Influence of the rolling direction on ductile damage during deep drawing of dual-phase steel

MÜLLER Martina[1,a*], WOLLENWEBER Maximilian A.[3,b], MEDGHALCHI Setareh[3,c], HERRIG Tim[1,d] and BERGS Thomas[1,2,e]

[1] Manufacturing Technology Institute MTI of RWTH Aachen University, Campus-Boulevard 30, 52074 Aachen, Germany

[2] Fraunhofer Institute for Production Technology IPT, Steinbachstraße 17, 52074 Aachen, Germany

[3] Institute for Physical Metallurgy and Materials Physics IMM, Kopernikusstrasse 14, 52074 Aachen, Germany

[a]m.mueller@mti.rwth-aachen.de, [b]wollenweber@imm.rwth-aachen.de, [c]medghalchi@imm.rwth-aachen.de, [d]t.herrig@mti.rwth-aachen.de, [e]t.bergs@mti.rwth-aachen.de

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Abstract. The spatial distribution as well as the amount of the accumulated damage within a component significantly affects its performance in terms of fatigue and crash behavior. One effective approach to control the amount of the accumulated damage is through precise adjustments of process parameters and setup. This paper explored the impact of sheet metal alignment with respect to the forming tools relative to the rolling direction of cold rolling on damage accumulation in sheet metal during deep drawing of a rectangular cup and a U-profile. Firstly, numerical analysis was performed to evaluate the load paths in form of stress and strain states that occur during deep drawing. Subsequently, experimental investigations were conducted to examine the effect of different alignments of the sheet metal with respect to the rolling direction on ductile damage. Therefore, the damage accumulation in the form of void area fraction in workpiece areas that are critical to performance was quantified and compared. Overall, the results have shown that the damage accumulation in form of void area fractions is dependent on the alignment of the sheet metal with respect to the rolling direction. The void area fraction of the rectangular cup could be reduced by 22.4% when considering a sheet metal that is aligned with the rolling direction parallel to the longest, straight sides of the geometry instead of a perpendicular orientation. For the U-profile it was demonstrated that a 45°-orientation of the rolling direction to the bending radius leads to the lowest damage accumulation reducing it by 50.38% compared to a 0°-orientation.

Introduction

The automotive industry is currently undergoing a transformative shift, strategically incorporating lightweight measures into the product design process. This shift is primarily fueled by the industry's commitment as main contributor to CO_2 emissions [1] to meet the ambitious climate targets set by the European Union [2]. Utilizing lighter vehicles has been acknowledged as an effective strategy to reduce CO_2 emissions in transportation [3]. Consequently, the adoption of high-strength materials has become a critical element of the design process, given the additional advantages of better vehicle performance and cost savings. Dual-phase steel is a frequently used material in the domain of lightweight design and the automotive industry. It constitutes a type of high-strength, low-alloy steel that comprises a soft ferrite matrix with a harder martensitic secondary phase in the form of islands. The plastic behavior of DP steels displays a low ratio between yield strength and tensile strength, pronounced work hardening, and exceptional overall formability reflecting the distinct mechanical properties of the two phases present. These characteristics allow for a considerable array of options for microstructural design due to the distribution of stress and strain between those phases [4]. Today, DP steels are primarily used for the production of body panels and frames by deep drawing.

Prior to the forming process, the sheets employed in deep drawing typically undergo a sequence of procedures, such as steelmaking, continuous casting, hot and cold rolling, and heat treatment. These procedures as well as especially the deep drawing process itself all have an influence on the evolution of damage in the material based on the premise that ductile damage means the formation, growth and coalescence of voids in the microstructure. This damage causes degradation of the performance of the corresponding component [5]. Based on this definition of ductile damage, dual phase steels differ from other steels in its evolution. While inclusions play a primary role in void initiation in various steels, different damage mechanisms take precedence in DP steels [5]. These mechanisms encompass martensite fracture, phase boundary detachment, and grain boundary decohesion, and their prevalence is notably influenced by the microstructure [6]. However, the dominant damage mechanisms in DP steels are primarily influenced by the microstructure, while the evolution of damage and its extent in the microstructure are contingent on the stress-strain state experienced by the material throughout the processing route. In general, the higher the hydrostatic tensile stress reflected in a positive triaxiality, the larger the voids and the more damage is caused by plastic deformation in the material [6].

