conventional pressure dependency, the state of the bond between the layers influences the heat transfer coefficient (HTC). This is implemented by coupling the HTC to the bond state, meaning that wherever a bond is achieved the HTC is significantly increased.

Fig. shows the resulting temperature distribution before the roll gap (left) as well as after the roll gap for bond failure (center) and the bond persisting (right). For this test case, the temperature of the roll is set to 80 °C, the outer-layer to 325 °C and the core-layer to 450 °C in order to demonstrate the functionality. Before rolling, the temperature exchange is very small. If the bond persists, the HTC is increased resulting in a temperature exchange near the contact area of the layers. If the bond fails, there is a small time-frame when the bond is initially formed where the HTC is increased. However, the HTC is decreased again after the bond fails.
yielding a small window where significant temperature changes occur in the contact area. In both cases the temperature at the surface of the outer-layer decreases due to contact with the surroundings.

**Fig. 4:** Temperature distribution before and after the roll gap for different bond states [10].

**Summary and outlook**

The measurements clearly show the significant positive effect of inter-pass times and negative effect of multiple deformations on the bond during hot roll bonding. Accounting for such effects requires simulations to account for bond formation under variable conditions. Therefore, the subroutine is employed to describe the bond behavior including thermal and mechanical interactions between the layers.

The next step is the derivation of bond strength models that account for changes in temperature, strain rate as well as inter-pass times and multiple deformations. In addition to a fundamental understanding of the governing mechanisms, this would enable designing industrial processes that are more efficient in the future.

**Acknowledgements**

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**References**


Influence of inhomogeneous deformation and material conditions on the design of the die plan during hot rolling of heavy plate and strip

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Keywords: rolling simulation, layer model, microstructure, inhomogeneity, multiscale model, residual stress

In the past three decades simulation of metal forming processes became a necessary tool for quality control, automation and the development of new materials technologies. Especially the demands of thermo-mechanical treatments considering the interaction of process entities like temperature, stress and strain state on the one hand and the dependencies of microstructure developments during hot rolling on the other hand require numerical tools which are able to describe these complex interrelations properly. In hot rolling applications the material flow is simulated with different approaches and models. Overviews of the concepts, differing in the computing effort necessary and used modeling depth, are given in [1-3].

Nowadays one of the key ingredients common to all modeling approaches are the stress and strain state tensors. Within this framework, Finite Element methods, boundary approaches or slab theory are used. In the given order the accuracy of the obtained strain rate and stress tensor decreases as well as the computational effort. Depending on the field of application the used modeling approach lies in between these extremes [2].

To combine the advantages of a higher modeling depth with a fast and flexible solution procedure an improved layer model, based on slab theory, was developed [4-8]. The model was first developed and tested as a symmetric model and is now extended to general asymmetric rolling conditions. Thereby asymmetries in relation to roll gap geometry, tribology, initial material state and temperature distribution are taken into consideration. Residual stresses are also available. While in [7-8] a rigid-plastic material state was used, the new approaches include elastic-plastic and visco-plastic materials with phase transformation. The micro structure model included is based on a softening behavior driven by solute drag supplemented by the description of precipitations.

In the paper a short overview of the main features and models included is given. The analysis of hot rolling processes requires a large modelling depth at a minimal computational time. Here, the focus is more and more on models describing an inhomogeneous material evolution. To meet the requirements, a fast simulation method for hot rolling was developed. The computation of the local strain state under consideration of the material evolution processes was performed with the program code LaySiMS. Depending on the number of layers considered, the inhomogeneous strain state in the roll gap can be approximated with sufficient accuracy. The discretization can be done with equidistant or inhomogeneously distributed layers where an inhomogeneous distribution of layers will give better results for processes with significant local gradients than equidistant discretization. Calculated results using the layer model compare well with those resulting e.g. from FE calculations. Therefore, the LaySiMS –system exhibits the advantage of dramatically reduced computational time with comparable accuracy of FE-approaches.

Actual developments of the layer model were made in two directions: On the one hand the model has been extended by further zones
of influence and on the other hand the influence of precipitation on the microstructure modelling has been extended in the LaySiMS software package.

Thus, forming zones with elastic inlet and outlet zones are now considered. Due to the additional implementation of an optional viscous layer model based on a Newtonian fluid as a subarea, casting-rolling processes can now also be described. At present, a simplified modelling of the phase transition to the solid state is carried out using a polynomial approach. In contrast to known models, two material models for the viscous and the solidified area are used in the simulation, Fig. 1 [9].

