Exceeding the Forming Limit Curve with Deep Drawing Followed by Electromagnetic Calibration*

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Abstract

We show that the materials quasi-static forming limit curve (FLC) can be exceeded by the process chain composed of deep drawing followed by electromagnetic forming. We form circular cups as close as possible to the FLC by deep drawing. These cups are then further formed (calibrated) by electromagnetic forming. The electromagnetic forming takes place in the punch edge radius region. The results show significant amount of material in this region exceeding the FLC by means of the process chain. Further research is needed to reveal the factors leading to this increase in forming limits.

Keywords

Process chain, Forming limits, Electromagnetic forming

1 Introduction

The forming potentials of the conventional one-step processes cannot satisfy the increasing demand for complex metal formed parts. In order to increase the forming potential, these processes may be combined with unconventional processes, comprising a process chain. Process chains composed of deep drawing and electromagnetic forming process are delivering promising results in that sense.

The process chain deep drawing followed by electromagnetic calibration was proposed in 1998 by Vohnout [1]. He demonstrated the advantage of the chain. In 2007

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Psyk et al. [2] carried out the process chain by embedding electromagnetic tools into the drawing punch. Risch et al. [3] embedded the electromagnetic tools into the female die in 2008.

Liu et al. [4] investigated the process chain in 2009. They tried to draw circular cups with 8 mm or 5 mm punch edge radius. They showed that the cup ruptures in case of 5 mm radius, while there is no rupture in case of 8 mm. Then, they took the cups with 8 mm punch radius, and formed them further. Namely, they got the 8 mm radius reduced to 5 mm using electromagnetic forming. By succeeding this reduction, they showed that the process chain improves the process limits. However, they did not supply any strain distribution results. So we do not know, if the materials quasi-static forming limit curve (FLC) was exceeded or not.

In 2011, Imbert and Worswick [5] formed sheet bands using a v-shaped punch with a 20 mm outer radius. Then, preventing draw-in, they attempted to form the bands further using a v-shaped punch with a 5 mm outer radius. That did not work. Alternatively, they attempted to do the same using electromagnetic forming. That worked. However, the strain distributions of the final products were still under the quasi-static FLC.

This paper shows that the quasi-static FLC of the material can be exceeded with the process chain comprising deep drawing followed by electromagnetic calibration. The process chain is applied on the forming of a circular cup. The cups are first drawn until the material in the punch edge radius region reaches the FLC. Then the material in this region is formed electromagnetically further. The results show that the quasi-static FLC is exceeded.

2 The Experimental Setup

For deep drawing a 10 MN Müller-Weingarten press was used. The punch, which was round, had a 130 mm diameter and a 20 mm or a 15 mm edge radius (*Figure 1*a). The drawing radius was 10 mm.

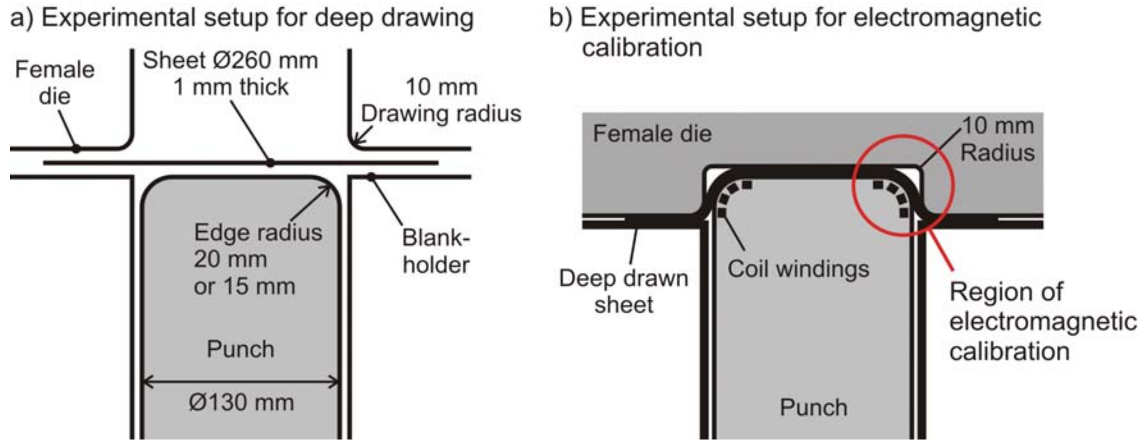

Figure 1 *The experimental setup*

The punch edge radius region of the deep drawn part was calibrated by electromagnetic forming (*Figure 1*b). A female die with 10 mm edge radius was used during this operation. This operation was also performed under the same press, only by replacing the steel deep drawing punch with the punch for electromagnetic forming.