Considering deep drawing, various investigations have explored the influence of different key factors that impact the process in the past. These factors include friction, blank holder force, blank shape, and punch velocity [7]. The primary focus of these studies has been on achieving defect-free components at the macroscopic level, such as avoiding wrinkling, illustrated by Chen et al. [9], minimizing sheet thinning, examined by Preedawiphat et al. [10], and controlling spring back, explored in the works of Durmaz et al. [11] and Nanu et al. [12]. Only a few, however, focused on ductile damage on a microscale as defined above. And these studies focused in particular on the influence of process parameters on ductile damage, as in [13-14]. Therefore, there are knowledge gaps in the context of this understanding of ductile damage, including its potential in manufacturing processes to enhance a components performance. This study investigates the influence of the sheet metal alignment with respect to the forming tools, concerning the rolling direction of cold rolling, on the accumulation of damage in sheet metal during deep drawing of a rectangular cup and a U-profile. The analysis involves performing numerical simulations to evaluate the load paths in terms of stress and strain states that occur during deep drawing as well as the numerical predicted damage state after forming considering an isotropic damage model. Subsequently, an experimental investigation is carried out to analyze the impact on the damage accumulation of various alignments of the sheet metal with respect to the forming tools in relation to the rolling direction. Consequently, the formation of damage in terms of void area fractions in performance critical areas of the workpiece are quantified and compared. The results are used to draw conclusions regarding the impact of the rolling direction on the damage state. Additionally, they provide insides into the optimal orientation of sheet metal taking into account the rolling direction and the alignment with respect to the forming tools to minimize damage accumulation. Furthermore, an evaluation is made of the extent to which the rolling direction should be considered in future damage models for numerical analyses.

Materials and Methods

Experimental deep drawing setup. For the study, a rectangular cup and a U-profile were considered. Workpieces with a similar geometry made of DP800 with various alignments of the sheet metal ($\varphi = \{0°, 45°, 90°\}$) in relation to the rolling direction were compared shortly before failure (Fig. 1a). Since the time of failure and the maximum possible punch strokes s_{St} without failure varied for each variant, the analysis time relied on the variant that failed first and was indicated by the punch stroke s_{St}. The deep drawing process is schematically depicted in Fig. 1b. The sheet thickness s_{SH} was set to s_{SH} = 1.5 mm and the punch speed v_p to v_p = 5 mm/s. The punch had a length l_p of l_p = 100 mm, a width w_p of w_p = 50 mm and a corner radius r_{pC} of r_{pC} = 10 mm (Fig. 1c). The drawing clearance c was c = 1.8 mm. The punch radius r_p was fixed at r_p = 3 mm and the reference die radius r_D at r_D = 3 mm. The sheet had a length $l_{s,rec.}$ of $l_{s,rec.}$ = 142 mm, a width w_s of w_s = 92 mm and a corner radius r_s of r_s = 10 mm.

