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Utilization of damage controlled forming processes - a case study on the design of airbag pressure bins

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Abstract

In order to benefit from damage-controlled forming processes in terms of high-performance lightweight components with known safety margins, a new design strategy is suggested that is based on the application of probabilistic safety concepts. Since we postulate that damage-controlled forming processes will lead to a significantly reduced scatter of critical loads, we can derive significantly reduced safety factors without changing the component´s geometry. Demonstration of the underlying strategy in a case study on airbag pressure bins will quantitatively reveal the possible utilization of damage-controlled forming processes.

Keywords: Damage in metal forming, Design strategy based on probabilistic safety concepts, Design of airbag pressure bins.

1. Introduction

The concept of damage-controlled forming processes aims to reduce ductile damage evolution during forming by influencing the load paths. This should make it possible to design components of the same geometry, but of higher performance. In contrast to conventionally produced components, the new ones from damage-controlled forming processes are characterized by a known safety reserve. In recent years, damage-controlled process variants have been researched both for the production of semi-finished products and for their processing into components. Examples of this include, among others, hot and cold rolling, extrusion, bending, deep drawing and roll forming [1], [2], [3]. Now that the fundamental feasibility of damage-controlled forming processes has been demonstrated, the question arises as to how these can be taken into account in component design, because only then will the efforts to control damage during forming of components also pay off in the form of higher performance and thus greater lightweight construction potential. Therefore, in the subsequent chapters it will be shown how the consideration of damage control during forming can be achieved with the help of probabilistic safety concepts. Moreover, a case study on the design of airbag pressure bins will serve as a first demonstrator for the new concept.

2. Options to consider damage-controlled forming processes in component design

The general idea of probabilistic safety concepts is to consider that both the loading conditions of the to-be-designed component as well as material´s resistance are uncertain. Fig. 1 shows that hence, for both the loading conditions (e.g. the applied inner pressure of an airbag bin or the applied cyclic stress amplitude of a component experiencing fatigue loads) and the corresponding resistance (e.g. burst pressure in the first

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or endurance fatigue strength in the latter case), distribution functions have to be plotted. Noteworthy, the resistance distribution functions strongly depend on the selected manufacturing route, because the evolution of forming-induced damage strongly depends on the conditions of forming. Therefore, the "effective resistance" covers all individual distribution functions. Its determination is usually based on experimental investigations.

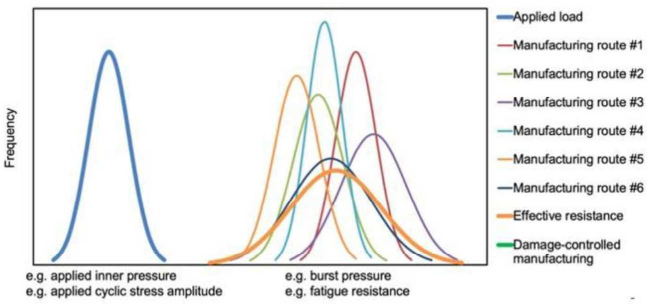

Fig. 1: Distribution functions of applied loads and resistance for different component manufacturing routes.

Preliminary work on the development of damage-controlled forming processes has already revealed that a major reason for the scatter of the critical load can be the scatter of the forming-induced damage. Furthermore, it has also been concluded that damage-controlled forming processes lead to a significantly reduced scatter of damage. Hence, Fig. 2 shows that there is a pronounced shift between the previously shown effective resistance and the resistance curve for the damage-controlled forming processes. Consequently, there is a remarkable additional and quantifiable safety margin on top of the indicated desired safety. It can be decomposed into one contribution resulting from the shift of the peak values towards higher resistance values and another contribution resulting from the significantly reduced scatter width.

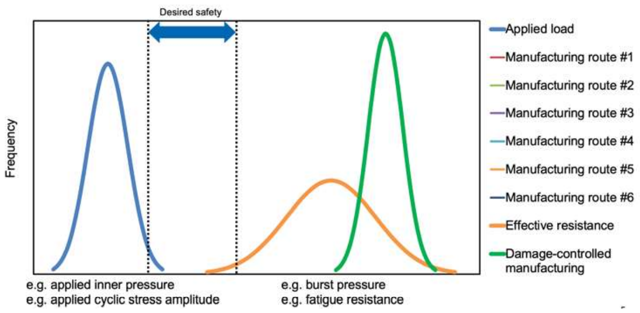

Fig. 2: Distribution functions of applied loads and resistance for different component manufacturing routes and damage-controlled manufacturing routes.

