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Influence of pass reduction in cold rolling on damage evolution in deep drawing of rotationally symmetric cups

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Abstract. Improvement of component performance by controlling the damage state after metal forming enables a reduction in sheet thickness and, consequently, in component weight and material cost. To establish methods for controlling damage in finished parts, the entire process chain from steelmaking and casting through hot and cold rolling to deep drawing must be considered. Previous research has shown that in hot rolling of an S355 steel, the influence of pass reduction on damage in the hot strip disappears when the accumulated pass reduction becomes large. However, the influence of cold rolling parameters on damage and specifically on its evolution in subsequent forming processes has not yet been systematically investigated. In the present work, specimens of the mentioned S355 steel are cold rolled with two different pass reductions and heat treated to obtain a DP800 dual phase steel. These specimens are deep drawn into rotationally symmetric cups with variation of the drawing die radius. Sheet specimens and deep drawn cups are investigated using scanning electron microscopy to determine the respective void area fractions. While no influence of height reduction on the void area fraction after cold rolling is found, the void area fraction after deep drawing differs with variation of the pass reduction. This effect is connected to the formation of a larger number of small voids in the material rolled with a larger pass reduction.

1. Introduction and state of the art

1.1. Initial situation

In 2015, the 196 parties to the United Nations Framework Convention on Climate Change agreed to pursue efforts to limit the increase in the global average temperature to 1.5 °C by reducing greenhouse gas emissions¹. In 2017, 22% of all CO₂ emissions were caused by the transportation sector². One way to reduce greenhouse gas emissions in transportation is lightweight design of the vehicles. This is commonly achieved by material substitution, design changes, or a reduction in material thickness. All three approaches must take into account the crashworthiness of the final part³.

Most body-in-white parts are manufactured from sheet metal⁴. In the process chain of steelmaking, continuous casting, hot and cold rolling, heat treatment, and sheet metal forming,
voids are introduced into the material and evolve depending on the respective stress states. Damage in the form of these voids reduces the performance of the component, which must be accounted for in the component design.

1.2. State of the art
The common process chain for producing sheet metal parts consists of steel making in the blast furnace and in the basic oxygen furnace, subsequent continuous casting, hot rolling, cold rolling, optional heat treatment[5], and a sheet metal forming process[6]. During steel making, inclusions are introduced into the material, which can act as damage initiation sites during deformation. Similarly, voids are introduced through shrinking during solidification in continuous casting. The stresses acting on the material in the subsequent forming processes cause damage evolution.

Damage evolution in forming processes has mostly been investigated with regard to material fracture and, consequently, the extension of the process boundaries of the respective forming processes[7]. HERING ET AL. have expanded this to determine the influence of damage on the service properties of cold forged parts[8].

1.2.1. Damage control in rolling
Damage initiation, evolution and ductile fracture in metal forming processes are commonly linked to tensile or shear stresses[9]. BAO AND WIERZBICKI[10] found a triaxiality threshold of $\frac{-1}{3}$, which was later adjusted stress-state dependently and lowered by BRÜNING ET AL.[11], below which no damage and fracture seems to occur during metal forming. Hence, the process of cold rolling (see fig. 1(a)) has received little attention regarding void nucleation due to it being mostly dominated by compressive stresses and highly negative stress triaxialities. The present studies for cold rolling focus either on the damage initiation during edge cracking[12] or aim to prevent strip tearing during tandem cold rolling[13]. The initiation of damage during cold rolling and especially its effect on the subsequent forming operations on the other hand has not been studied extensively.

Figure 1: Process parameters in cold rolling and deep drawing

1.2.2. Damage control in sheet metal forming
The approach of controlling the damage state in formed metal components to increase their service performance has recently been investigated with increasing effort. Besides cold forging[8] and hot forming[14], sheet metal forming has gained significant attention. MEYA ET AL. found that the superposition of radial stresses in a bending process allows a significant reduction in damage[15] and consequently an improvement of the service performance of the part[16]. In deep drawing, a significant influence of the drawing
die radius $r_{dd}$ on damage evolution was found in finite element (FE) simulations, while the influences of the blank holder force $F_{bh}$ and the punch velocity $v_p$ were less pronounced[17].

1.3. Motivation and objective
The performance of the formed component is determined, besides microstructure, residual stresses, and material strength, by the damage state after the final forming step. Because damage evolution depends on both the initial damage and the stresses acting on the material during forming, the complete process chain must be investigated. Different rolling strategies cause different stresses acting on the material during cold rolling, which in turn results in different damage states. These different damage states evolve during deep drawing. Knowledge of the cause-effect relationship between the damage state after rolling and damage evolution during deep drawing will enable a more specific process design of the deep drawing process, which will allow an improvement in the performance of the formed component.

