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Damage dependent material properties in a Finite Element Simulation of a hybrid forward extrusion process

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Abstract

The occurrence of damage and fracture limits modern forming processes. An example for such a process is the full forward extrusion of steel, where accumulating damage results in characteristic chevron cracks. To prevent chevron cracks, in conventional extrusion, the billet is pre-heated before forming. As an alternative development in a hybrid approach the workpiece is heated resistively, by applying an electric current during extrusion. This results in an inhomogeneous temperature distribution in the workpiece, influenced by the local resistivity of the material, which in turn is dependent both on temperature and damage. While the press force is measured and a cut through the final part gives information on the occurrence of failure, it is not possible to measure local temperatures within the workpiece during forming. Since experimental results show that press force does not significantly change with resi stive heating, numerical methods have to be used to investigate the influence of property changes of the material on the local temperature in the workpiece. In this work a 3D Finite Element Method model using Abaqus/Standard is presented that is capable of simulating the highly nonlinear hybrid forward extrusion process (thermomechanical and electric field) incorporating a remeshing routine. Subsequently, this model is extended to couple a strain based damage with electrical resistivity. Validation is performed by comparisons with experimental results for the conventional cold, pre-heated and hybrid approach. Notably, the results show a significant influence on the temperature distribution in the workpiece for simulations with strain coupling compared to those with unaffected material properties. This in conclusion shows how the presented method of coupling material properties to strain values enables new possibilities to design and optimize complex forming processes.

Keywords: Damage, Hybrid Extrusion, Finite Element Method (FEM)

1. Introduction

Metal forming relies on materials which exert a certain amount of ductility. However, at some point, critical failure occurs and thus limits forming capabilities. A major driver in the damage evolution of steel is the increasing number of dislocations with increasing plastic strain. The dislocations aggregate at inclusions and grain boundaries. In the first phase, this process manifests itself as work hardening on the macroscopic scale. But when a critical stress at those accumulations is exceeded, small voids form. With increasing strain, the small voids grow and coalescence with neighbouring ones, putting even more stress on the yet intact material in-between. Said sections are then prone to necking, ultimately leading to failure [1].

Deformation and resulting fracture are known to alter the electrical resistance of metals. Contributing to this effect is the mentioned growth of dislocation density with plastic strain. This has been quantified for multiple grades of steel [2,3]. With the

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formation of micro fractures and pores, the local resistivity of the material is further increased [4]. Additionally, a direct influence of grain size on resistivity during the process of recrystallization is known [5].

So far, the mentioned observations are applied to monitor wear and fatigue of components in a laboratory environment [6]. Similarly, industrial implementations exist, such as for supervision of oil pipelines [7].

Also with regard to forming processes, the described connection between deformation, damage and electrical properties are of interest. Conductive heating of sheet metal before deep drawing is known to reduce springback and increase formability [8], and the method was further developed to use with spline forming by heating the side walls of a cup conductively before forming [9]. Also, a hybrid incremental forming process was demonstrated, where an electric current was passed through the tool tip into the metal sheet to heat it locally [10].

It becomes apparent that damage, even without macroscopic failure, and resulting effects need to be incorporated into simulations of forming processes to properly optimize them. This study will exert said adaption for a new variant of forward extrusion that has been proposed by Klocke et al. [11]. Here, resistive heating during the extrusion process alters the temperature distribution and material flow in the workpiece. To reproduce this forming process numerically using the Finite Element Method (FEM), the following requirements for the simulation model must be met:

- Solver: coupling of plastic and thermal effects with electrical field equations,
- Material: material properties, especially resistivity, with its dependence on a damage value,
- Discretization (spatial): remeshing because of large deformations.

The purpose of this study is the implementation and validation of a model that fulfils these requirements. The feedback of damage to electro-mechanical material characteristics for use of electro-thermal-mechanical FE analyses has not yet been implemented on large deformation forming processes.

