LARGE STRAIN FLOW CURVE IDENTIFICATION FOR JOINING BY FORMING OF SHEET METAL

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Abstract

Joining by forming of sheet metal implies local severe plastic deformation of the sheet metal. The forming process can be optimized with the aid of numerical simulations provided that an accurate large strain flow curve of the material is available. In this paper, the requirements for identifying large strain flow curves are scrutinized. To this end, numerical stress state analysis for the mechanical joining is performed. The aim is to use the latter information to select candidate material tests including novel inverse procedures to determine the post-necking strain hardening behaviour of sheet metal. Flow curves of DC04 obtained through the homogeneous stack compression test, the strain rate controlled hydraulic bulge test and the post-necking tensile experiment are compared.

1. Introduction

The predictive accuracy of finite element simulations for joining by forming (e.g. clinching, self-pierce riveting, etc.) of sheet metal largely depends on the adopted material model. In general, joining by forming processes generate severe local plastic deformation of the sheet metal. Moreover, due to the small dimensions of the forming tools (e.g. punch or rivet) compared to the nominal sheet thickness, joining by forming processes of sheet metal must be regarded as a bulk forming problem. The crux of the problem is that the plastic material behavior of sheet metal is conventionally determined using material tests which are confined to homogeneous plane stress conditions. In addition, conventional sheet metal material tests are of limited usefulness because necking limits uniform deformation while true plastic strains of 2-3 are generated in joining by forming processes. During joining by forming of sheet metal a multitude of stress states is generated accompanied with large plastic straining of the material. From a simulation point of view, however, plastic anisotropy of the sheet metal can be safely ignored for predicting the metal flow. Indeed, the metal flow is strongly constrained by the joining tools preventing plastic anisotropy to manifest itself at the length scale of the joint. As such, joining by forming is usually simulated assuming a von Mises material solely requiring a large strain flow curve to account for strain hardening. As sheet metal itself often exhibits plastic anisotropy, however, it is crucial to identify the flow curve using a material test which generates a stress state resembling the dominating stress state during the joining by forming process. To this end, this paper scrutinizes the objective requirements for accurate flow curve determination in joining by forming.

2. Stress state analysis

If the material exhibits plastic anisotropy, it is important to calibrate the von Mises yield criterion to a stress state which dominates the joining process. The latter procedure can be regarded as stress state fitting, and, consequently, selection of a proper material test requires a stress state analysis. Since the deformation is complex, numerical simulation is used for the stress state analysis. The left side of Figure 1 shows finite element simulations of clinching and self-pierce riveting with semi-tubular rivet (SPR-ST) in the final process stage. It can be seen, that in the sheets through clinching equivalent plastic strains around 2 and for SPR even above 3 occur.

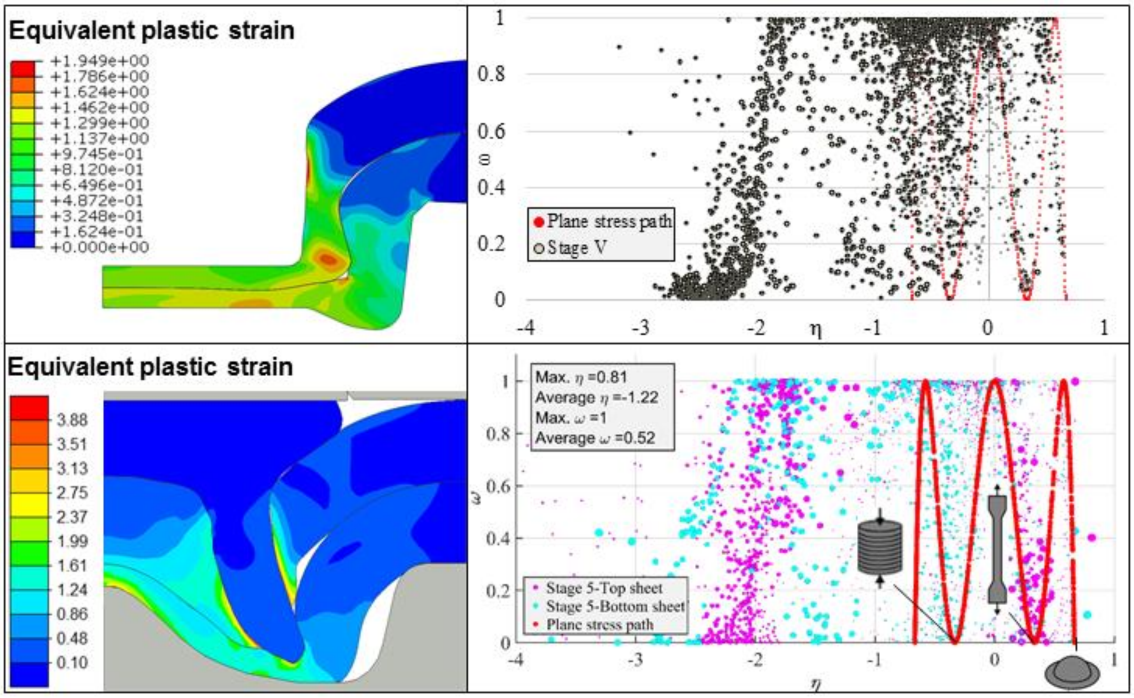

Figure 1. Stress state analysis in clinching and self-pierce riveting of DC04-DC04 in the final process stage (left :Joint contour; right: $\omega - \eta$ diagram)

A 3D stress state can be unambiguously described by the Lode angle ξ and the triaxiality η [1]. The right side of Figure 1 shows all plastically deforming material points (bubbles) in the final process stage in the (ω - η)-diagram, where the stress metric ω is defined as $\omega = 1 - \xi^2$. For shear-dominated stress states ω equals 1, while for axisymmetric stress states ω equals 0. The size of the bubbles in the (ω - η)-diagram corresponds to the magnitude of the equivalent plastic strain in the considered material point. The red curve shown in the panel is the so-called *plane stress path* derived from the plane stress von Mises yield locus. Material points lying on this path exhibit a plane stress condition which can be probed using a sheet metal material test. Material points which deviate from the plane stress path are subjected to a 3D stress state. It can be inferred from the (ω - η)-diagrams in Figure 1 that through both processes a variety a stress states occur in the sheets. Thereby the upper sheets are partly shear-dominated with some regions subjected to axial tensile stresses and the lower sheets are mostly overlaid by axisymmetric compression stresses.