![Diagram](image1.png)

**Fig.1:** Subdivision of deformation for the horizontal twin roll casting process (a) and its influence on the distribution of longitudinal stresses $\sigma_x$ (b) [9] (material: AZ31; a) $x_{0i}$ - starting point for solidification, $x_{Si}$ - solidification point of layer i, $x_{01}$ - start elastic deformation, $x_1$ - start of plastification of solid layers, $x_{Bi}$ - plastification of next layer, $x_N$ - position of neutral line, $x_2$ - fully elastic cross section at the exit, $x_3$ - start ridged movement; b) layer: 1 - blue, 2 - red, 3 - green, dashed: 4 = 2, 5 = 1) [9]

The microstructure model in the program package has been modified so that the softening is not only delayed by solution drag, Fig.2, but also by pinning effects. This eliminates the previously observed effect of partially accelerated softening during or after precipitation.

![Diagram](image2.png)
Influence of inhomogeneous deformation and material conditions on the design of the die plan during hot rolling of heavy plate and strip

Fig. 2: Simulation of inhomogeneous deformations states and its effect on microstructure evolution

References


Feasibility study for producing nanostructured bainitic casts using Lost Wax technology

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**Keywords:** cast steel, nanostructure, bainite, nano-bainite, lost wax

**Introduction**

Nanostructured bainite, called super bainitic steel or NANOBAIN, is a common feature of steels after expensive plastic work and heat treatments [1, 2]. The excellent properties of this steel are mainly due to the formation of a nanostructure consisting of extremely fine, 20–40-nm-thick, plates of ferrite and retained austenite, without carbides at ferrite/austenite boundaries [3,4]. The concept of new steel is based on suppressed carbide precipitation by alloying with about 1.5 wt.% silicon, which has very low solubility in cementite and greatly retards its growth from austenite [1]. Industry is looking for a cost-effective solution in ultra-strength materials manufacturing. Among many methods of super bainitic steel production like forging [1, 2] or rolling [5], casting is most promising because it enables obtaining a near-net shape of an element in one operation step, giving hope to substantially reduce machining and to obtain high integrity structural components. The application of advanced casting technology, e.g. the lost wax technique combined with modern approaches to steel designing and heat treatment, allows to obtain parts with a wall thickness below 1 mm and high strength.

**Results**

In the present study, low carbon steel with an increased concentration of manganese and silicon, corresponding to typical nano-bainitic materials, has been used for the first time to obtain ultra-strength cast iron. The special stepped geometry samples (with a wall thickness from 1 to 25 mm) were designed and manufactured by the lost wax process. For this purpose, wax based on paraffin was injected into a steel die to obtain a stepped model with high surface quality and roughness. Next, the ceramic mold base on Zircon (prime)/Fused Silica (back-up) with 6 - 7 mm of wall thickness and 25.8 ± 0.24 % of porosity was produced. Various conditions of the melting and casting as well as the ceramic die temperatures were studied to find the optimal relationship between the microstructure and casting conditions, thus allowing to limit the segregation and casting defects. Figure 1a shows the pouring process of low carbon steel to a preheated ceramic die.
The pouring process of low carbon cast iron to a ceramic die.

The heat treatment, i.e. annealing, was used to generate a homogenized structure of cast iron (Fig. 2). It consists of dendrites containing coagulated carbides and needle ferrite. The dark contrasted areas between the dendrites are probably highly tempered martensite formed in places enriched with carbon and alloying elements.

Fig. 1: The pouring process of low carbon cast iron to a ceramic die.

Fig. 2: The microstructure of cast iron after annealing.

A feasibility study for obtaining nanostructured bainite in cast iron preceded experimental investigations (dilatometry) and a theoretical analysis (JMatPro software), which allowed to get CTPi and CTPc diagrams. Varied parameters of austenitization and isothermal treatments (temperature and time) were applied to achieve a submicron-bainitic structure (alpha bainite laths with size average of 150 nm separated austenite) within thin-wall casts with high strength and plasticity (Fig. 3).

Fig. 3: The TEM microstructure of cast iron steel after the bainitic treatment with marked α-Fe and γ-Fe laths.