The electromagnetic punch had to include the coil windings. Coil windings are the tools of the electromagnetic forming. They have to be fixed in the vicinity of the workpiece, without being in electrical contact with it. These requirements were fulfilled by the punch seen in *Figure 2*.

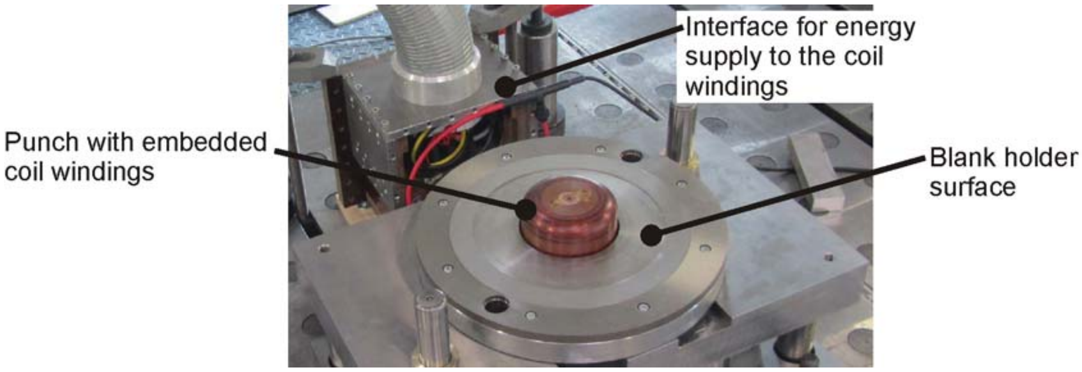

Figure 2 *The electromagnetic punch assembled to the deep drawing equipment*

To supply energy to the coil windings, a 7000 Series Magneform facility, manufactured by the company Maxwell and modified by the company Poynting was used. This facility has four separate capacitor banks, which can be used alone or in any combination with each other. The bank used for this study had 8 kJ maximum energy capacity with 8.16 kV maximum charging voltage. It had a capacitance of 237 μF, an internal inductance of 98 nH, and an internal resistance of 6.9 mΩ.

The material selected was EN AW-5083 with temper designation H111. 1 mm thick round sheets with 260 mm diameter were used as specimen. The drawing depth was 50 mm in all the experiments. The strain distributions and the forming limit diagrams (FLD) of the parts were measured using a three-dimensional optical measurement system called ARGUS from the company GOM. In this system, the workpiece must be rasterized before being formed. After forming, pictures of the workpiece are taken from several angles. The strains on the rasterized surface and the FLD of the part can then be calculated automatically.

3 Results

3.1 Deep drawing with 20 mm punch edge radius

Here we generated deep drawn specimens for the following electromagnetic forming. The material *at the punch edge radius region* had to come close to the forming limit curve without failure. To reach that aim, we wanted to make sure of two conditions: Firstly, as much material as possible should flow from the punch bottom to the punch radius. Secondly, the process should be conducted until the process limits.

To make sure that the material flows from the punch bottom to the punch radius, we used a lot of lubricant and also a special film at the punch–workpiece interface, while using only the special film at the flange. To make sure that the process is conducted until the process limits, we increased the blank holder force gradually with steps of 20 kN until seeing a material failure.

The material does not fail at 520 kN blank holder force; it fails starting from 540 kN (*Figure 3*). The strain distribution in case of 520 kN is close to the forming limit curve (FLC), so it is suitable for our aims. The FLC seen in *Figure 3* was obtained by standard Nakajima tests in collaboration with the Institut für Werkstoffkunde of Leibniz Universität Hannover.