The objective of the work presented here is the knowledge of the cause-effect relation between the damage state in the form of voids in the material after cold rolling and the evolution of damage during deep drawing of rotationally symmetric cups from a DP800 dual phase steel.

To achieve this objective, the damage in cups deep drawn from differently rolled material is characterized.

2. Methods and materials
To allow the investigation of different damage states after rolling, a micro-alloyed mild steel S355 was rolled with variation of the rolling strategy and subsequently heat treated to make a DP800 dual phase steel at the Institute of Metal Forming (IBF) of RWTH Aachen University. Two types of DP800 sheet were then water jet cut into blanks for the deep drawing process. The blanks were deep drawn with variation of the drawing die radius at the Laboratory for Machine Tools and Production Engineering (WZL) of RWTH Aachen University. Finally, both the rolled sheet and the deep drawn cups were characterized with regard to their respective void area fractions using scanning electron microscopy (SEM) and a convolutional neural network.

2.1. Rolling and heat treatment
A micro-alloyed mild steel S355 (composition see [tab. 1]) with a length of $l_b = 650\,\text{mm}$, a width of $w_b = 260\,\text{mm}$ and a height of $h_b = 140\,\text{mm}$, was rolled to a thickness of $h = 1.5\,\text{mm}$. The sheet was subsequently heat treated to obtain a DP800 dual phase steel. First, the rolling mill BÜHLER VRW400 (roll diameter $d_r = 410\,\text{mm}$) was used to roll out the material to a thickness of $h_1 = 20\,\text{mm}$ with a pass reduction of $\Delta h_1 = 15\,\text{mm}$. After cutting and reheating the strip was further rolled to a thickness of $h_2 = 5\,\text{mm}$ and after a second reheating to a thickness of $h_3 = 3\,\text{mm}$ with a gradually decreasing pass reduction. The rolling velocity was $v_r = 15\,\text{m}\,\text{min}^{-1}$ and the heating and reheating temperature was $T = 1,200\,^\circ\text{C}$. After air cooling, the strip was sandblasted and a 4-high rolling mill was utilized for cold rolling of the strip to a thickness of $h_s = 1.5\,\text{mm}$ in two different pass reductions: $\Delta h = 0.10\,\text{mm}$ and $\Delta h = 0.75\,\text{mm}$ resulting in a total of $n = 15$ and $n = 2$ passes, respectively. Afterwards, the radiation furnace NABERTHERM

| Element | C | Si | Mn | Cu | Al | Mo | Ni | Cr | V | Nb | Ti | Co |
|---------|---|----|----|----|----|----|----|----|---|----|----|----|
| Wt.%    | 0.1 | 0.4 | 1.8 | 0.05 | 0.03 | 0.02 | 0.05 | 0.2 | < 0.005 | 0.04 | 0.02 | 0.005 |
N 761 was used to transform the strip into DP800 by an intercritical heat treatment for \( t_1 = 180 \text{s} \) at \( T_1 = 725 \text{°C} \) under Argon atmosphere and subsequent quenching in water. A final sandblasting was performed to eliminate possible surface inhomogeneities and mitigate their effect on the following deep drawing process.

2.2. Deep drawing

Deep drawing was performed on a SCHULER HPX-400 hydraulic forming press using a modular deep drawing tool which allows the replacement of the drawing die, the blank holder, and the punch. The drawn cups had a diameter of \( d_1 = 60 \text{mm} \). Preliminary drawing experiments showed that a blank holder force of \( F_{bh} = 6.8 \text{kN} \) and a blank diameter of \( d_0 = 85 \text{mm} \), resulting in a drawing ratio of \( \beta = 1.42 \), were feasible for deep drawing. The blanks were lubricated on both sides with FUCHS WISURA LS 710 mineral oil based lubricant using a paint roller. The rolling direction of the original sheet was marked on the blanks with a laser marker to allow identification after deep drawing.

