Avoiding Bending in Case of Uniaxial Tension with Electromagnetic Forming *

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Abstract

During electromagnetic forming, excessive bending of the specimen takes place due to high velocities and inertia. We show that the excessive bending can be prevented by optimizing the coil geometry in case of uniaxial tension. The process is simulated with various coil geometries, and the resulting amount of bending is compared to the case of standard Nakajima Test. The comparison shows that the bending can be minimised to acceptable levels to be able to call the method a decent way of determining forming limits. The results should be verified experimentally.

Keywords

Forming limits, Electromagnetic forming, Nakajima Test

1 Introduction

To determine the quasi-static forming limits of a material there are standard tests like Nakajima Test and Marciniak Test. In these tests, the material should be formed monotonically on distinct strain paths until failure. There is not a standard test in case of electromagnetic forming. The main reason for this is the difficulty to let forming proceed on a certain strain path monotonically: The specimen bends and twists in several planes due to practical impossibilities, high velocities, and inertia.

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In this paper, we focus on the electromagnetic forming on the strain path of uniaxial tension, and propose a solution to the problem of bending.

To stretch material uniaxially, a narrow specimen is formed into a die cavity. If this is performed with a spiral coil, the centre of the specimen cannot be pushed with the electromagnetic forces. This leads to excessive bending in the centre. In order to avoid this, instead of a spiral one, a straight coil should be used. This improves the situation in the centre, however; without an optimization of the coil geometry, a flat coil leads to excessive bending at the rim of the specimen.

Only if we can avoid any excessive bending, we can be sure that the forming proceeds monotonically on the strain path of uniaxial tension. And only in this case, we can be sure that the maximum strain achieved is the forming limit for uniaxial tension.

We simulate the electromagnetic forming of a narrow specimen into a round die cavity. This is done with a straight coil, and the coil geometry is optimized to minimize any unwanted bending. The simulation results are compared with the results of a conventional Nakajima-Test. The comparison shows that the unwanted bending and wavy form of the specimen can be minimized by coil geometry optimization.

2 State of the Art

Several researchers observed the bending of the specimen during forming into a die cavity. The bending was seen both in cases of a spiral coil or a straight coil.

Kleiner et al. (2005) investigated forming into a conical die using a spiral coil [1]. Simulation showed a "*strongly inhomogeneous velocity distribution in the sheet metal*". They stated: "*In case of spiral coils, the pressure in the centre of the workpiece is always zero; therefore a homogenous distribution is not achievable*". This inhomogeneous velocity distribution leads to the bending of the specimen during forming (see Figure 1).

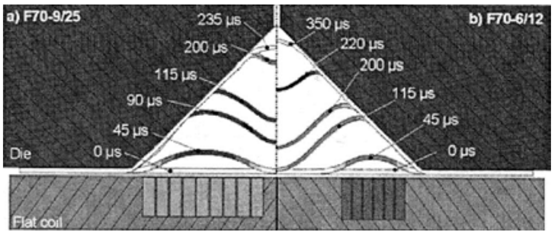

Figure 1 *The wavy forms the specimen takes in case of electromagnetic forming with spiral coils. A round specimen is formed into a v-shaped die cavity [1]*

Golovashchenko (2007) used a straight coil to form on the strain paths of plane strain and uniaxial tension (see Figure 2a) [2]. He reported a "*nonuniformly distributed electromagnetic field*" and a "*nonmonotonic character of deformation*". He observed a "*fold in the center of the sample*" (Figure 2b). By stating "*The shape is different from typical dome shape of samples after FLD testing*", he revealed that the method is not suitable to determine forming limits like in a decent "*FLD testing*" method.