After quantifying the depicted curves, the additional safety margin can be exploited for weight reduction without taking the risk of reducing the desired safety margin. This will be the final step towards exploiting the potential of damage-controlled forming processes.

3. Case study on airbag pressure bins

Experimental foundation

In an airbag gas generator, a small pyrotechnic charge triggers a chemical reaction to produce the gas for the inflation of the airbag. This exerts highly dynamic loads on the housing of the gas generator, which is commonly cold forged. The ability of the part to withstand these loads highly depends on the material properties after forming, i.e. work hardening, residual stresses and damage state. The nucleation, growth and coalescence of voids during forming depends on stress states in the forming zone. Hydrostatic tensile stresses, characterized by positive triaxialities, promote damage evolution [4], while compressive stresses can also reduce void volume [5]. Ductile damage is not only the cause of macroscopic fracture but does also reduce the material's impact toughness [6].

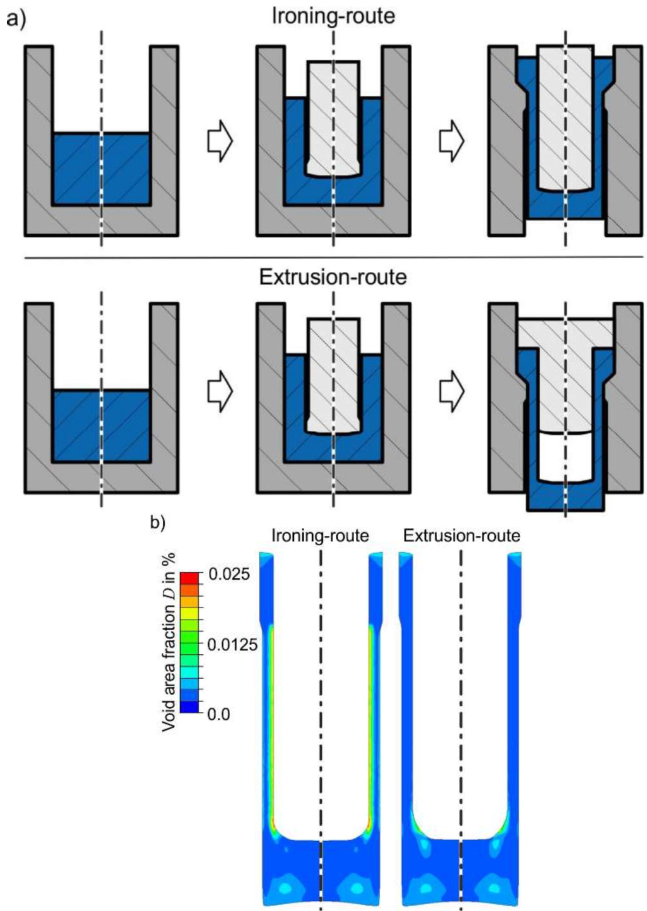

Fig. 3: a) Cold forging of pressure vessels by backward can extrusion followed by either ironing or forward hollow extrusion and b) predicted damage evolution.

Accordingly, a reduction of forming-induced damage results in higher performance of produced parts [7]. This can be achieved either by adjusting process parameters or by choosing alternative process sequences in multi-stage forming processes. For demonstration, a pressure bin as used in an airbag gas generator is cold forged by a sequence of can extrusion and ironing as well as can extrusion and hollow extrusion.