3. Large strain flow curve identification

The stress state analysis suggests that, if the sheet metal exhibits plastic anisotropy, the lower sheet should be characterized using a material test which induces an axisymmetric stress state (assuming symmetry between tension and compression) with $\eta < -2$ and $\varepsilon_{eq}^{pl} \approx 3$. Obviously, there is no sheet metal test available for the latter conditions. In this section, three material tests dominated by an axisymmetric stress state are used to determine the large strain flow curve of DC04 sheet with a nominal thickness of 1 mm and an average r-value of r_{avg}=1.64. A quasi-static tensile test in Rolling Direction (RD) was conducted on a standard tensile machine with a load capacity of 10 kN. The pre-necking strain hardening (labelled *Tensile Test (RD)*) is shown in Figure 2. Additionally, the tensile machine was equipped with a stereo Digital Image Correlation (DIC) system to measure the full-field displacements fields within the diffuse neck during a quasi-static Post-Necking Tensile Experiment (PNTE). The energy method [3] was used to inversely identify Swift's hardening law using 124 load steps. The dashed red curve shown in Figure 2 is the resulting PNTE-flow curve. It has been shown that the energy method [3] extends the validity of the standard tensile test. More importantly, it enables to enhance the fitting quality of phenomenological hardening laws in the post-necking regime. For ductile metal sheet, the PNTE enables to probe an equivalent plastic strain in the order of 0.7 to 1 under a positive triaxiality ($\eta = \frac{1}{3}$). The hydraulic bulge test (HBT) enables to probe large plastic strains under a positive triaxialty ($\eta = \frac{2}{3}$) and balanced biaxial tension. The solid red curve shows the flow curve measured using the strain-controlled HBT. It can be inferred that the flow curves obtained by the uniaxial tensile test and the HBT differ in absolute stress level which is a typical observation for low carbon steel sheet with $r_{avg} > 1.5$ exhibiting differential work hardening [4]. Deep into the post-necking regime, the PNTE-flow curve exhibits slightly more strain hardening than the flow curve determined using the HBT.

The stack compression test (SCT) [2] is an axisymmetric test enabling to probe large plastic strains under a negative triaxialty ($\eta = -\frac{1}{3}$). In terms of stress state, the SCT is equivalent to the HBT provided that symmetry between biaxial compression and tension can be assumed. The SCT was carried out on a electro-mechanical press with a maximum press force of 100 kN using 3 or 4 disks of the DC04. Lubrication was applied to minimize the effect of friction. The orange circles in Figure 2 show the experimentally acquired flow curve using the SCT. It can be inferred that for $\varepsilon_{eq}^{pl} < 0.1$ identical flow curves are obtained through SCT and HBT. Beyond that point, however, the HBT-flow curve exhibits less strain hardening than the SCT-flow curve. It must be noted that in the post-necking regime, the SCT-flow curve exhibits a similar strain hardening rate as the PNTE-flow curve. The discrepancy between the flow curves obtained through the HBT and the SCT suggests that the hydrostatic stress component affects the flow stress.

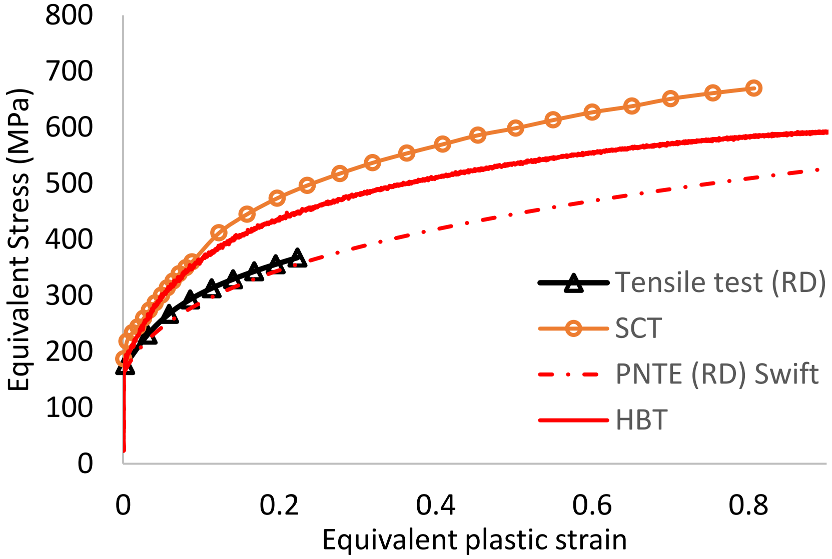

Figure 2. Identified flow curves for DC04

5. Conclusions

The paper presents a strategy for identifying large strain flow curves for simulation of joining by forming. Stress state analysis for clinch forming and SPR-ST is performed and used to select candidate material tests. Three material tests are used to identify the large strain flow curve of DC04. Further research is required to understand the different post-necking strain hardening behavior identified using the stack compression test and the hydraulic bulge test. Future work will embark on the assessment of the most appropriate material test for simulating clinch forming and SPR-ST.

6. References

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