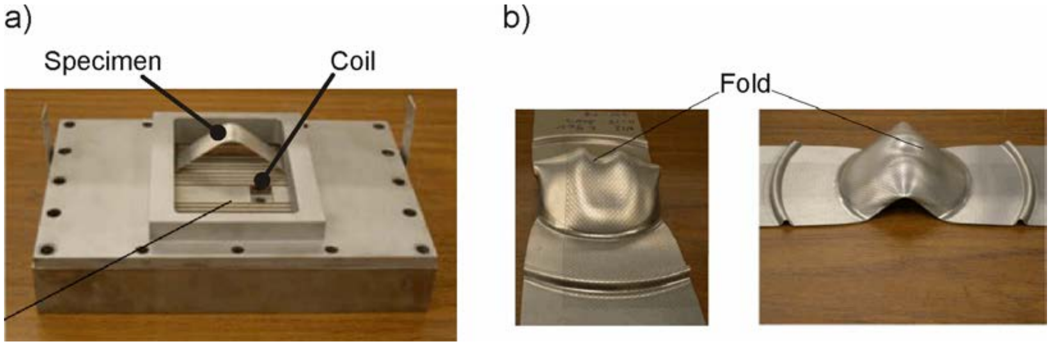

Figure 2 *a) Straight coil windings laying under the specimen b) The specimen after being formed with a straight coil [2]*

Kamal (2005) introduced a coil design, which is called Uniform Pressure Actuator, to be able to use straight coils more effectively [3]. In this design, a conductive part is added to the setup. This part is called the conductive outer channel. The channel and the workpiece form a closed circuit and the induced current flows through it. Imbert et al. (2006) used this design and compared the results with a spiral coil [4]. They reported drastic improvement in the uniformity of the velocity distribution, and thus less bending of the specimen.

They obtained this result by using a straight and a flat coil, and focused on the bending in the centre, not on the bending at the rim. Our simulation results show that a flat coil induces severe bending at the rim. In this paper we are going to change the flat shape of the coil, and optimize it to prevent bending.

3 Methods

3.1 The Finite Element Model

The specimen material is EN AW-5083 with temper designation H111. The quasi-static flow curve of the material was obtained by conventional tensile tests. The high strain rate flow curves until 1000 s^{-1} were determined by the company Nordmetall GmbH using a rotating wheel test, and published by Engelhardt et al. in 2010 [5]. These flow curves do not exhibit a significant strain rate dependency. That is why, the strain rate dependency of the workpiece material was neglected during the simulations.

The specimen is a scaled version of standard Nakajima Test specimen that is used to create uniaxial tension. Its dimensions can be seen in *Figure 3*. It is modelled with approximately 15000 nodes and 10000 3-dimenisonal brick elements with single integration points. The specimen thickness is divided into three elements. The element aspect ratio varies between 1 and 2.15.

The coil width was varied between 8.5 mm and 10 mm during the optimization. The thickness profile of the coil was also varied during the optimization. At the thickest point the coil is 14 mm thick (see *Figure 3*). The coil was modelled with 10000 nodes and 12000 3-dimensional brick elements with single integration points. The element aspect ratio varies between 1.3 and 2.

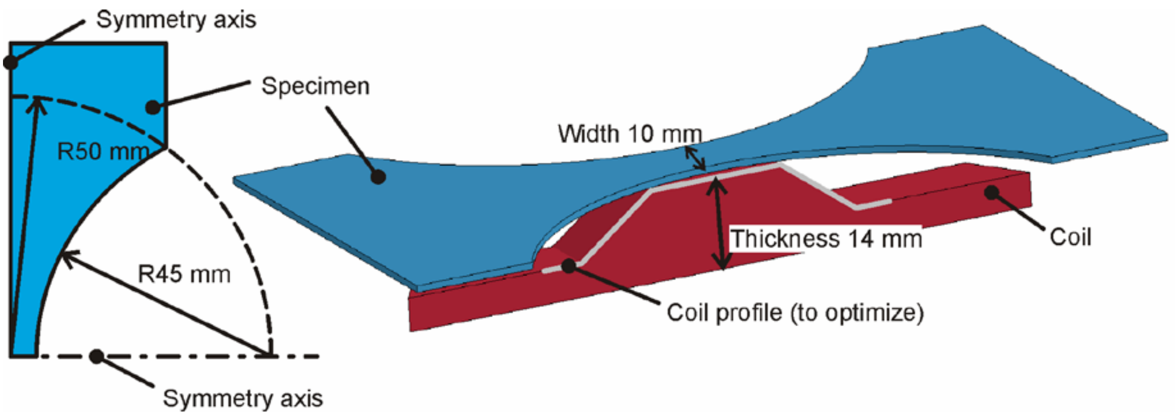

Figure 3 *The geometries of the specimen and the coil. The specimen has a thickness of 1 mm.*