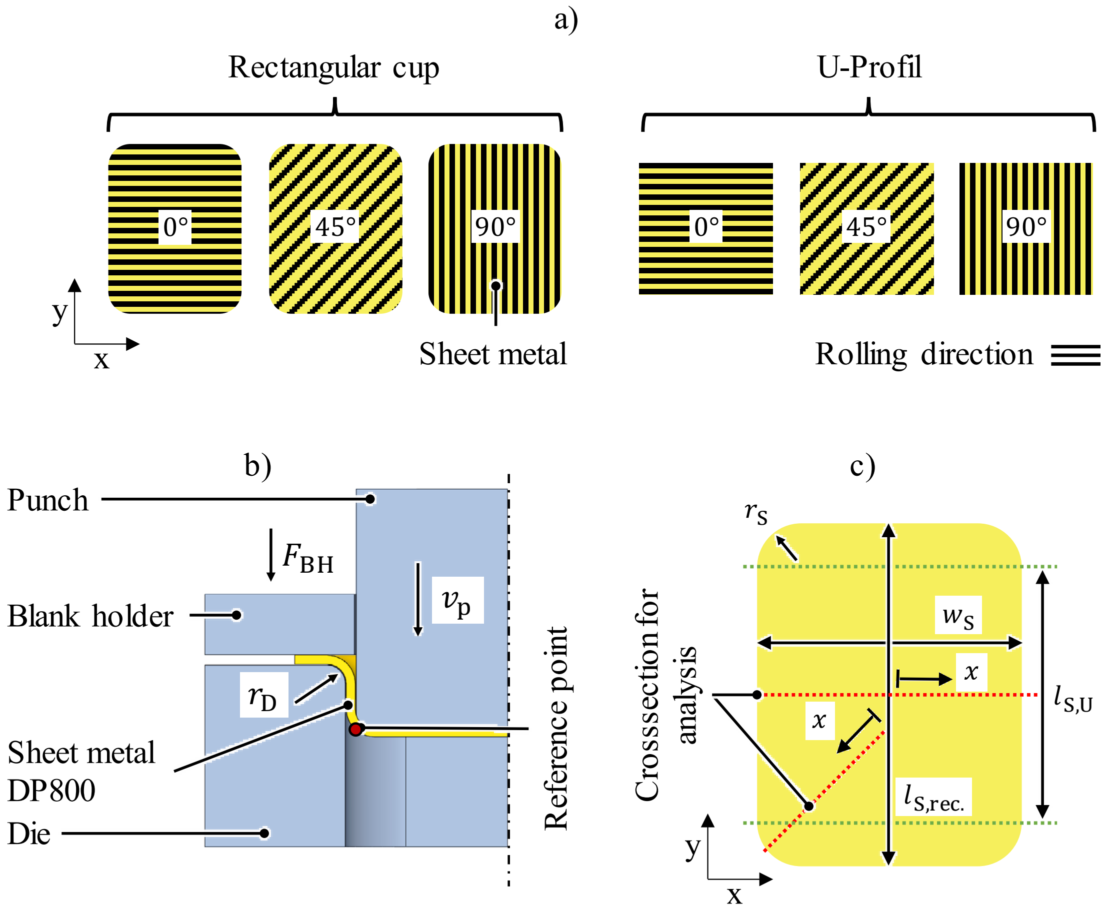

Fig. 1: Schematic illustration of a) sheet metal alignment considering rolling direction, b) deep drawing process and c) sheet metal

The analysis of the damage accumulation concentrated on a reference point in the cross section (Fig. 1b) chosen at the outer bend of the bottom-to-wall transition, aligning with potential future applications for the workpieces. The damage states after forming in the reference point were examined in the form of void area fractions considering an area of ≈ 1.5*0.3 mm^2. Corresponding scanning electron microscopy (SEM) images were analyzed using the machine learning algorithm developed in Kusche et al. [15] and Medghalchi et al. [16], which was specifically trained for the DP800 used in this study. The images were taken at an acceleration voltage of 20kV with image resolution of 3072 pixels per 100 µm.

Numerical deep drawing setup and process model. The influence of the deep drawing process on load paths in form of triaxiality η, lode angle parameter $\bar{\theta}$, von Mises equivalent stress σ_{vm} and plastic equivalent strain φ_{pl} as well as on the damage state was investigated numerical by using Abaqus/Explicit. The analysis focused on the reference point, which was also utilized for determining the void area fractions (Fig. 1b). A volume measuring 1.5x1.5x0.3 mm^3 was employed for this purpose. To numerically predict the damage state as the damage parameter D, an isotropic coupled damage model based on Lemaitre's approach was applied [17]. The model was calibrated in rolling direction for the DP800 used in this study. The model's parameters are listed in detail in Sprave et al. [18].