2.3. Damage characterization

Damage characterization was done in accordance with [18]. The specimens from the rolled material were selected randomly from the sheet. All specimens were prepared in the plane defined by the rolling direction and the sheet normal direction (see fig. 2 (a) and 2 (b)). In the cups, analysis was performed on an area of width \( w_{\text{SEM,cup}} \approx 3.68 \text{mm} \) and height \( h_{\text{SEM,cup}} \approx 0.33 \text{mm} \) beginning at the end of the transition between cup floor and cup wall and extending into the cup wall (see fig. 2 (c)). The specimens were hot-embedded in conductive embedding material. They were then ground with SiC paper down to a grit size of \( g = 4,000 \) for \( t_g = 2 \text{min} \) each at \( F_g = 25 \text{N} \) and a rotational velocity of \( n_g = 150 \text{min}^{-1} \). The specimens were polished with polycrystalline diamond suspension with diamond sizes \( s_d = 6,3,1 \text{µm} \) and finally for \( t_{\text{OPS}} = 1 \text{min} \) using OPS suspension. To remove material smeared over voids during polishing, the specimens were etched for \( t_e = 10 \text{s} \) in 1% Nital solution.

SEM analysis was performed using a ZEISS SIGMA 500 VP SEM. To be compatible with the neural network, the individual images needed to be 3072 pixels in width and 2304 pixels in height, which results in a width of the individual image of 100 µm. A panorama image with these specifications was recorded with an overlap of 20%, 46 images in x direction and 5

(a) SEM plane in non-deep drawn sheet  (b) SEM plane in deep drawn cups  (c) location of SEM analysis in deep drawn cups

nd – normal direction
td – transverse direction
rd – rolling direction

Figure 2: SEM analysis planes and locations in non-deep drawn sheet and in deep drawn cups
images in y direction, corresponding to a width of $w = 3.68 \, \text{mm}$ and a height of $h = 0.33 \, \text{mm}$. To ensure that the position of the images was as close to the outer surface of the specimens as possible, the embedding material was left in the topmost row of images (see fig. 3(a)). The embedding material was then cut from the individual images and the image contrast was adjusted (fig. 3(c)). The resulting contrast-adjusted images were then stitched using IMAGEJ and the stitching plugin developed by Preibisch et al. [19]. A resulting panorama image is shown in fig. 3(d).

Within the images, potential void sites were identified using a DBSCAN algorithm based on the grayscale values of the images. For each potential void site, a 299x299 pixel image was extracted (see fig. 3(b)), which was then used in an Inception v3 convolutional neural network to classify the site as an inclusion or as a void. Sites classified as voids with a confidence of more than 80% were counted as such. The area of the voids is calculated by the convex image of the respective site.

3. Results

The panorama images are split up into sections of 15,360 pixel width. The void area fraction is then calculated for the individual sections. Because the rolled sheet is not differentiated along its length, the damage state after rolling is characterized by the average void area fraction of the nine sections. For a pass reduction of $\Delta h = 0.1 \, \text{mm}$, a void area fraction of

![Figure 3: SEM image preparation for use in the neural network](image-url)
$V = (1.18 \pm 0.34) \times 10^{-5}$ is calculated, while for a pass reduction of $\Delta_h = 0.75$ mm, a void area fraction of $V = (1.35 \pm 0.46) \times 10^{-5}$ is calculated. For the deep drawn specimens, FE simulations predict a damage distribution in the drawing direction. Consequently, fig. 4 shows the distribution of the void area fraction in the deep drawn cups in the individual sections along the cup wall.

![Diagram showing void area fraction distributions in cups drawn from sheet rolled with different pass reductions $\Delta_h$.](image)

**Figure 4:** Void area fraction distributions in cups drawn from sheet rolled with different pass reductions $\Delta_h$.

The void area fractions increase during deep drawing. The cup drawn from material rolled with $\Delta_h = 0.10$ mm with a drawing die radius of $r_{dd} = 3$ mm (fig. 4(b)) exhibits void area fractions between $V = 0.4 \times 10^{-4}$ and $V = 0.7 \times 10^{-4}$. In the cup drawn from the same material with a drawing die radius of $r_{dd} = 9$ mm, void area fractions between $V = 0.2 \times 10^{-4}$ and $V = 0.5 \times 10^{-4}$ are observed. Significantly higher void area fractions are found in the cups drawn from material rolled with $\Delta_h = 0.75$ mm. A drawing die radius of $r_{dd} = 3$ mm shows void area fractions between $V = 0.7 \times 10^{-4}$ and $V = 1.1 \times 10^{-4}$. Similarly, in the cup drawn from this material with a drawing die radius of $r_{dd} = 9$ mm, void area fractions between $V = 0.4 \times 10^{-4}$ and $V = 0.6 \times 10^{-4}$ are found. No consistent trend with regard to the damage distribution within the individual cups can be observed.

