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Editorial

Modelling and Simulation of Sheet Metal Forming Processes

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1. Introduction and Scope

Numerical simulation of sheet metal forming processes has become an indispensable tool for the design of components and their forming process, in industries ranging from the automotive, to the aeronautics, packing and household appliances. The strong contribution of virtual try-out to reduce the time-to-market and the cost of developing new components has been the main promoter for its extended application, along with the increasing computational power. The Finite Element Method (FEM) is the main numerical tool used in this context.

Nowadays, the automotive industry continues to drive the development of numerical simulation of sheet metal forming processes due to the strong environmental and safety standards that have led to the development of materials with better strength-to-weight ratio or new forming processes. Newly introduced materials allow to produce components from thinner sections, while maintaining satisfactory strength and stiffness, which ultimately results in a reduction of the overall structure mass, a crucial step to meet the ever-stringent standards of passenger safety and gas emissions [1]. However, as is well known, the increased mechanical strength of metallic materials is usually accompanied by a reduction of their ductility. This poses new challenges for predicting forming defects, leading to alternative strategies to the Forming Limit Diagram (FLD) concept. Moreover, the research effort has also been focused on the development of numerical models that enable the virtual try-out of forming processes, involving non-isothermal temperature environments or high strain rates, to try to explore the best formability of the material under these conditions. This requires an enhanced modelling of the material behaviour as well as process conditions, which demands for an improved integration between experimental and numerical analysis. The aim is to be able to integrate the several processes involved in the production of a sheet metal component in the virtual analysis of the forming processes and in-service behaviour. The analysis of the post-forming behaviour should also take into account the scatter in mechanical properties induced by the manufacturing processes. These research trends are reflected in the papers published in this issue, as analysed in the following section.

2. Contributions to the Special Issue

Researchers were invited to submit innovative research papers on modelling and numerical simulation of sheet metal forming processes. Thirteen research papers were published in this Special Issue of *Metals*, entitled "Modelling and Simulation of Sheet Metal Forming Processes", which highlight some of the research trends in the field [2–14].

The FEM virtual try-out for cold forming components is commonly supported by the concept of forming limit diagrams (FLDs), introduced to characterize the ductility of metal sheets [15,16]. The experimental determination of FLDs involves performing various mechanical tests on metal sheets with different samples geometries to reproduce a certain range of monotonic loading paths. However, this experimental approach is both expensive and time consuming, particularly at high temperatures. For these reasons, different theoretical approaches have been develop for the prediction of FLDs, among which the Marciniak–Kuczynski (M–K) theory [17] is the most widely applied. In their paper, Fan et al. [10] used the M-K theory to predict the FLD for a TA32 alloy, for a temperature range between 700 °C and 800 °C, taking into account strain rate effects. The parameters of the thermomechanical hardening law considered in the M-K theory were fitted using experimental results from hot tensile tests. The results from these tests are also used to identify the normal anisotropy coefficient and select the Logan–Hosford yield criterion that allows a better correlation between the theoretical and experimental FLD, determined using the Nakazima test. Also, the theoretical FLD is used to study the initial blank shape of a component produced by Hot Press Forming (HPF), showing that the FLD concept can also be extended to this type of process.

The HPF technology is widely used to prevent formability problems and reduce springback. In addition to the parameters of conventional cold press forming, the blank temperature, the strain rate and the quenching methods also affect the formability and complicate the analysis of hot forming processes. Seo et al. [5] performed direct and indirect hot press forming of a ultra-high-strength steel (UHSS) boron steel, 22MnB5, considering different initial blank temperatures and blank-holding forces, in order to evaluate the formability but also the mechanical properties of the material after the forming process. The knowledge of such properties is very important to predict the failure in UHSS sheet metals during a car crash. Bayat et al. [7] propose the use of the M-K theory to predict the FLD for a 22MnB5, taking into account the scatter in material properties at different regions of formed components. Therefore, the hardening behaviour is characterized by performing uniaxial tensile tests of specimens extracted from structural components of a car, enabling the definition of a range for the hardening law parameters. In this context, Bayat et al. [7] suggest replacing the single FLD by a band of forming limits, using statistical approaches to calibrate its bounds.