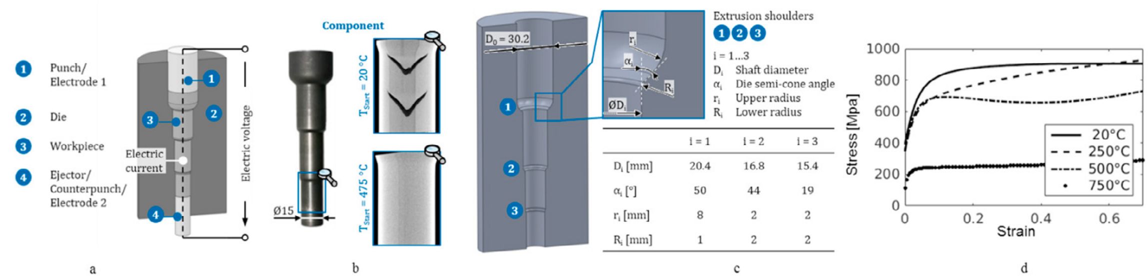

Fig. 1: a) solid forward extrusion process extended with resistive heating b) shape of the formed part and computer tomographic image of cold and warm formed part in the region of extrusion shoulder three c) geometry of the extrusion die (based on [11,15]) d) flow curves for different temperatures at a constant strain rate of 1 s^{-1}

2. Hybridized solid forward extrusion

Hybridized solid forward extrusion is an adaption of conventional solid forward extrusion where a punch presses a metal cylinder through the die. In order to make use of work hardening, conventional solid forward extrusion is often realized as cold forming. Doing so leads to the formation of chevron cracks once the workpiece formability is exceeded. This is due to tensile stresses and occurs on the rotational workpiece axis [12]. The cracks can, for instance, be avoided by increased process temperatures [11]. Figure 1 shows an extruded component made of Cf53 (AISI 1055) where extrusion has to be performed at initial temperatures T_{Start} > 475 °C to thermally avoid chevron cracks [11].

When industrial extrusion is executed at the process limits, chevron cracks usually occur below the last extrusion shoulder, as this is where highest tensile stresses arise. In Fig. 1 b computer tomographic images of a sample with failure and one without are given. This can be counteracted by applying direct current (DC) resistance heating within the forming tool during extrusion. It effectively provides local heating in the area that is prone to develop cracks. Figure 1 a shows the concept of this hybridized process. Punch and ejector are in contact with the workpiece throughout the process and at the same time function as electrodes. The local heating in the area of interest is achieved by passing the electric current through the reduced cross-section, compared with the rest of the workpiece. It also has to be assumed that change in electric resistivity due to a high dislocation density is largest in the region of the third shoulder.

3. FE model

The FE model of hybridized solid forward extrusion, as described in the previous section, is based on a cold solid forward extrusion process and being partially extended. Due to the higher flexibility in terms of adapting the numerical code, the FE software Abaqus is chosen. The implicit solver is used because of the suitability for quasi-static problems such as extrusion.

The die is modelled as discrete rigid with the geometry according to Fig. 1 c. It is discretized using 63248 three dimensional triangular three-node elements (R3D3). The punch is modelled as analytical rigid. The workpiece made of Cf53 has an initial diameter $D_0 = 30$ mm and an initial height $h_0 = 54$ mm. Making use of rotational symmetry, one quarter of the workpiece is modelled. Modelling the workpiece axial symmetrical is not suitable because the electric solver needs a volume to perform the calculation. It is initially discretized by 3456 hexahedral eight-node trilinear elements for displacement, electric potential and temperature (Q3D8). While the number of elements is constant for the tool, due to remeshing it changes for the workpiece (approx. 22000 elements at the end of the simulation).

The Cf53 workpiece material is modelled using temperature-dependent flow curves which are derived from cylinder upsetting tests with frictionless Rastegaev specimens up to logarithmic strains of $\varphi = 0.7$ at the Institute of Metal Forming (IBF) (Fig. 1 d). Beyond the effective true strains reached in the cylinder upsetting tests, an ideal-plastic material behaviour is assumed. Heat conductivity λ ($\lambda_{T=20°C} = 47.39$ W/mK, $\lambda_{T=800°C} = 23.42$ W/mK), thermal expansion α_{exp} ($\alpha_{exp,T=20°C} = 10.80$ K^{-1}, $\alpha_{exp,T=800°C} = 13.20$ K^{-1}), mass density ρ ($\rho_{T=20°C} = 7.8161$ t/m^3, $\rho_{T=800°C} = 7.5685$ t/m^3), the Young's modulus E (E = 210 GPa) and Poisson's ratio ν ($\nu = 0.3$) are modelled following temperature dependent standard values [13,14]. The joule heat fraction is modelled with 1.0 and the dissipation due to plastic flow as 0.9.

A time-dependent velocity profile v(t) is defined for the punch as mechanical boundary condition. It corresponds with the profile which was experimentally measured in the past at the Laboratory for Machine Tools and Production Engineering (WZL) for the three-shouldered extrusion process. The profile was published in [15]. A hard contact is modelled in normal direction. Tangentially friction is implemented as penalty formulation with a Coulomb friction coefficient $\mu = 0.03$ for the cold conditions and $\mu = 0.05$ for the pre heated sample, which are in a normal range for lubricated extrusion processes [16]. Heat transfer between the workpiece and the tool components is modelled using a Neumann boundary condition with a constant coefficient of $\alpha_{con} = 6$ mW/(mm^2·K), representing a standard value according to [17-19].