To analyze the damage distribution, a parameter x was introduced which passes through the corner of the component in the case of the rectangular geometry, or through the exact center of the component in the case of U-profiles (Fig. 1b). The geometry was reduced to a quarter using symmetry. Table 1 summarizes the mesh parameters and body types. The sheet was depicted by a dense mesh of volume elements (C3D8R). Structured shell elements were employed to mesh the punch, blank holder and die (R3D4). While the planar regions of the active parts were represented by a few large elements, the curvatures of the active parts were represented by many small elements. This ensured an effective balance between precise geometric representation of the parts and computational efficiency. The blank holder's movement, specifically when it first came into contact with the sheet, followed a velocity profile. To prevent the sheet's natural oscillations resulting from the blank holder's impact, the blank holder's displacement was defined as a sigmoid function. This function reduced the blank holder speed during contact buildup, thus minimizing its impact effect. The blank holder was forcefully and strategically moved with a hard contact and interaction properties set to general contact to ensure force control.

Table 1: Mesh parameters and body types

Name	**Mesh**	**Type of body**	**Global seed size**	**Max. deviation factor**	**Min. size control**
Sheet	C3D8R	Solid deformable body	0.5	0.005	0.01
Punch, blank holder, die	R3D4	Discrete rigid	10	0.005	0.01

Results

Analysis of load paths. The load paths in form of triaxiality $\boldsymbol{\eta}$, lode angle parameter $\boldsymbol{\bar{\theta}}$, von Mises equivalent stress $\boldsymbol{\sigma_{vm}}$ and plastic equivalent strain $\boldsymbol{\varphi_{pl}}$ of the deep-drawn U-profile and rectangular cup are shown in Fig. 2. The triaxiality $\boldsymbol{\eta}$ curve of the U-profile initially increases degressively up to an equivalent plastic strain $\boldsymbol{\varphi_{pl}}$of about $\boldsymbol{\varphi_{pl}}$ = 0.025. The value then oscillates around a level of $\boldsymbol{\eta}$ = 0.55 until its end. The lode angle parameter $\boldsymbol{\bar{\theta}}$ course of the U-profile decreases exponentially up to an equivalent plastic strain $\boldsymbol{\varphi_{pl}}$ of $\boldsymbol{\varphi_{pl}}$= 0.05. The von Mises equivalent stress $\boldsymbol{\sigma_{vm}}$of the U-profile, on the other hand, shows a degressively increasing curve. However, just before the maximum plastic equivalent stress $\boldsymbol{\sigma_{vm}}$is reached, the value of $\boldsymbol{\sigma_{vm}}$drops again.

The course of the triaxiality η of the rectangular cup rises steeply up to an equivalent plastic strain φ_{pl} of φ_{pl} = 0.02 and reaches a positive extreme value. After a slight drop in the triaxiality η up to an equivalent plastic strainφ_{pl} of φ_{pl} = 0.14, the curve of the triaxiality η then increases almost linearly until the end of the forming process. Up to an equivalent plastic strain φ_{pl} of φ_{pl} = 0.02, the curve of the lode angle parameter $\bar{\theta}$ decreases and reaches a negative extreme value. The curve of the lode angle parameter $\bar{\theta}$ of the rectangular cup then increases to an equivalent plastic strain φ_{pl} of φ_{pl} = 0.22. After the respective increase in the lode angle parameter $\bar{\theta}$, the curve of the lode angle parameter $\bar{\theta}$ decreases and reaches a second negative extreme value at the end of the forming process. The von Mises equivalent stress σ_{vm} of the rectangular cup initially increases degressively as a function of the equivalent plastic strain φ_{pl}

until an equivalent plastic strain φ_{pl} of φ_{pl} = 0.22 is reached. The von Mises equivalent stress σ_{vm} then drops off abruptly towards the end of the forming process.