It is well established that ductile failure in metals occurs due to the presence of defects such as voids and micro-cracks [18]. On the macroscopic scale, damage is observed as the degradation of material properties, e.g., the elastic stiffness, the yield stress or other measurable material properties. This is the approach adopted in continuous damage mechanics, which introduces an internal damage variable to be able to predict the ductile fracture. Cherouat et al. [11] coupled the damage potential, introduced by Lemaitre [19], with an elasto-visco-plastic material model in order to predict the onset of ductile damage for different forming processes. The occurrence of large inelastic deformations commonly implies a severe distortion of the computational domain, whose boundary is also altered by the elimination of the fully damaged elements. In this context, the authors propose a 3D adaptive remeshing scheme, for linear tetrahedral finite element, to enable tracking the evolution of large plastic deformations. The proposed model is used to analyse different processes, including blanking, multi-point and incremental forming and deep drawing of a front door panel. The results highlight the importance of the coupling between elastoplastic and damage behaviour on the damage evolution at large plastic deformations, but also of using remeshing techniques to assure the computational efficiency as well as to avoid convergence problems. Yue et al. [9] also used a coupled damage model to analyse the influence of kinematic hardening and ductile damage on springback prediction. In order to study the influence of the kinematic hardening, experimental three-point bending tests were performed for the AA7055 aluminium alloy, with specimens submitted to uniaxial tension until different pre-strain levels. The results show that both kinematic hardening and ductile damage influence the springback prediction, particularly for non-proportional strain paths.

The accuracy of the numerical results of sheet metal forming processes depends of the constitutive model selected for describing the material behaviour. In general, FEM analysis of complex forming processes is performed with phenomenological models. This was the approach adopted by Thuillier et al. [6] to describe the bake hardening effect, which is a thermal induced phenomenon that is widely explored, in particular by the automotive industry. Thuillier et al. [6] performed an experimental characterization of this effect for a low carbon steel (E220BH) and proposed a phenomenological model for its description. The specimens used in the experimental approach are pre-strained using a hydraulic bulge test device and a dedicated equipment was designed to characterize the dent resistance. The phenomenological model was validated through the numerical simulation of this multi-step process, i.e., bulge followed by dent at the pole by a vertical movement of a hemispherical punch.

The use of phenomenological models implicitly includes the strategy for identifying the model parameters, which is generally seen as an optimization problem [6,9,11,13]. Forming processes involving non-isothermal temperature conditions and/or high strain rates require constitutive models with more parameters. In this context, the Johnson–Cook hardening law was used to study the gas detonation forming [2], which is a high-speed forming process, with the potential to form complex geometries, including sharp angles and undercuts. The authors neglected the thermal softening, but included damage evolution [2]. Cherouat et al. [11] adopted the same hardening law only to take into account the strain rate effect. These authors used an inverse approach to identify the constitutive parameters, suggesting the use of the stage up to the maximum load of uniaxial tensile tests for the identification of the plastic parameters, while the stage after the maximum load is used only to identify the damage parameters. The results highlight that the damage evolution is sensitive to the element size, which can be mitigated by the adoption of the proposed remeshing technique. In fact, the identification of coupled damage models parameters still poses many challenges, as also mentioned in the work of Yue et al. [9].

Electromagnetic forming (EMF) is another widely used high-speed forming process, in which the deformation is promoted by the application of a magnetic force. Cui et al. [12] developed a three-dimensional (3D) sequential coupling method to analyse the electromagnetic uniaxial tensile test using a runway coil. As the magnetic force field depends on the specimen deformation, the mechanical and the electromagnetic problems must be coupled whenever the process involves large deformations. Sequential coupling allows the analysis of the influence of process parameters, such as tools conductivity, relative coil position and discharge voltages, for the strain paths observed in the specimen. In this context, numerical simulation is used to support the development of an experimental procedure and improve knowledge concerning the analysis of results.

