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Experimental and numerical investigation of increased formability in combined quasi-static and high-speed forming processes

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ABSTRACT

The formability of deep drawing can be extended by combining it with a subsequent high-speed forming method such as electromagnetic forming. However, up to now, no sufficient systematic understanding of the underlying principles or of a successful design of such coupled processes has been gained. Hence, in this work, a methodology for the analysis and design of such process chains is presented. This approach comprises a new method for the experimentally based determination of quasi-static and high-speed forming limits along close to proportional strain paths, a constitutive visco-plastic, anisotropic material model with a rate dependent ductile damage formulation, which allows for the accurate numerical prediction of forming limits for complicated forming operations under a largely varying strain rate, and finally the actual application of both to a combined quasi-static and high-speed forming operation. In doing so, material areas are identified that are deep drawn up to a degree immediately before necking occurs and then electromagnetically be formed beyond the quasi-static forming limit without damage. This proves that an extension of formability is here achieved due to a change in strain rate rather than in the strain path.

1. Introduction

The strain rate sensitivity of certain classes of materials in terms of an increased forming limit under high strain rate forming was firstly reported by Clark and Wood (1950). Due to this peculiarity, high-speed forming processes appear as a suitable approach to overcome the limitations of quasi-static forming: Extended forming limits lead to an increased freedom of design and, consequently, allow for producing parts with a more complex geometry, such as, e.g., sharp corners or other intricate features. With regard to process control, efficiency, and reduction of production costs, a sequential combination of quasi-static and high-speed forming operations is the most promising implementation of high-speed forming techniques. In this case, the conventional quasi-static forming step is used to produce a preformed geometry. Subsequently, parts of the workpiece with critical geometry features requiring strain beyond the quasi-static forming limits are treated by a high-speed process. Electromagnetic forming is an appropriate candidate for such a process combination, since the required tool coils can efficiently be integrated in a classical forming setup, such as, e.g., provided by deep drawing. However, it has been shown that an actual extension of quasi-static forming limits requires a careful adjustment of the parameters of both processes (cf., e.g., Taebi et al., 2012). This indicates the importance of a systematic scientific understanding of process depending forming limits for the design of suitable industrial process chains to accomplish challenging forming tasks. In this work, three building blocks of a corresponding methodological base are provided: a new measurement facility for the determination of quasi-static and high-speed forming limits along close to proportional strain paths, that are similar in the quasi-static and in the high-speed case, a precise numerical model allowing for accurate prediction of forming limits for complicated forming operations under a largely varying strain rate, and finally the actual application of both to a combined quasi-static and high-speed forming operation. The experimental contribution will allow for an extension of the concept of a forming limit curve (FLC) to high-speed

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processes. The required close to proportional high-speed strain paths are guaranteed by equivalent geometric conditions during quasi-static and high-speed testing as well as by consideration of the requirements of established industry standards. The pragmatic application of FLCs for the design of forming operations including high-speed methods will certainly suffer from the same problems known in the quasi-static case: it has to be clarified if the strain paths of the particular process of interest are sufficiently close to proportional strain paths to permit a reliable prediction of forming limits. To clarify this question exemplarily for a particular process chain is part of this work. The presented numerical model is based on a constitutive material model that accounts for a number of effects particular important for damage evolution in combined forming processes with strain rate sensitive, anisotropic materials at a largely varying strain rate. To reliably identify the relatively large number of parameters of the material model, an accurate and efficient mathematical optimization scheme is also provided in this work. Next, the state of the art in the relevant fields of research is documented.

1.1. High strain rate forming limits

Under favorable conditions, the forming limits of metals can be increased by a factor of two or more by a high strain rate processes, as shown by Wood (1967). Correspondingly, Balanethiram and Daehn (1992) present an increase of the forming limit in the biaxial stretch region by a factor larger than two for steel. Similar results for aluminum and copper have been reported in Balanethiram and Daehn (1994). The mechanisms leading to increased formability at high strain rates are still a matter of discussion. Seth et al. (2005) attribute this effect to inertial stabilization with additional support due to compressive stresses resulting from the impact of the tested sheet on the die. While some other researchers like Gerdooei and Dariani (2008) also assume that inertial effects stabilize the neck growth in the specimens, Hadianfard et al. (2008) refer to effects caused by a modified strain rate sensitivity after a material dependent threshold rate has been reached. Further, Tucker et al. (2010) assume an additional variation of the stress state as necking progresses, reinforcing effects resulting from the material's strain rate sensitivity. The strain rate compressive behavior of Alulight and Duocel aluminum alloy foams has been investigated by Deshpande and Fleck (2000) in the range of $10^{-3}\,\mathrm{s}^{-1}$ to $5000\,\mathrm{s}^{-1}$. No elevation of the dynamic stress versus strain curves has been observed compared to the corresponding quasi-static curves. The principal connection between damage and strain rate sensitivity has already been studied in an earlier work by Hutchinson and Neale (1977). There, a nonlinear long-wavelength model is established in order to estimate the correlation of strain rate dependence and necking retardation for a cylindrical bar subject to uniaxial loading. The authors also emphasize the significance of the correlation between the attainable strain states and corresponding changes in the three-dimensional stress distribution during necking. Their analytical approach has been transferred to different forming scenarios, e.g., cladding processes, using strain rate sensitive layer materials by Hu et al. (2014). Fressengeas and Molinari (1985) extend Hutchinson's model by including inertial and thermal effects. Hutchinson and Neale (1978) also discuss the connection between a material's degree of strain rate dependence and theoretically determined forming limits for biaxially stretched sheets. TEM investigations by Huh et al. (2009) reporting on modifications of dislocation structures at higher strain rates support the relation between increasing strain rate sensitivity and retarded damage evolution.