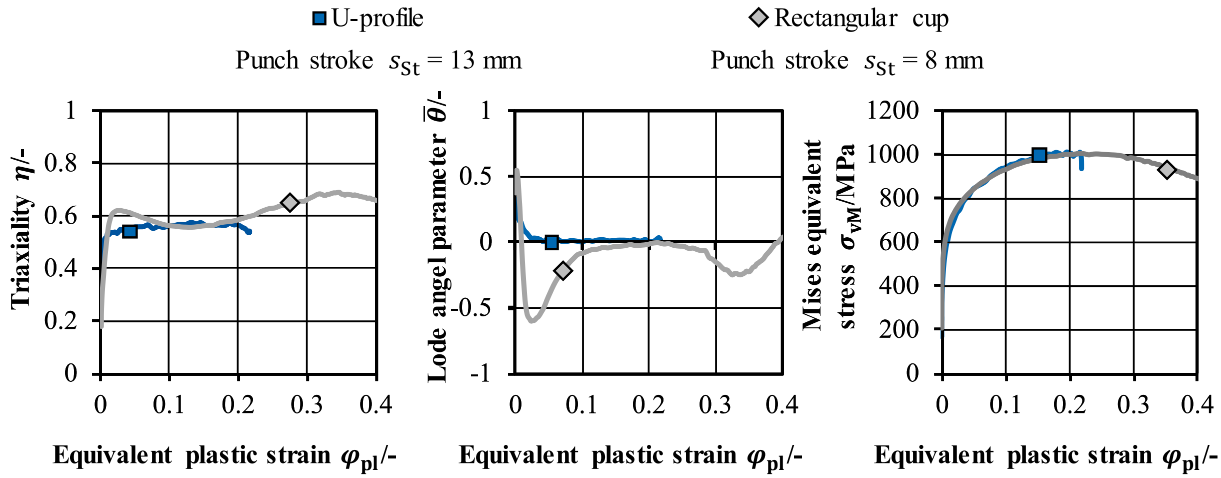

Fig. 2: Load paths during forming of the U-profile and the rectangular cup at reference point

Analysis of numerical predicted damage state after forming. Fig. 3 presents the damage distribution resulting from deep drawing of the U-profile, where the bottom, transition, and wall areas are taken into account. The bottom area indicates no numerical predicted damage correlation with deep drawing. However, the transition area, from the floor to the wall, displays a continuous numerical predicted damage area. This numerical predicted damage area consists of a local maximum of the damage parameter $\boldsymbol{D}$ at the beginning of the transition area and a successive more uniform damage distribution. The global maximum of the damage parameter $\boldsymbol{D}_{\mathbf{max}}$ arises in the lower end direction of the wall, towards the flange. The damage parameter $\boldsymbol{D}$ at the reference point is predicted as 0.04.

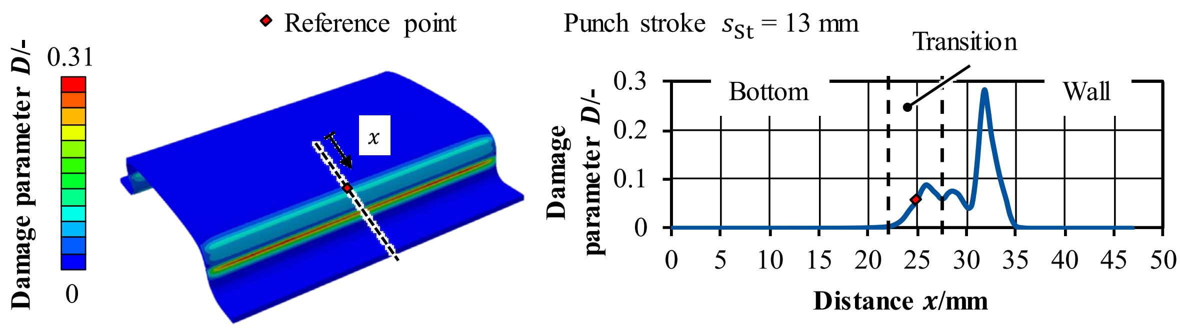

Fig. 3: Numerical predicted damage distribution in U-profile

Fig. 4 demonstrates the progression of the damage parameter $\boldsymbol{D}$ throughout the rectangular cup over distance $\boldsymbol{x}$. It is noteworthy that the bottom of the cup is not impacted by deep drawing considering the numerical predicted damage state. As the transition area is approached, the damage parameter $\boldsymbol{D}$ progressively increases and reaches its maximum $\boldsymbol{D}_{\mathbf{max}}$ before it decreases. The predicted damage parameter $\boldsymbol{D}$ is $\boldsymbol{D}$ = 0.19 at the reference point.