Over the years, several benchmarks have been proposed to analyse the influence of the constitutive model and numerical strategies on formability and/or springback predictions, in particular within the NUMISHEET conference series. The "Benchmark 2 - Springback of a Jaguar Land Rover Aluminium" [20] is consider in the work by Mulidrán et al. [3], to analyse the influence of the yield criteria on springback prediction. The results show that the use of more advanced yield functions may improve the results accuracy. Nevertheless, the identification of the anisotropy parameters of these type of yield criteria requires experimental data covering a wide range of stress/strain paths. In the collected works, the characterization of the mechanical behaviour of the metallic sheets was mainly performed with uniaxial tensile tests [3,4,6,7,10,13], although some researchers have also resorted to shear tests [3,9,11]. Simões et al. [8] presented a numerical study that contributes for the understanding of the mechanical phenomena that occur in the material under Knoop indention, enhancing and simplifying the analysis of the results obtained in Depth-sensing indentation tests. This hardness test is particularly attractive for the determination of the near-surface properties, the characterization of brittle materials and post-forming properties; also, it is sensitive to the indenter orientation, making it a useful tool to analyse the materials anisotropy.

Besides the unquestionable advantages of applying numerical simulation in forming process design, numerical models also allow for better understanding of the influence of process parameters. In this context, the work by Neto el al. [13] focused on the effects of the geometry and dimensions of the forming tools on the formability and final thickness distribution of metallic thin stamped bipolar plates (BPPs) for fuel cells. Rufini et al. [4] analysed the influence of several geometrical characteristics and process parameters on the thinning prediction in the bending process of stainless steel pipes. They concluded that the ratio between the curvature radius and the pipe diameter dictates the failure or success of the operation, which is in agreement with empirical knowledge and the experimental results.

Despite the increasing computational power, the numerical analysis of complex geometries, involving features with small curvature still poses challenges. In this context, the adoption of simplifying assumptions can help to understand specific details of the process. This approach is commonly adopted, for instance, in the BPPs formability analysis, where most of the numerical studies of the stamping process reported in the literature consider plane strain conditions. This formability analysis can be complemented by studying specific zones of the BPPs plates, in particular the area including a U-bend channel section [13]. Process conditions can also be simplified, without compromising the numerical results accuracy. This approach was adopted by Patil et al. [2] to simulate the gas detonation forming of a cylindrical cup, by directly applying the detonation pressure as a load in the finite element (FE) model. This requires the proper experimental acquisition of the averaged pressure evolution during the process, close to the blank. The numerical model enables the analysis of the influence of the peak pressure on the damage prediction. However, the fracture prediction requires the modelling of the complete blank, to account for improper alignment of the blank in experiments. Also, in the case of the bending process of stainless steel pipes, the authors report that some discrepancies between experimental and numerical results maybe related with the presence in the experimental tests of an additional support element on the machinery, which was not contemplated in the simulation model [4]. These results highlight the importance of an accurate analysis of the experimental process conditions, to enable a proper analysis of the numerical simulation results. This requires the validation of the model using experimental results, which can be difficult in the early design stages for large size components. Tomáš et al. [14] propose the use of the similitude theory to help engineers to select the blank material using a scaled model. In their study, this theory was applied to study the deep drawing process of a bathtub made from cold rolled low carbon aluminium-killed steel, using both a numerical and a physical model. The comparison between numerical and experimental thickness variations, along some predefined sections, is used to select the constitutive model that enables a better description of the material mechanical behaviour.

3. Conclusions and Outlook

The Special Issue "Modelling and Simulation of Sheet Metal Forming Processes" presents a collection of research articles covering the relevant topics in the field in innovative ways. The guest editors are aware of the quality of the contributions and hope that this collection of works may be useful to researchers working in the field, promoting more research studies, debates, and discussions that will continue to bridge the gap between physical and virtual reality.

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