**Summary**

The application of appropriate casting conditions in the lost wax technology of low-carbon steel, combined with a heat treatment consisting of annealing followed by austenitization and isothermal treatment, allow to obtain nanostructured bainite within thin-wall elements. The microstructure consisted of an intimate mixture of carbon supersaturated ferrite plates with the average thickness of 150 nm, and retained austenite.

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**References**


Effect of the casting and extrusion conditions on the microstructure and mechanical properties formation of copper electrical busbars

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Keywords: Microstructure evolution, physical properties, mechanical parameters, copper alloy, continuous extrusion, conform.

Introduction

Copper is the most common material for the electrical conductors production, but being one of the best materials in terms of electrical conductivity, pure copper does not have high strength characteristics required in some applications of conductors. The use of plastic deformation methods, providing intensive grinding of the metal structure, that allows to control the physico-mechanical properties of materials, increasing their functional characteristics. So, for the production of long-length conductors from alloys based on aluminum or copper, the process of continuous extrusion of Conform is extremely effective [1].

The kind of the microstructure transformation and the formation of the mechanical properties of 10 × 60 mm rectangular busbars made of ECu-57 alloy depending on the technological parameters of casting and pressing are studied. Busbars samples, which are made of rods cast at rate of 300 and 500 mm/min and extruded at rate of 4.5 and 6 m/min were investigated.

Methods and materials

Samples for research were made on the technological equipment of the Svelen Ltd.

The bar stock was cast from ECu-57 copper (Cu ≧ 99.9% w.) by continuous drawing from the melt using UPCAST® technology. The model of the casting machine is SL10-QL-S-B-8/20, equipped with a three-channel induction furnace, the number of casting streams is 8.

Further, the cast bar was extruded at different rate on the MFCCE 350. It is equipped with the working wheel with a diameter of 350 mm, rotating from the main engine with a power of 160 kW. The range of regulation of the peripheral extrusion speed is 1...14 rpm, the pressing temperature is 480 °C.

Results

The work was carried out in the development of the previous researches [2, 3], devoted to the study of the processes of structure evolution in the deformation zone during continuous extrusion. The analysis of the macrostructure of copper rods 16 mm in diameter casted at different drawing rates of 300 and 500 mm/min shows the difference in grain size (Fig. 1).

The rods cast at a linear drawing rate of 300 mm/min, on average, have a larger grain size than the rods cast at a higher rate - 500 mm/min. This fact is explained by the discrete casting character, namely: drawing in increments of 4...5 mm; stopping to form a crystallization front; moving to the hot zone of the graphite mold and, then, further moving along the cold part of the graphite tube to the exit of the mold. At a higher casting speed, the residence time in the hot zone is shorter, what does not allow growing sufficiently large grain.

However, at a lower drawing rate, a more homogeneous structure is formed.
Effect of the casting and extrusion conditions on the microstructure and mechanical properties formation of copper electrical busbars

Fig. 1: Macrostructure of M1 copper cast rods at different drawing rate: a. 300 mm/min; b. 500 mm/min

Cast rods were extruded into a 10x60 mm rectangular busbar at press rate of 4.5 and 6 m/min. To study the microstructure and hardness divided into 4 parts busbars samples were used (with pitch - 7.5 mm).

In both cases of extrusion at different rate, the grain size at the edge of the busbar is larger than at the center, which may occur due to the additional influence of exothermic heat generated by the active friction forces in the deformation zone when passing through the matrix, since the contact area is larger at the edge of the busbar than in its center. A significant effect of the pressing rate on the formation of the microstructure is not observed (Fig. 2). Thus, within the technological capabilities of the equipment, these speeds should be considered comparable.

Fig. 2: The busbars microstructure in the central longitudinal section at the appropriate speeds: a - drawing rate 300 mm/min, b - 500 mm/min; 1 - extrusion rate 4.5 m/min, 2 - 6 m/min.

The effect of casting rate after extrusion is practically not traced due to global restructuring (destruction) of the cast structure and dynamic recrystallization caused by the action of temperature in the deformation zone [4].