Except for the undecided theoretical discussion, the allocation of relevant experimental data is also a serious problem: Up to now, no satisfactory test methods to determine forming limit diagrams at high strain rates according to industrial standards, such as DIN EN ISO 12004-2, are available. Kiliclar et al. (2011) use a drop tower testing device for the investigation of aluminum sheet metal specimens of different widths to represent various possible stress and strain levels. In Kiliclar et al. (2012), the investigations are extended by a high-speed crash testing machine. With both methods a maximum punch speed of $10\,\mathrm{m\,s}^{-1}$ has been reached. Although the test setups have proven to be principally suitable to predict dynamic forming limit curves for the tested materials, the achieved maximum strain rates of approximately $10^{2}\,\mathrm{s}^{-1}$ are not sufficient to achieve a state of increased formability. With experiments using electro-hydraulic forming, Rohatgi et al. (2011) could reach higher strain rates. To achieve strain rates in the range from $2500\,\mathrm{s}^{-1}$ to $2800\,\mathrm{s}^{-1}$, Chu et al. (2012) use an electromagnetic punch stretch test. Yasar et al. (2006) reported that the velocities of the shock waves in their detonation forming tests lie between $2500\,\mathrm{s}^{-1}$ and $2800\,\mathrm{s}^{-1}$. However, none of these test methods works with a defined strain path, can guarantee proportional loading, or is strictly reproducible. Particularly, the deformation achieved cannot be standardized or directly compared to quasi-static results.

1.2. Deep drawing followed by electromagnetic forming

Vohnout (1998) proposed to combine deep drawing with electromagnetic forming: At first, a part is formed at a large-scale by deep drawing, while fine details are produced by a subsequent electromagnetic forming step. Psyk et al. (2007) and Risch et al. (2008) have implemented this idea by embedding electromagnetic tool coils into a drawing punch or die. The advantage of such a process combination is demonstrated by Liu et al. (2009): Initially verifying that by a sole deep drawing process under defined conditions cups with a minimum edge radius of 8 mm can be produced, they subsequently apply an electromagnetic forming operation and observe that the edge radius can be decreased to 5 mm without failure. This proves that this process combination provides a larger design space for forming operations than a single deep drawing operation. However, since the evolution of strains has not been studied, it cannot be concluded that this improvement is actually caused by exceeding quasi-static forming limits. In contrast, strain measurements by Imbert and Worswick (2011) carried out in connection with the experiments showed that all strain values achieved in the final product remain below the quasi-static FLC. In their experiments, they formed sheet bands made of AA5754 quasi-statically with a V-shaped punch achieving a minimum edge radius of 20 mm. Subsequent electromagnetic forming reduced the radius to 5 mm without failure. The authors attribute the improved design space obtained by the process combination to a better strain distribution. Moreover, since no data on material damage for high strain rates is given for the employed material, it is not clear whether the material possesses a distinctive strain rate sensitivity at all. If the latter is true, it would underpin the conclusions drawn by Imbert and Worswick (2011), but the question whether the quasi-static forming limits can be exceeded by the above mentioned process combination for strain rate sensitive material would remain open.

1.3. Material and damage modelling of metals

From the point of view of constitutive material modelling, an anisotropic viscoplastic material model accounting for nonlinear kinematic, isotropic hardening, and damage is relevant for a metallic work piece undergoing a forming process at strongly varying strain rates with possibly nonlinear strain paths. Hence, in order to consider pressure sensitive metals, Yoon et al. (2014) suggested an asymmetric yield function, which extended classical $J2$-plasticity by also including the third deviatoric stress invariant in the Lode parameter. Further anisotropic effects are incorporated by two fourth order linear transformation tensors depending on the second