Since large deformation in FE-analyses results in a distorted mesh, the mesh must be renewed. A reference implementation [20] providing this functionality is used. The maximum allowable volume difference in between the deformed and new mesh is set to 0.1 %. After each remeshing the Abaqus/Standard solution mapping facility is used to transfer the field variables onto the new mesh.

The model is then extended by means of DC resistance heating, using the coupled thermal-electrical-structural analysis in Abaqus/Standard. The electrical conductivity is set to $5.2 \cdot 10^6$ $(\Omega m)^{-1}$ at room temperature [14]. There is no valid data available in literature over a wide range of temperatures. Therefore, an extrapolated value of $1.2 \cdot 10^6$ $(\Omega m)^{-1}$ at 600 °C is assumed. An electric current I then is passed through the workpiece according to Fig. 1 a.

4. Strain dependent resistivity

Algorithm packages and programs do exist for aforementioned thermomechanical-electrical field equations, however there are restrictions to value-dependent material properties. Many commercial FE codes provide the possibility to simply define material properties dependent on temperature, strain or strain rate. If other interrelationships are of interest, user defined materials may be implemented using subroutines, like the user defined material (UMAT) in Abaqus. However, the complexity of implementing and testing such routines should not be underestimated. As a simpler alternative, here, the Abaqus user defined field (USDFLD) subroutine is adopted to calculate additional fields that can be used by standard functions to manipulate material properties. This approach deemed successful for a sheet metal forming process, where the elastic modulus was made dependent on the plastic strain [21]. Similarly, an input like the resistivity of the material can be specified as a function of calculated fields, such as a damage value or plastic strain.

As stated previously, work hardening goes along with an increase in dislocation density [1], which in turn changes the local resistivity of steels [5]. This connection is now used in the simulations performed for the hybrid extrusion process presented in section 2. Based on the observation of a nearly linear [2] correlation between strain and normalized resistivity is extrapolated linearly up to a logarithmic strain of $\varphi = 3.5$ (maximum strain in the third extrusion shoulder). This leads to strain correlated conductivity values of $1.4 \cdot 10^6$ $(\Omega m)^{-1}$ for the deformed state at room temperature and correspondingly to $0.4 \cdot 10^6$ $(\Omega m)^{-1}$ at 600 °C. It must be noted that the interrelationship between strain and local resistivity is still under research. Therefore, here calculated numerical results will only allow for a qualitative interpretation. Despite the indicated limitation, the purpose of this paper of discussing innovative process models incorporating material interdependencies remains. A quantitative analysis of the results requires a more precise determination and characterization of the above mentioned alloy properties and microstructural states.

5. Results and validation

The FE model presented in section 3 is highly nonlinear due to its numerous properties and boundary conditions. A simple technique to validate the model, which has been proposed before in [15], is the comparison of punch force.

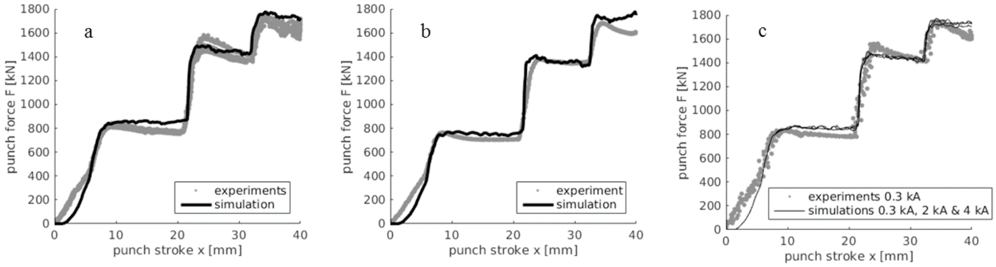

Fig. 2: Comparison of measured and simulated punch forces for (a) cold (b) pre-heated to 450°C and (c) hybrid condition

Forces predicted by the simulation are shown together with the corresponding measured forces from experiments for the cold, pre-heated and hybrid condition in Fig. 2. Measured and experimentally determined forces show a favorable agreement. The good match of the rising force at each shoulder at nearly the same punch stroke in experiment and simulation is an indication of a properly implemented remeshing-procedure and volume loss is negligible. A total of up to 15 remeshing operations are performed in each of the simulations and the total calculation time is below 12 h on a standard workstation. Because elastic properties of the tools are not modelled, deviations are observed in the beginning of all tests from 0 mm to 6 mm punch stroke.