Study of the mechanical properties of products processed according to different modes (Fig. 3) showed that there are insignificant trends in hardness growth at the busbars edges made of rods cast at the rate of 300 mm/min, and in the case of using rods cast at a higher rate (500 mm/min) an increase in hardness is also observed in the central part of the busbars. On average, the busbars hardness was 65 ... 68 HRV. With increasing rate, the hardness decreases slightly, on average by 1 ... 2 HRV.
Effect of the casting and extrusion conditions on the microstructure and mechanical properties formation of copper electrical busbars

Conclusion

Study of the microstructure and mechanical properties of busbars shows that the technological parameters of casting and extrusion within the selected ranges are not dominant in the formation of the mechanical properties and structure of semi-finished products. Parameters can be determined by the technological capabilities of the equipment complex, even the appearance of defects and damage on the busbar surface, not related to structural transformations in the material can be detected.

It must be emphasized that extruded busbars cannot be considered as finished products and require additional heat treatment to meet the requirements of product standards.

References


Fig. 3: The distribution of hardness across the width of copper busbars processed according to the following casting - pressing modes: 1 - 300 mm/min - 4.5 m/min; 2 - 300 mm/min - 6 m/min; 3 - 500 mm/min - 4.5 m/min; 4 - 500 mm/min - 6 m/min
Manufacture of hybrid components with tubular reinforcement by composite hot extrusion and subsequent cold forging

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Keywords: Composite hot extrusion, Cold forging, Solid bonding

Fig. 1: Composite hot extrusion process with subsequent lateral extrusion [4]

Introduction

The weight reduction of hybrid components is gained by load-adapted use of different materials while governing all relevant interface conditions. Thus, hybrid components are in great demand and subject of this publication. Cold forging of hybrid components is a process, where multiple billets are combined throughout the deformation process [1]. In this case, the bond is generated by force fit, form fit or metal bonding [2]. However, parameters such as surface expansion and contact pressure have to exceed certain threshold values to achieve a metallic bond [3]. Another approach is the use of billets, where the bond has already been created by former metal forming operations. The process of composite hot extrusion can be used to produce hybrid billets featuring a metallic bond in the interface of the materials. A composite hot extrusion process for semi-finished products made of AA6060 with tubular internal reinforcement (AA7075) has been introduced in [4]. A feasible process window considering the extrusion ratio and the reinforcement position could be found to manufacture hybrid extrudates maintaining metallic bonding. Investigated process route, consisting of composite hot extrusion and subsequent lateral extrusion is shown in Fig. 1.

Hot forging processes of hybrid components having a magnesium core and an aluminum shell, produced by cladding, have been investigated in [5]. The authors found, that the metallic bond can be maintained throughout the entire forging process. A model for estimation of compound damage based on mean stress relation and strain distribution has
been developed, where simulative results were in good agreement with the experiments [6]. However, these findings are not directly applicable to the proposed cold forging process. Thus, investigations on the changing interface conditions during cold forging are necessary to gain a thorough understanding of the process parameters and their influence on the strength of metallic bond of the forged component. Earlier investigations on the basics of lateral extrusion disclosed process limits for different process parameters considering damage of monolithic steel workpieces [7]. Furthermore, flange-shaped hybrids with a steel sleeve and an aluminum core were manufactured by lateral extrusion maintaining force fit and form fit [8]. The authors gave suggestions for process parameters to avoid gaps between the two materials in the outer flange area.

The findings of former investigations on lateral extrusion of flange-shaped parts are a basis to investigate the process presented in here. The overall aim of this research project is to develop a robust process route for cold forging of hybrid billets where the metallic bond does not detach during lateral cold extrusion.

Research hypothesis investigated in this publication is, that mean stress distribution acting in the interface between both materials after extrusion can be used to predict the critical zones, which may provoke bond detachment due to tensile stresses. Therefore, a corresponding numerical model is set up, representing the hybrid as a one-body object with heterogeneous material parameters. Suitable tool geometry parameters for reduced tensile mean stresses in the bonding surfaces during lateral extrusion are target of this publication.

**Materials and Methods**

**Description of hybrid billets and lateral extrusion process**

A billet consisting of an aluminum 6060 matrix and a tubular continuous reinforcing element made from 7075 was cut from a composite extruded profile (Ø 20 mm) to be used for the lateral extrusion process. Fig. a) shows the hybrid billet, manufactured by composite hot extrusion. The billet was ground and then etched with sodium hydroxide solution, which led to the dark coloration of the 7075 element. The dimensions of the tubular reinforcement were chosen in such a way, that metallic bonding is most probable due to the prevailing stress-strain state during composite hot extrusion. The light microscope image in Fig. 2. a) shows the interface of the outer diameter of a polished specimen. Along the interface, inclusions could be detected, but separation of the material layers was not found. A metallic bond was assumed based on the numerical investigations of the compound extrusion process in [4] and the metallographic analysis in Fig. 2. a).