The dimensions of the drawing ring are given in *Figure 4*. The edge radius of it is 5 mm. A 25 kN blank holder force and a draw bead at Ø150 mm was used in the model.

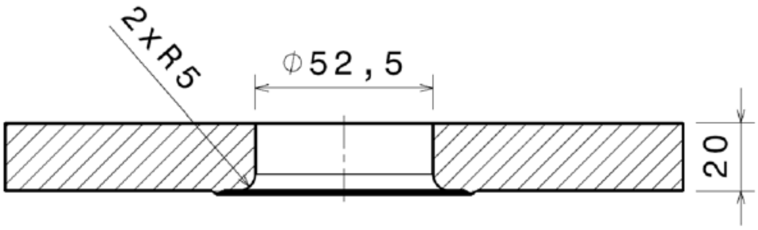

Figure 4 *The drawing ring has a round opening*

For the electromagnetic part of the simulation, the machine called SMU 0612 FS was modelled with its 80 μF capacitance, 4.2 mΩ internal resistance, 40 nH internal inductance, and 9 kJ maximum energy. This machine is used by the Institute of Forming Technology and Lightweight Construction (IUL) for electromagnetic forming, and was manufactured by the company Poynting GmbH.

The simulation was conducted with LS-DYNA v980. The electromagnetic, thermal and the mechanical parts of the problem were loosely coupled with each other. The electromagnetic matrices were updated every 5 microseconds. The electromagnetic and thermal solutions had a time step of 0.04 microseconds, while the mechanical solution had a time step of 0.02 microseconds.

In order to evaluate the simulation results, they were compared with a conventional quasi-static Nakajima Test. For that, Nakajima Test was simulated using the same specimen geometry with the electromagnetic simulation. A semi-spherical punch (Ø100 mm) was used in the Nakajima Test simulation. This simulation was performed by explicit finite element method using LS-DYNA v980.

3.2 Optimization

The optimization was performed manually, without using any special software. The width and the thickness profile of the coil were optimized. Three different widths were simulated: 8.5 mm, 9.25 mm, and 10 mm, which is equal to the specimen width. The various thickness profiles that were simulated can be seen in *Figure 5*.