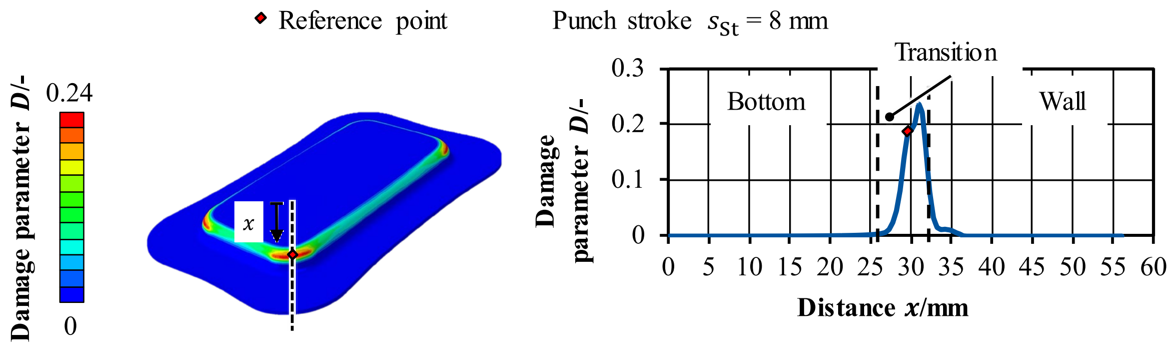

Fig. 4: Numerical predicted damage distribution in rectangular cup

Analysis of accumulated damage after forming. Fig. 5 displays the void area fraction $\boldsymbol{\delta}$ at the reference point in dependence of the alignments of the sheet metal in relation to the rolling direction. In the case of the rectangular cup, it is apparent that the void area fraction $\boldsymbol{\delta}$ decreases as the angle of the alignments of the sheet metal increases. The values reach a maximum of $\boldsymbol{\delta}_{\mathbf{rec.cup.,0°}}$ = 0.058 %, $\boldsymbol{\delta}_{\mathbf{rec.cup.,45°}}$ = 0.051 % and $\boldsymbol{\delta}_{\mathbf{rec.cup.,0°}}$ = 0.045 %. Considering the U-profile, the values reach a maximum of $\boldsymbol{\delta}_{\mathbf{U-profile.,0°}}$ = 0.026 % and $\boldsymbol{\delta}_{\mathbf{U-profile.,45°}}$ = 0.0129 %. The sheet metal workpieces in the 90°-orientation were not analyzed, as these failed despite being deep-drawn with the same deep drawing setup.