---

**Fig. 2**: a) Cross section of composite billet and magnification of bonding zone b) Lateral extrusion process
The lateral extrusion process is shown in Fig. 2. b). The composite billet is inserted into the lower die, then the dies are closing until they reach a specific die distance $T$. Subsequently, the upper and lower punch counteract on both workpiece face sides and finally lead to the deformation process. The parameters die distance $T$, the punch stroke $s$ as well as the die radius $R$ can be adjusted. Numerical simulations with full factorial parameter variations were used to investigate the effect of different flange geometries on the mean stress distribution in the interface.

**Numerical model of lateral extrusion process**

The persistence of bond during deformation is strongly influenced by the stress-strain state at the interface. To get an idea of the location of critical zones for bond detachment, the mean stress distribution in the bonding boundary was calculated by finite element analysis. DEFORM 2D® was used for the deformation analysis and simulations were conducted as 2D axisymmetric rigid plastic problem. To reduce calculation time, only the upper half of the process was considered assuming horizontal symmetry with constant reinforcing element position along the axial direction (see Fig. 3. a). The workpiece was modelled as a single body with three layers featuring the different aluminum alloys bonded together by previous hot extrusion process. Contact mechanics between the workpiece layers were neglected based on the assumption of metallic bond. The friction conditions and other model boundaries are shown in Fig. 3. b). The number of elements was defined to 4,000 and the punch velocity was set constant to $v = 10$ mm/s. The workpiece material data were gained by compression tests performed at the Institute for Metal Forming Technology at the University of Stuttgart. The cylindrical compression test specimens were machined from extruded monolithic rods from 6060 and 7075 without further heat treatment. The extrusion ratio for the monolithic rods was chosen similar to the one in composite hot extrusion. As a consequence, valid material data for the subsequent numerical simulations of lateral extrusion could be provided. The target of numerical simulations was a suggestion for the magnitude of tool geometry parameters to reduce tensile mean stresses in the bonding surfaces during lateral extrusion.

<table>
<thead>
<tr>
<th>FE Code</th>
<th>DEFORM 2D®</th>
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<tbody>
<tr>
<td>Model</td>
<td>axial and horizontal symmetry; rigid plastic</td>
</tr>
<tr>
<td>Punch velocity</td>
<td>10 mm/s</td>
</tr>
<tr>
<td>Workpiece</td>
<td>One object, 3 layers (AA6060-AA7075-AA6060)</td>
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<tr>
<td>Initial Temp.</td>
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<tr>
<td>Mesh</td>
<td>4,000 elements</td>
</tr>
<tr>
<td>Friction</td>
<td>Workpiece-Tools: shear friction, $m = 0.4$</td>
</tr>
</tbody>
</table>

*Fig. 3: a) Numerical model of the lateral extrusion process and b) model boundaries*
Results and Discussion

The effect of different process parameters on the outside- and inside boundary stress state of the reinforcing element was investigated first. Based on the investigations in [8], it was assumed, that tensile mean stresses in the flange favor detachment of bond and thus should be reduced by choosing more suitable tool parameters. Tracking points alongside the bonding boundary of the initial workpiece were used to calculate the mean stress distribution in the interfaces of the two materials. The tracking points were set up with a constant distance at the inside and outside interface and then calculated throughout entire forming process. Fig. shows exemplary results for the tool parameters \(R = 3\) mm, \(T = 10\) mm and a specific process step, represented by the ratio \(\Delta x/T = 0.74\). In the cylindrical area of the workpiece the mean stresses at both boundaries were calculated as equal. Subsequently, bending of the reinforcement is initiated, which leads to a slight compression on the outer side boundary and a decompression on the inner side. The maximum mean stress values occur in the horizontal symmetry plane (P150) for both inside and outside boundary. Tensile mean stresses of up to 100 MPa are prevailing in this area due to free material flow outboard into the flange zone.

The maximum mean stress values could be detected also for earlier process steps \(\Delta x/T < 0.74\) and other parameter variations between P125 and P150. Consequently, this area is assumed to be most critical towards tensile mean stresses at the interface between both materials. For the following analyses, the global mean stress maximum of each parameter set between P125 and P150 was evaluated.