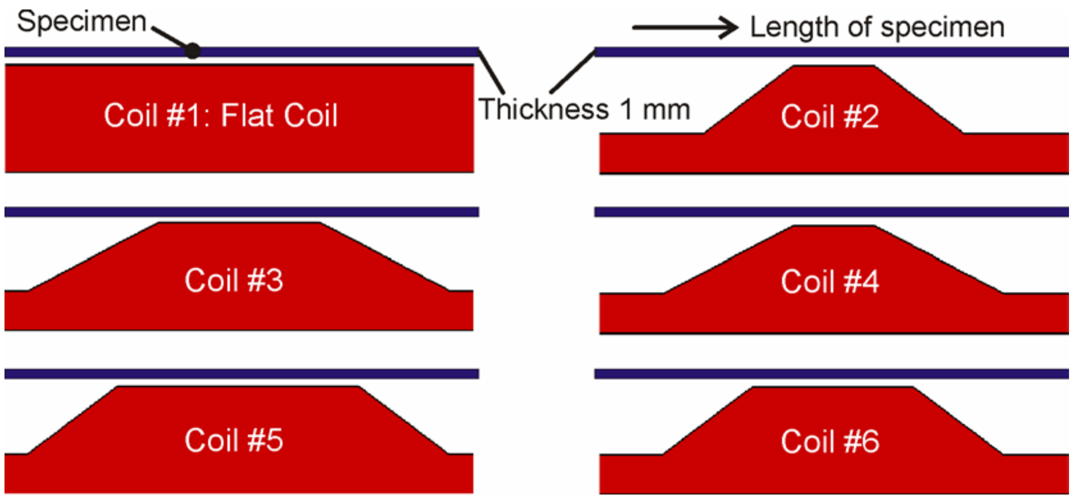

Figure 5 *Thickness profiles that were used in the simulations.*

The forms that the specimen takes during electromagnetic forming and Nakajima Test were compared with each other. This was done at two different forming depths: 2.8 mm (at the beginning of the process) and 12 mm (towards the end of the process). For that, the simulation was stopped at the desired forming depth, and a section cut along the length or width of the specimen was taken. In order to see the details of the cross-section geometry better and notice the nuances between them, the displacements were scaled up. The corresponding scaling ratios are given in the captions of the figures *Figure 6*, *Figure 7*, and *Figure 8*.

4 Results

4.1 Specimen profile along the length

To see the specimen profile along the specimen length, a section cut normal to the specimen width was taken. *Figure 6* and *Figure 7* show this section view. *Figure 6* reveals the comparison between three different coil designs at the beginning of the process (forming depth 2,8 mm). *Figure 7* shows the same comparison towards the end of the process (forming depth 12 mm).

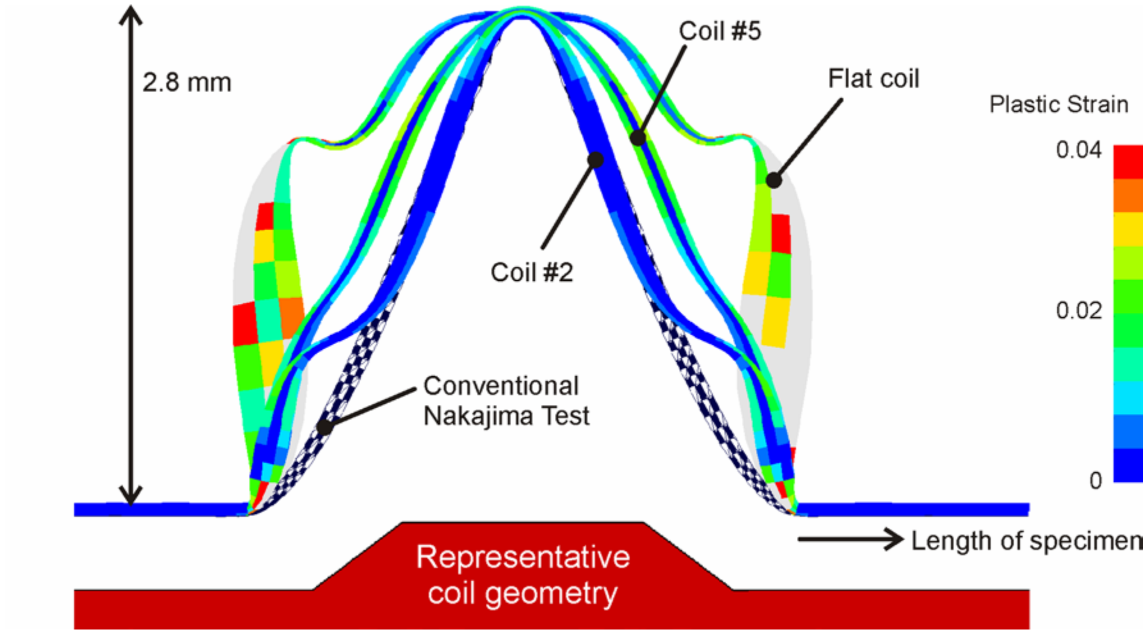

Figure 6 *Cross-sectional views of specimen in cases of different coil geometries given in* ***Figure 5****, and in case of conventional Nakajima Test. Displacement scale factor: 20*