The pressure bins are made from a cylindrical billet of the case hardening steel 16MnCrS5. The chemical composition is listed in table 1. The microstructure of the material consists of a ferritic matrix with perlite and manganese sulphide inclusions. These inclusions often lead to damage initiation, either by fracturing or by delamination at the matrix-inclusion interface [8]. Using quasistatic tensile tests at room temperature, the yield strength $R_{p0,2}$ was determined 310.2 ± 1.92, while the ultimate strength is 498.2 ± 2.52

First, a can with an outer diameter of 30 mm and an inner diameter of 13.4 mm by backward can extrusion is formed. In a second step, the outer diameter of the can is reduced to 28.5 mm, either by ironing or forward hollow extrusion (Fig. 3a). Both routes result in the same product geometry. The damage evolution in both routes is determined using the uncoupled damage model described in [9]. The model is implemented as a user subroutine in the FEM code Simufact Forming 15.0. To handle the severe deformation in backward can extrusion automatic re-meshing is utilized. The workpiece is modelled by von Mises plasticity with isotropic hardening. The hardening behavior is obtained by upsetting tests at 20°C, 200°C and 400°C.

Table 1. Prescribed chemical composition

C	Si	Mn	S	Cr
0.14-0.19	0.4	1.0-1.3	0.02-0.04	0.8-1.1

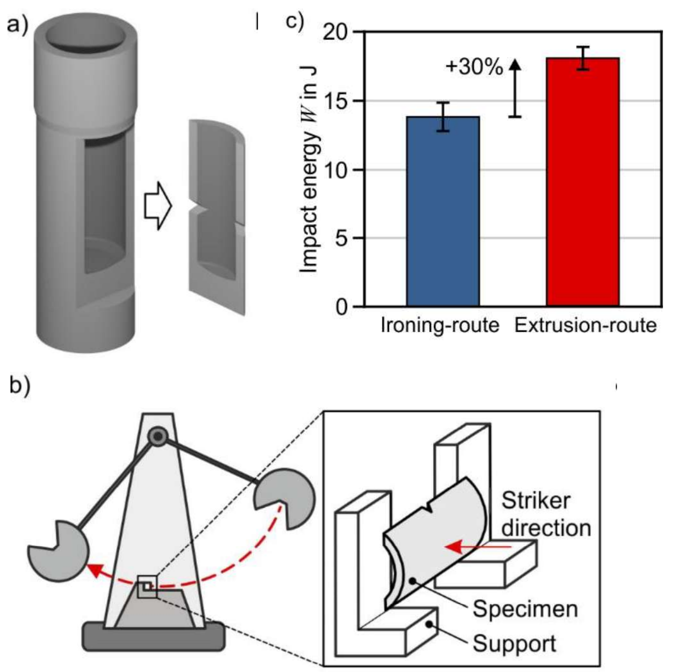

Fig. 4: a) extraction and b) testing of non-standard Charpy specimen from pressure vessels and b) resulting impact energies.

Due to the thin-walled geometry of the pressure bin the wall area is considered most crucial in case of pressure loading. In the ironing-route, larger void area fractions are observed in the wall-area (Fig.3b). To test the performance of the vessels under dynamic loads like the pyrotechnic charge in gas generators, a non-standard Charpy impact specimen is cut from the vessels (Fig. 4a) and tested on a Charpy hammer (Fig. 4b). Due to less forming induced damage, the bins forged via the hollow extrusion route show 30% higher absorbed impact energy (Fig. 4c). The increased impact toughness correlates well with the determined void area fraction, demonstrating the validity of the model.

Modelling the damage behavior

A major requirement for the application of probabilistic safety concepts is the availability of a sufficient amount of data indicating the component´s resistance against fracture. Hence, it would be logical to perform huge amounts of burst tests on airbag pressure bins produced by damage-controlled forming processes. However, due to the high costs of such tests and their technical complexity, alternatives are required. A solution can be to replace the experimental investigations with their numerical simulation with damage mechanics approaches. The used model is a coupled damage mechanics model which integrates the damage variable D into the yield potential (1). It is known as the Modified Bai-Wierzbicki (MBW) Model and was developed at the IBF based on the work of Bai and Wierzbicki [10], [11].

$$\sigma_{yld} = \bar{\sigma}(\bar{\varepsilon}_p)(1-D) \tag{1}$$

Indicator functions are used for damage initiation and failure, which are defined according to equation (2). (The equations for ductile damage initiation are analogous and are therefore not shown here). η_{avg} is the averaged stress triaxiality and $\bar{\theta}_{avg}$ the averaged normalized lode angle parameter.

$$I_{df} = \int_{\bar{\varepsilon}_{df}^{p,c}}^{\bar{\varepsilon}_p} \frac{d\bar{\varepsilon}_p}{\bar{\varepsilon}_{df}^{p}(\eta_{avg},\bar{\theta}_{avg})} \tag{2}$$