A full-factorial parameter study was set up by variation of die distance \(T = 8\ldots12\) mm and die radius \(R = 1\ldots5\) mm with an increment of each 1 mm. The results of parameter variation are shown by two exemplary cases. First, the die radius \(R\) was varied with constant die distance \(T\), then the die distance \(T\) was varied with constant die radius \(R\). Keeping the die distance \(T = 10\) mm constant, the die radius \(R\) was varied in a range of \(R = 1\ldots5\) mm. Fig. 5. a) shows the relationship between radius variation and maximum mean stress in the evaluation area according to Fig. . Objecting a proper comparison of the numerical results, the same values for the lateral extrusion length \(\Delta x\) were chosen. The larger the die radius, the smaller the maximum mean stress at the inside boundary. The radius variation seems to have a small influence on the maximum mean stress at the outside boundary for \(T = 10\) mm. However, a slight reduction of the mean stress at the outside interface with increasing die radius \(R\) could be found for reduced die distances \(T\).

![Mean stress distribution alongside the bonding boundary during lateral extrusion](image-url)
Manufacture of Hybrid Components with Tubular Reinforcement by Composite Hot Extrusion and Subsequent Cold Forging

The die distance $T$ was varied with constant die radius $R = 3$ mm in a range of $T = 8\ldots12$ mm. Fig. 5 b) shows the relationship between die distance variation and maximum mean stress in the evaluation area. The smaller the die distance $T$, the lower the maximum mean stress at the inside boundary, whereas at the outside only a slight decrease could be found. Analogous relations were found for other die radii. Assuming, that tensile mean stresses in the evaluation area at the outside flange area favor detachment of bond, small die distances and large radii should be chosen for reduced risk of bond detachment.

**Summary and Conclusion**

Lateral extrusion of hybrid billets featuring an aluminum 6060 matrix and 7075 tubular reinforcing element was considered to indicate critical zones and parameters favoring increased tensile mean stresses and thus detachment of bond. A numerical model for finite element analysis was set up for the cold forging process. The model represents the hybrid as a one-body object with heterogeneous material parameters. The tool geometry parameters die radius $R$ and die distance $T$ were varied to study their influence on maximum mean stress in the area of largest flange diameter and consequently their influence on bond detachment. The following findings were obtained as results of the presented investigations:

- A one-body numerical model with heterogeneous material properties is suitable for the analysis of the mean stress distribution in the interface between the materials of the hybrid billet.
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- The mean stress distribution at the inside and outside interface show global maximum values at the largest flange radius. Thus, this region is considered as the most critical for bond persistence during deformation. The maximum mean stress values are always higher on the outside than on the inside boundary.

- The maximum mean stresses and thus the risk of bond detachment at the largest flange radius of the present process at both boundaries can be reduced by increasing the die radius $R$ and decreasing the die distance $T$ assuming a constant ratio $\Delta x/T$.

Outlook

To validate the findings presented in this publication, experimental investigations on lateral extrusion of hybrid billets will be performed. Microscopic images of the interface between the materials will show how the process parameters influence detachment of bond during cold forging process. Further numerical simulations will be conducted to study, which stress components during lateral extrusion are most decisive for bond persistence, as in this publication, however, only the mean stress was subjected. Furthermore, the elastic behavior of the forged component after ejection and its effect on stress state in the bond will be analyzed. In addition to the lateral extrusion experiments, bond strength investigations by means of tensile and shear tests will be carried out to define feasible process windows for cold forging of flange-shaped hybrid components.

Literature


On identifying the post-necking strain hardening behavior of DP600 sheet through exploiting the diffuse neck in a tensile test

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This paper deals with an improved energy method enabling to extract the post-necking strain hardening behaviour of DP600 steel sheet by exploiting the information hidden in the diffuse neck of a standard tensile test. Validation of the identified post-necking strain hardening behaviour is pursued by comparing with the strain-rate controlled bulge test. It is shown that the energy method enables to accurately determine the post-necking strain hardening behaviour at a minimum of experimental effort. The identification procedure converges very fast (after a maximum of 5 minutes), hence the high potential for industrial valorisation of the energy method.
Upcoming events