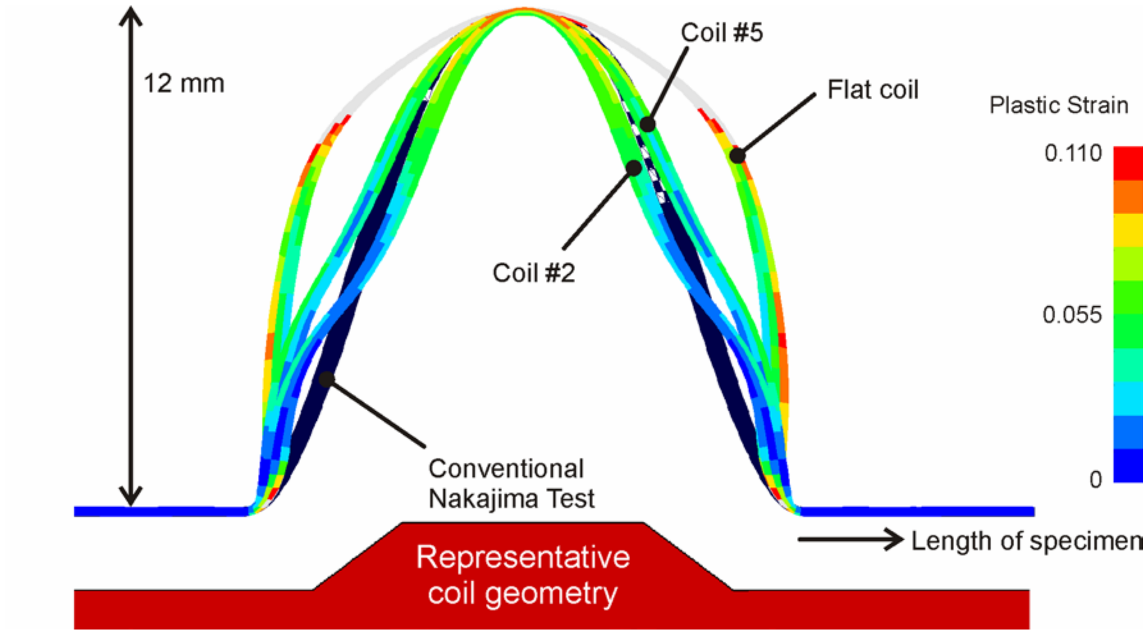

Figure 7 *Cross-sectional views of specimen in cases of different coil geometries given in* ***Figure 5****, and in case of conventional Nakajima Test. Displacement scale factor: 5*

4.2 Specimen profile along the width

To see the specimen profile along the specimen width, a section cut normal to the specimen length was taken. *Figure 8* shows this section view. *Figure 8* reveals the comparison between coils with three different widths: 8.5 mm, 9.25 mm, and 10 mm.