The plastic strain at failure is thresholded by a cut-off stress triaxiality $\eta_c = -1/3$ (3). This reflects the fact that no fracture happens under compressive strains [12]. If $\eta_{avg} > \eta_c$ the plastic strain is defined according to equation (4) and is depending on the stress triaxiality and Lode angle parameter. The parameters F_{1-4} are fitted based on experiments showing different stress states.

$$\bar{\varepsilon}_{df}^{p}(\eta_{avg},\bar{\theta}_{avg}) = \begin{cases} +\infty & for\ \eta_{avg} \leq \eta_c \\ f_{df}(\eta_{avg},\bar{\theta}_{avg}) & for\ \eta_{avg} > \eta_c \end{cases} \tag{3}$$

$$f_{df}(\eta_{avg},\bar{\theta}_{avg}) = (F_1 e^{F_2\eta} - F_3 e^{-F_4\eta})\bar{\theta}^2 + F_3 e^{-F_4\eta} \tag{4}$$

Based on this, the damage variable D can be defined (5). G_f is a parameter controlling the degree of degradation of the mechanical properties and is also calculated based on experimental data.

$$D = \begin{cases} 0 & for\ I_{ddi} < 1 \\ \frac{\bar{\sigma}_{ddi}^{c}}{G_f}(\bar{\varepsilon}_{df}^{p} - \bar{\varepsilon}_{ddi}^{p}) \cdot I_{df} & for\ I_{ddi} \geq 1 \wedge I_{df} < 1 \\ 1 & for\ I_{ddi} \geq 1 \wedge I_{df} \geq 1 \end{cases} \tag{5}$$

It should be noted that only the ductile fracture locus (DFL) is calibrated in this study, the ductile damage initiation (DDI) is kept constant.

For the model calibration, Charpy samples were taken out of the different airbag bins, and Fig. 5 reveals that there are remarkable differences between the individual load-deflection curves measured during the instrumented Charpy tests, with the green shaded area indicating the region into which the individual curves of all tests have fallen.

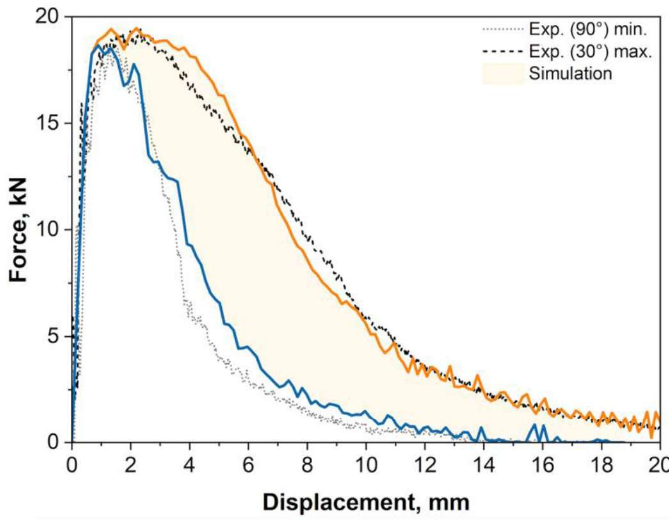

Fig. 5: Load-deflection curves of instrumented Charpy tests on samples from airbag pressure bins. The green shaded area indicates the region into which the individual curves of all tested samples have fallen.

For each of those tests, the corresponding failure criteria must be calibrated in order to be able to express the scatter of the burst pressures. Fig. 6 reveals the range into which the failure criteria for the different samples have fallen.

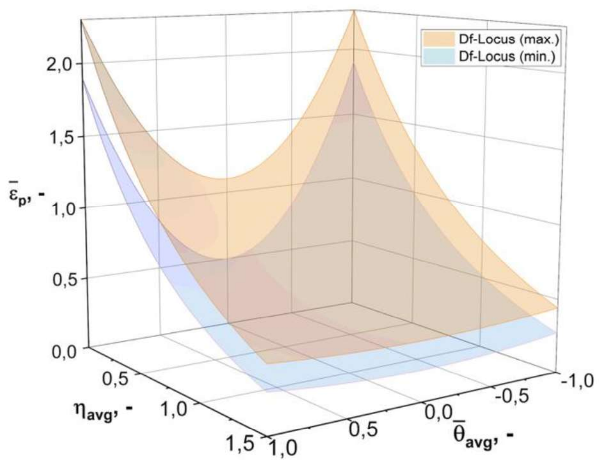

Fig. 6: Ductile fracture loci for the different manufacturing routes as inversely calibrated based on the Charpy test results.