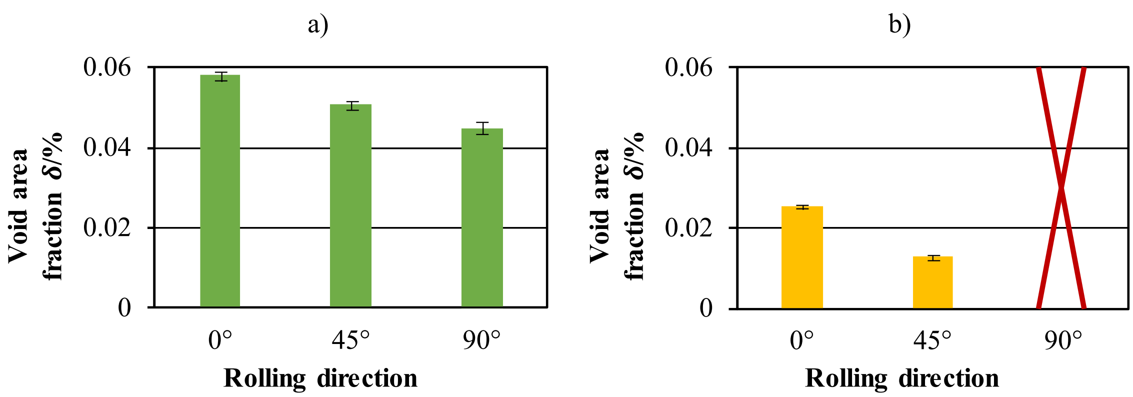

Fig. 5: Void area fraction $\boldsymbol{\delta}$ at reference point of a) rectangular cup and b) U-profile after deep drawing in dependence of the alignments of the sheet metal in relation to the rolling direction

Conclusion

When comparing the load paths in the reference point of the two considered geometries, noticeable disparities can be observed although the same punch edge and corner radius cause the two geometries to have a similar curvature. Firstly, the two geometries differ significantly in the required equivalent plastic strain φ_{pl} at the reference point which is considerably higher for the rectangular cup than for the U-profile. Furthermore, the stress state in form of triaxiality η and lode angle parameter $\bar{\theta}$ of the rectangular cup indicate that non-proportional loading occurs during forming, shifting between the plain strain tension region and the biaxial tension region. This makes a corresponding numerical prediction of the damage state much more complex, as, in principle, a larger number of different loadings should be used for accurate calibration. In contrast, the stress values of the U-section are almost exclusively in the plain strain tension range.

The different stress and strain states are also reflected in the numerically predicted damage state at the reference point, which differs significantly in its value. The rectangular cup yields a value almost five times greater than the U-profile. This difference is also reflected in the determined void area fractions, with the rectangular cup having a void area fraction at least three times higher than that of the U-profile, regardless of the rolling direction. Accordingly, the numerical results are in qualitative agreement with the experimental results.

Considering the measured void area fractions of the rectangular cup as a function of the alignments of the sheet metal with respect to the forming tools relative to the rolling direction, there are differences in the values obtained. For the rectangular cup, it was shown that the damage accumulation is lower if the sheet metal is aligned with the rolling direction parallel to the longest, straight sides considering a 90°-orientation to the rolling direction. This enabled the void area fraction to by reduced by 22.4% from $\delta_{\mathrm{rec.cup.,0°}}$ = 0.058 % to $\delta_{\mathrm{rec.cup.,90°}}$ = 0.045 %. For the U-profile, on the other hand, it was demonstrated that a 45°-orientation leads to the lowest damage accumulation reducing it by 50.38% from $\delta_{\mathrm{U-profile.,0°}}$ = 0.026 % to $\delta_{\mathrm{U-profile.,45°}}$ = 0.0129 %. Therefore, it can be deduced that geometry features with a convex radius should have a 90°-orientation to the rolling direction with respect to the forming tools, while long, straight sides, as they occur with the U-profile, should be orientated at 45° to the rolling direction with respect to the forming tools in order to achieve the lowest possible damage accumulation. However, the interaction between performance, rolling direction and damage accumulation still needs to be evaluated in order to be able to draw a general conclusion.

Outlook

Based on the results of this study, there is an endeavour in forthcoming research to refine the damage model to address material anisotropy. This entails assuring that the model comprehends the divergent behaviour of materials in distinct directions and thus taking into account a tensorial damage parameter. Moreover, non-proportional load paths need to be considered so that the model can handle different types of loads more accurately, especially when forces aren't applied uniformly. Both approaches are expected to improve the model's ability to predict the damage state, since especially with complex geometries, the geometry features, such as corners or straight sides, reflected in the rectangular cup and U-profile, may not always be aligned parallel or orthogonal relative to the rolling direction with respect to the forming tools. In addition, further investigations are necessary to understand the microstructural reasons that lead to damage as well as to determine the performance of the components depending on the alignment of the sheet metal to the rolling direction with respect to the forming tools.

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