The distribution of void sizes in the rolled material is shown in fig. 5(a) for a pass reduction $\Delta_h = 0.10$ mm and in fig. 5(b) for a pass reduction $\Delta_h = 0.75$ mm. While for $\Delta_h = 0.10$ mm, the void density is almost constant at about $n = 50$ mm$^{-2}$ up to a size of $A = 0.40 \mu m^2$, the material with $\Delta_h = 0.75$ mm contains significantly more small voids ($0.06 \mu m^2 < A < 0.15 \mu m^2 : v = 238$ mm$^{-2}$). This is reflected in the deep drawn material, where less small voids are found in the $\Delta_h = 0.10$ mm material (fig. 5(c)) compared to the $\Delta_h = 0.75$ mm material (fig. 5(d)). The increased void area fractions in cups drawn with a drawing die radius of $r_{dd} = 3$ mm is primarily reflected in an increase in the number of voids of medium size ($0.15 \mu m^2 < A < 1.00 \mu m^2$).

**4. Discussion**

The increase in pass reduction in cold rolling results in the formation of a larger number of small voids, with the overall void area not changing significantly. With regard to the stress...
Figure 5: Void area fraction distributions in the cups

state, an increase in the pass reduction results in smaller stress triaxialities $\eta$, indicating a more pronounced compressive state. One possible explanation for the observed formation of a larger number of small voids when compared to a smaller pass reduction is that the more pronounced compressive stress hinders the growth of voids. This promotes void nucleation at more sites, ultimately leading to a larger number of small voids. An increase in pass reduction also leads to a decrease in the number of passes ($n = 2$ at $\Delta h = 0.75 \text{ mm}$ compared to $n = 15$ at $\Delta h = 0.10 \text{ mm}$). With more consecutive passes, the stress acts on the material more often, which allows the voids that have already nucleated to grow rather than new voids to form.

With regard to deep drawing, it is important to note that the damage state after the deep drawing process is different in the materials rolled with different pass reductions although the void area fraction before deep drawing is virtually equal. This means that the void area fraction alone is not sufficient to describe the damage state when damage evolution is to be investigated within a process chain. The results discussed here suggest that the larger number of small voids found in the material rolled with $\Delta h = 0.75 \text{ mm}$ lead to an increased void area fraction in the deep drawn parts. This can be explained by the increased number of voids available for void growth during the deep drawing process, which allows the voids to grow more, resulting in an increase in the overall void area fraction. This hypothesis is supported by the observation that in the cups drawn from $\Delta h = 0.75 \text{ mm}$ material, the void area distribution is more biased towards larger voids. Specifically with a drawing die radius of $r_{dd} = 3 \text{ mm}$, there are more voids of a medium size ($0.40 \mu m^2 < A < 1.00 \mu m^2$) than small voids ($0.06 \mu m^2 < A < 0.16 \mu m^2$).
5. Summary and outlook
Steel blocks from S355 steel were hot rolled to a thickness of $h_3 = 3\, \text{mm}$, cold rolled to $h_s = 1.5\, \text{mm}$, and heat treated into a DP800 dual phase steel. During cold rolling, the pass reduction was varied as $\Delta h = 0.10; 0.75\, \text{mm}$. From the DP800 sheet, circular blanks with a diameter of $d_0 = 85\, \text{mm}$ were water jet cut. These blanks were deep drawn into rotationally symmetrical cups with a diameter of $d_1 = 60\, \text{mm}$ with variation of the drawing die radius $r_{dd} = 3; 9\, \text{mm}$. The rolled material and the cups were characterized with regard to damage in the form of voids in the material using SEM and a convolutional neural network.

It was found that an increase in the pass reduction during cold rolling does not significantly change the void area fraction in the rolled material, but does cause the formation of a larger number of small voids. This is explained by the more pronounced compressive stress state caused by the increase in pass reduction. The increased number of voids can then grow during deep drawing, causing an increase in the void area fraction when compared to the material rolled with a smaller pass reduction.

To investigate the effect of pass reduction during cold rolling on the damage state after rolling and after sheet metal forming, further research is required. Damage characterization of the material before cold rolling and before heat treatment will allow better insight into the mechanisms that cause the difference in the void area distribution. Micro-scale simulations of the damage evolution based on the load paths in the material during rolling will further improve the understanding of the mechanisms. To analyze the effect of the void area distribution on damage evolution during sheet metal forming, a combination of stopped sheet metal forming experiments and numerical modelling will allow an explanation.

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