Freiberger Kalibreurstag
31 August – 1 September 2021

In this year, the Workshop of International Centre for Groove Pass Design is dedicated to the design of roll passes with special emphasis on profile rolling. The keynote lecture on the current topic introduces the participants to original and modern technology concepts for the hot and cold rolling of profiles. In the first part, the user is taught basic knowledge of material behavior during forming, its forming limits and the resulting restrictions on rolling technology as well as basic processes of material flow, optimum form filling as well as force and work consumption. In the second part, knowledge and skills are to be deepened in practical application. On the basis of experimental trials made on rolling mills at the Institute of Metal Forming of TU Bergakademie Freiberg, practical skills for the design of roll passes are learned.
Plant equipment

**Continuous rolling plant**
The heart of the rolling mill at the Institute of Metal Forming. A multi-stand-by continuous rolling mill for the simulation of real hot-rolling processes for flat or long products in laboratory scale.

**SACK - Reversing rolling mill**
With the appointment of Dr.-Ing. Otto Emicke as a professor at the Chair for Rolled Works and Transport at the Bergakademie in 1928, the history of the rolling mills at today's Institute for Metal Forming begins. The SACK reversing scaffold was already designed in the design phase as a pure test mill according to the plans of Prof. Emicke and officially put into operation in June 1930. In revised and modernized form, the mill is still used today for extensive and demanding research in the field of rolling flat and long products at the Institute for Metal Forming.

**Cold rolling mill**
The Institute for Metal Forming has a cold-rolling reversing stand, which can be operated in duo and for special thin dimensions or solid materials in the quarto installation, for investigations concerning the rolling of thin sheet and cold strip as well as for research into new technology concepts for cold-rolling.

**The three-stand open three-high rolling mill**
For research and technology development in the field of long products, the Institute for Metal Forming has an open three-stand open three-high rolling mill with an extensive series of calibrations for rolling round bars and wires with different cross sections.

**Gleeble HDS-V40**
With the Gleeble HDS-V40, the Institute of Metal Forming has a powerful facility for simulating technological process chains in a small laboratory scale and for determining the deformation characteristics and properties of metallic materials.
Multidirectional test system BÄHR MDS-830

The multidirectional test system MDS-830 from BÄHR-Thermoanalyse GmbH is designed as a multiaxial forming system and offers the possibility of studying the influence of transformation on the phase transformation exactly, and thus allows the generation of U-ZTU diagrams as well as the generation of classical ZTU diagrams to reproduce the influence of forming processes on the conversion kinetics.

Biaxial test facility BÄHR BTA-840

With the biaxial test facility BÄHR BTA-840, the Institute of Metal Forming has a further prototype device for the determination of material characteristics under complex stress and forming conditions. The system makes it possible to apply samples with one or two-axis stress and shape change states. For this purpose, the system is equipped with four hydraulic cylinders which are aligned at right angles in a plane and can be individually controlled in order to transmit tensile or compressive stress to the sample, which is used, among other things, to simulate deep drawing and drawing processes.

Quenching and forming dilatometer BÄHR DIL 805 A/D

The DIL 805 A / D quenching and forming dilatometer from BÄHR allows the investigation of phase conversions as a function of the temperature-time regime and thus allows statements on phase proportions and compositions depending on the process control.

Hot-forming simulator

The hot-forming simulator (WUMSI) of the Institute of Metal Forming is used to determine flow curves and material characteristics. The servo hydraulically controlled machine can perform both single-stage and multi-stage forming operations in the printing area and is thus suitable for the simulation of real multi-stage processes, but also for the determination of e.g. static recrystallization parts by double spotting experiments.
Universal testing machines

The institute has three universal testing machines for 50, 100 and 300 kN nominally forces. In addition to the classical material tension testing by room and elevated temperatures, the machines are also used for bending, shear and adhesion material tests by means of special mounting devices.

Sheet metal test machine BUP 600

The double-acting sheet metal testing machine for 600 kN nominally force makes it possible to carry out of different material characterization und formability tests by room and elevated temperatures such as the bulge test, the Erichsen cupping test, the deep-drawing cup test, the Fukui test, the LDH test, the hole expansion test or the determination of forming limit curves. The machine is equipped with a DIC-system AutoGrid for the local formability determination.

Magnetic measuring station MPG 100D

The magnetic measuring station MPG 100D from Brockhaus has a number of measuring coils so that, in addition to sheet metal strips, it is also possible to measure circular blanks, which allows the determination of the magnetic properties depending on the orientation direction.