Notably, there is nearly no variance between simulated punch forces in the hybrid process for different currents I. Even in the third extrusion shoulder no significant changes in force among the simulations with I = 0.3 kA and I = 4 kA are observed, despite unequal local temperatures. This can be explained by the fact that the simulated material Cf53 shows a blue brittleness at a temperature of approx. 250 °C which is implicitly considered by the experimentally determined flow curves. The phenomenon results in higher flow stresses and less ductility up to a temperature of 400 °C.

In Fig. 3 a-c the computed temperatures are shown as contour plots for the cold, fully coupled (strain feedback, I = 4 kA) and pre-heated workpiece simulations. Additionally, the temperature along the core is plotted for different currents with and without strain coupling as well as for the pre-heated condition in Fig. 3 d. It can be observed that in the vulnerable region of the third extrusion shoulder, where fracture is most likely to develop, the strain feedback on the electrical resistivity has a notable influence on the calculated core temperature of the workpiece as well as on the temperature distribution. This reflects the assumption of the process design for hybrid extrusion that the resistive heating influences the temperature distribution mostly in the third extrusion shoulder. Taking the coupling of resistivity to strain into account the simulations show that a potential material interrelationship cannot be neglected in the process model. As mentioned in section 4 these observations cannot be accurately quantified at this time due to extrapolated material properties regarding resistivity. In a previous study [11] it has been shown that the occurrence of chevrons is highly temperature dependent. Although the simulations for I = 2 kA and I = 4 kA have not yet been experimentally validated, it can be assumed that the prediction abilities to further develop the hybrid approach is extended with the presented model.

Notable is the case of I = 4 kA electric current, where the dissipated heat due to joule heating outweighs the heat flux into the tool. This results in a significant influence of the local resistivity and the strain dependent and independent simulations show considerable differences in the maximum core temperature as shown in Fig. 3 c. Based on this simulation-based knowledge, the process can be optimized towards minimal energy consumption or also other tool concepts incorporating an optimized heat flux.

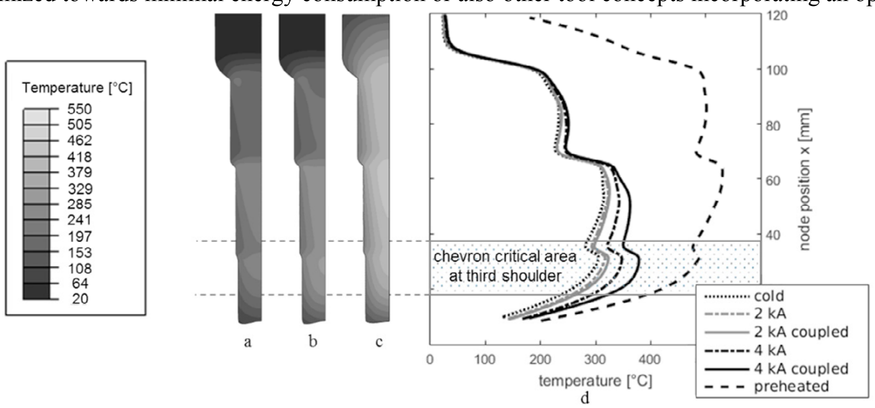

Fig. 3: Comparison of the simulated temperature field for (a) cold, (b) 4 kA sample with strain feedback, (c) the pre-heated samples after the process and (d) temperatures for different conditions along the core

6. Conclusion

Innovative hybrid forming processes demand for new methods and implementations of FE models to accurately simulate and optimize them. One application is the interrelationship of strain and damage to material properties like the local electrical resistivity. To investigate the necessity of implementing such interrelationships, a conventional solid forward extrusion process was modelled and later extended with DC resistance heating. This included a strong coupling between plastic strain and local resistivity of the steel that was used. Experiments do not show significant changes in the punch force for various processing conditions. This behaviour is reproduced by the presented model. At the same time, the simulations of resistively heated samples show different local temperatures at the end of the process for the coupled and uncoupled approach. For high electric currents, significant differences in the temperature distribution between constant and strain dependent material properties could be predicted.

In a future work, the material interrelationship could be extended to a suitable damage criterion like the Cockroft-Latham criterion to investigate the effect of damage dependent material parameters on the probability of failure in the hybrid extrusion process.

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