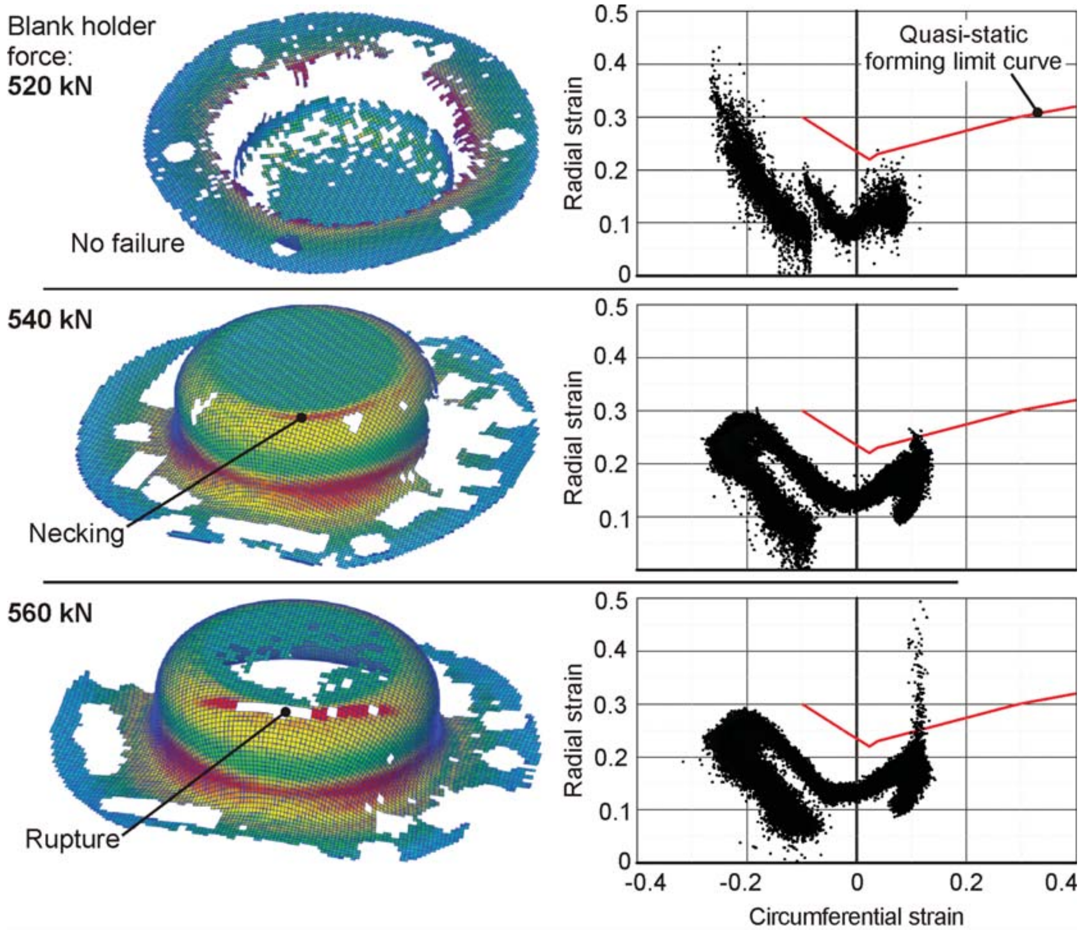

Figure 3 *The results of deep drawing experiments with 20 mm punch edge radius*

3.2 Electromagnetic calibration starting from 20 mm punch edge radius

The specimens formed with 520 kN blank holder force without failure were electromagnetically calibrated.

The aim of the electromagnetic calibration was to explore the forming limits of the material. So it was conducted until the material experiences necking or rupture. For that, the electromagnetic forming energy was increased gradually with steps of 0.4 kJ. The material failed at 6.8 kJ.

Figure 4 shows significant amount of material above the FLC after the process chain. The figure also shows the strain path of a selected material point. The point stands adjacent to the crack in the punch edge radius region. This point exceeds the FLC drastically without undergoing strain path change due to the process chain.