In the last step of the case study, the calibrated fracture loci have been used to simulate the burst tests. This is done to provide the scatter of the burst pressure and to derive new safety factors for the design of the airbag pressure bins for the case of damage-controlled forming processes. Since not all the simulations results are already available, only a comparison between the fracture evolution in experiment and simulation can be shown in Fig. 7, making it plausible that the accuracy of the simulation is sufficient to quantify the burst pressure in the future.

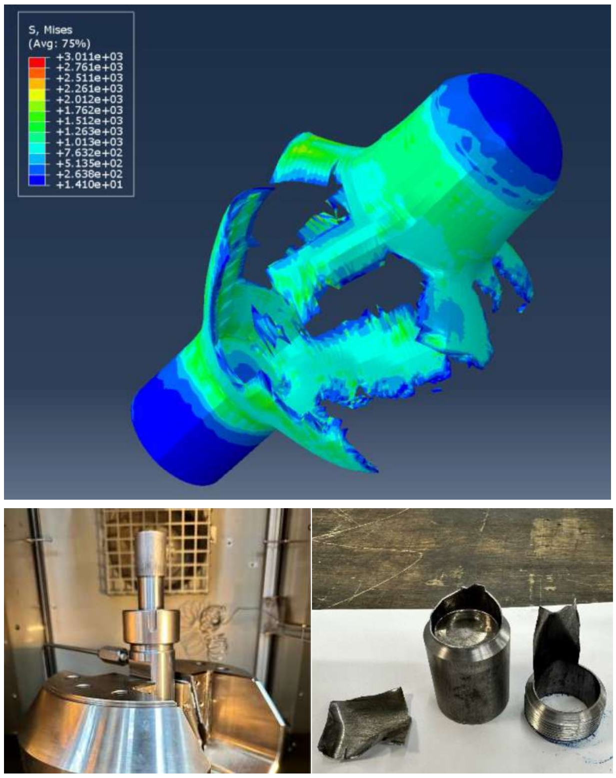

Fig. 7: Fracture evolution in the burst pressure simulation in Abaqus/CAE (2022) (upper image) – Experimental setup for burst tests and fractured sample (lower image)

4. Conclusions

Damage-controlled forming processes aim to reduce ductile damage evolution during forming by influencing the load paths. Damage controlled process variants have been identified for many different forming processes, like hot and cold rolling, extrusion, bending, deep drawing and roll forming. However, so far no option has been suggested to consider the higher performance of components produced in damage-controlled forming processes during the component design phase. Consequently, the lightweight potential of damage-controlled forming could not be fully exploited.

With the suggested procedure to apply probabilistic safety concepts, both the shift of the mean resistance values and the reduced scatter of resistance parameters can be considered. A major obstacle for the application of the probabilistic safety concepts is the high cost and complexity of the required experiments, in particular since a remarkable amount of such investigations is needed to quantify the scatter of resistance parameters. Therefore, the application of damage mechanics simulations is suggested to replace the full-scale experiments. The reproduction of scattered full-scale experimental results is then achieved by the use of scattering failure criteria. These can be calibrated based on much more simple and less costly experiments, so that finally, the unexplored safety margins can be quantified and turned into lightweight engineering.

The presented case study on airbag demonstrates that the performance of a pressure vessel used for airbag gas generators can be increased by damage-controlled design of process sequences. Based on a model prediction, pressure vessels are forged via ironing or forward hollow extrusion of a can extrudate. Charpy tests on the cold forged parts validate the predicted increase of performance for the forward hollow extruded vessel. Furthermore, Charpy tests reveal the scatter of forming-induced damage, so that the scattering of the failure criteria can be quantified. In recent studies, the effect of this forming-induced damage on the burst pressure is revealed numerically.

Acknowledgements

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