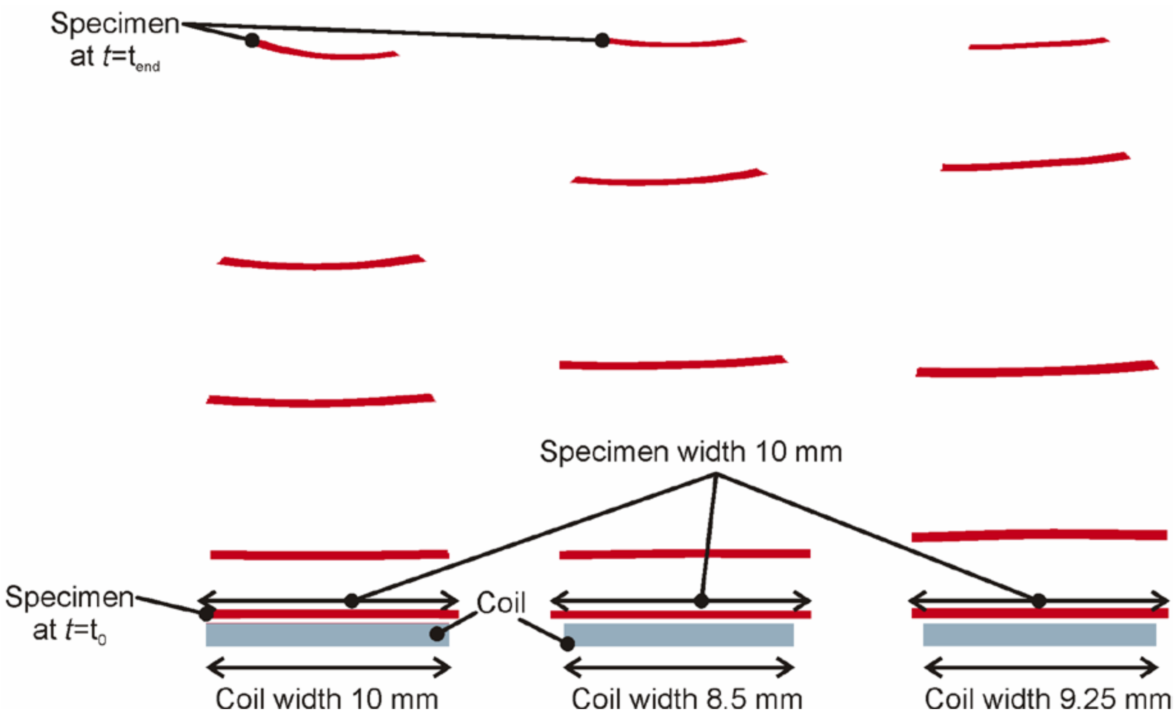

Figure 8 *Cross-sectional views of specimen during the test, in case of different coil widths. Figure not to scale. Displacement scale factor: 5*

5 Discussion

Figure 6 shows that the specimen experiences severe bending in case of a flat coil. The change of coil profile, in which it is thicker in the middle and thinner at the rim, improves the situation drastically.

At the beginning of the forming process (*Figure 6*), in case of Coil #2, the profiles of the quasi-static and electromagnetic cases overlap perfectly in the centre. Only the slight bending at the rim distinguishes the two results. In case of Coil #5, the profile does not overlap perfectly with the quasi-static case. The electromagnetic forming stretches the specimen more, compared to Nakajima Test. When we compare the results with Coil #2 and Coil #5, we see that Coil #2 leads to more bending in the specimen profile: The specimen profile with Coil #2 is wavier than the one with Coil #5.

Towards the end of the forming process (*Figure 7*), in case of Coil #5, the profiles of the quasi-static and electromagnetic cases overlap in the middle. Only the slight bending at the rim distinguishes the two results. When we compare the results with Coil #2 and Coil #5, we see that coil Coil #2 leads to more bending in the specimen profile: The specimen profile with Coil #2 is wavier than the one with Coil #5.

Coil #5 delivers at both the beginning and the end of the process the minimum amount of bending. This is an acceptable amount to call the test as a decent method of determining forming limits. This can be seen when the cross-sections delivered by Coil #5 and Nakajima Test are compared in figures *Figure 6* and *Figure 7*. The results show that it is logical to select Coil #5 as the optimized coil geometry.

Figure 6 and *Figure 7* show the bending in the plane normal to the width of the specimen. *Figure 8* shows that the specimen also experiences bending in the plane normal to the length of the specimen. Such a bending does not occur when the forming is conducted quasi-statically with a punch. This bending is a severe disadvantage of using an electromagnetic coil instead of a punch, and must be minimized.

Figure 8 shows that the least bending occurs when the coil width equals 9.25 mm. So it is logical to select 9.25 mm as the optimized coil width.

6 Conclusion

In order to determine the electromagnetic forming limit of a material in case of uniaxial tension, a narrow specimen can be formed electromagnetically into a die cavity. However, during this process, the specimen experiences excessive bending in the planes normal to its length and width. Simulation results show that this bending can be minimized by optimizing the coil geometry. The optimized coil geometry delivers specimen geometries which are very similar to the specimen geometries encountered during the standard Nakajima Test.

To verify the conclusions drawn from the simulations, experiments should be conducted with the optimized coil geometry, and the results should be compared with the Nakajima Test.

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