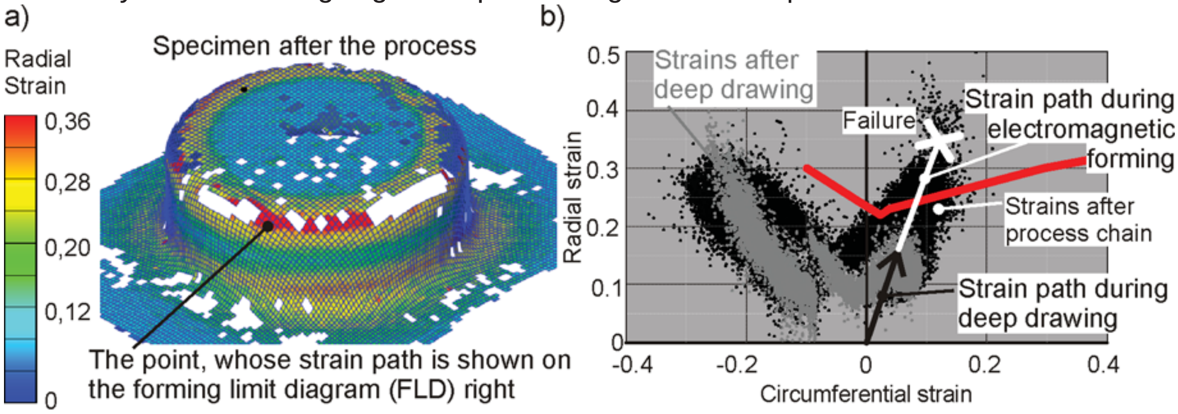

Figure 4 *a) Radial strain distribution on the specimen after the whole process chain. b) Forming limit diagrams (FLD) after deep drawing and after the whole process chain. A point adjacent to the material crack was selected to follow its strain path. The obtained strain path is shown with the arrows.*

3.3 Sharpest radii reached

Measurement on the part given in *Figure 4* reveals that the material fails starting from the outer radius of 13 mm (*Figure 5*a). To check, if this radius can be reached by one-step deep drawing at the same conditions, we performed deep drawing using 520 kN blank holder force and a punch with 15 mm edge radius. The result was material failure (*Figure 5*b).

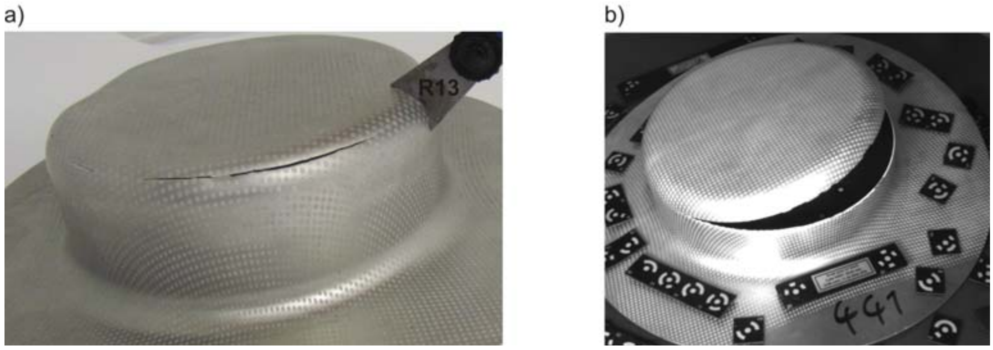

Figure 5 *a) The sharpest radii reached by the process chain without failure is 13 mm. b) One-step deep drawing cannot reach 15 mm punch edge radius under 520 kN blank holder force.*

4 Discussion

The experiments show, first of all, that the quasi-static FLC of the material can be exceeded by the process chain. Two factors may be causing this increase in the forming limits. The first factor is the impulse nature of the electromagnetic forming. It is claimed by several researchers like Seth et al. [6], Golovashchenko [7], and Thomas and

Triantafyllidis [8] that the impulse forming processes can exceed the quasi-static forming limits. The second factor is the strain rate *change*. It is well known that the strain path *change* can affect the forming limits. Similarly, strain rate *change* may also be affecting the forming limits. We know that the selected point exceeding the FLC in *Figure 4* does not undergo strain path change. However, it undergoes a strong strain rate change. Further investigation is needed to distinguish between these two factors, or to reveal the real cause of the increase in the forming limits.

The experiments show, secondly, that the investigated process chain is capable of extending the process limits of deep drawing. The results supply three evidences for that.

The first evidence: The deep drawing operation was conducted on a specimen until process limits by increasing the blank holder force. Starting from this specimen, the electromagnetic forming could form further.

The second evidence: For a given blank holder force, the process chain can produce a part, which cannot be produced by deep drawing. With the process chain it is possible to create under 520 kN blank holder force a cup with 15 mm edge radius. However, this is not the case for deep drawing (*Figure 5*).

The third evidence: The quasi-static FLC of the material can be exceeded by the process chain. However, it is widely known that it is not possible with a one-step conventional deep drawing operation.

5 Conclusion

Taking advantage of the process chain composed of deep drawing followed by electromagnetic calibration, the quasi-static forming limit curve (FLC) of the material can be exceeded. Further research is needed to reveal the factor making this exceeding possible.

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