Universal forming press

The Institute of Metal Forming has a modern oil-hydraulic universal forming press with a maximum pressing force of 10 MN, which can be operated selectively in the press or drop hammer mode.

The testing possibilities for the press include:

**Massive forming:**
- Open die forging (in press or drop hammer operation)
- Drop forging [die forging] (in press or drop hammer operation)
- Cast-forging
- Thixoforming
- Extrusion
- Impact extrusion
- Powder pressing and forming

**Sheet Metal forming:**
- Deep drawing
- Press hardening
- Hydroforming (IHU)
Twin-roll casting plant Mg wire

In order to complement the field of research on the production and processing of magnesium products, the Institute has had a pilot research facility for the continuous production of magnesium long products using the twin-roll casting process since the end of 2017. The technology developed and patented at the TU Bergakademie Freiberg, which has been researched at the Institute for magnesium flat products since the early 2000s, was transferred to the manufacture of wires.

With the pilot plant that has now been constructed, which was funded to the tune of five million euros by the Saxon Ministry of Science and the Arts via the European Regional Development Fund (ERDF), the light metal can be produced in an energy- and resource-efficient manner for the first time anywhere in the world via twin-roll casting. Magnesium wires can be used, for example, in biomedicine or in joining technology in the form of screws or welding rods.

The plant consists of an electrically heated melting furnace with a capacity of 400 kg magnesium. The melt is then transferred to a headbox, from where the molten metal is transferred to the casting nozzle and then to the rolling gap. If the melt is poured between the two rotating, water-cooled rolls into the oval groove, it begins to solidify from the outside to the inside and undergoes its first transformation. Wires and rods up to a diameter of 20 centimeters with a length of up to eight meters are produced continuously. The twin-roll casting technology saves process steps and thus material and energy costs, while at the same time improving productivity and cost-effectiveness.

Pilot plant for magnesium sheet and strip production

One of the major pillars in the research and activity profile of the Institute of Metal Forming is the work in the field of the production and processing of magnesium flat products. For this purpose, the Institute of Metal Forming possesses a worldwide unique prototype facility to explore the technology of twin-roll-casting as well as the strip rolling technology for the production of magnesium sheet material.

The plant consists of a twin-roll-casting mill for the production of twin-roll-cast material, an air circulating furnace for heating and heat treatment of twin-roll-cast and rolled coils and a quarto reversing stand for rolling of the twin-roll-cast starting material to the desired final thickness.
Digital microscope Keyence VHX-6000

The Keyence VHX-6000 Digital Microscope is a next-generation optical microscope integrated with cutting edge technology including a 0.1x to 5000x 3D microscope which provides a large depth-of-field observations and a 100mm x 100mm stage with a 3-Axis motorized motion. An advanced imaging and measurement system that provides the highest level of image clarity and flexibility, and streamlines communication between every user. The Keyence microscope allows to capture fully-focused images from any angle and measure and annotate directly on the image.

Scanning Electron Microscope Zeiss Gemini 2

Scanning electron microscope with a wide variety of detectors and additional options. In addition to energy-dispersive X-ray spectroscopy (EDX), Institutes microscope also has wavelength-dispersive X-ray spectroscopy (WDX), which enables precise detection of many accompanying elements and the finest C distributions. Thanks to the highly efficient EBSD detector with a recording speed of more than 3000 pps, fast coupled EBSD / EDX mapping can be carried out for phase identification and crystal orientation determination. Zeiss Gemini 2 SEM has an in-situ heating-compression module with a maximum force of 10 kN and a controllable temperature in the range from RT up to 1000 °C. The fast EBSD / EDX detectors open up the possibility of in-situ investigations of the dynamic microstructural changes during and after hot deformation as well as during phase transformation and precipitation processes, that control the material properties of metals.

Vacuum Induction Furnace Seco/ Warwick VIM50

Alloy elements influence all processes that occur after melting. Therefore, one of the most important focuses of our institute is the investigation of the influence of alloy concepts on the deformation behavior, the microstructure and the mechanical properties of the materials. That's why our institute has a vacuum induction furnace with a capacity of one liter for the rapid and independent production of laboratory melts with a given chemical composition. The close proximity to our Continuous rolling plant enables the conducting of a direct rolling, whereby the technology of casting and rolling systems can be modeled and examined.