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Influence of the Workpiece Stiffness on the Electromagnetic Sheet Metal Forming Process into Dies

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Electromagnetic sheet metal forming is a high speed forming process using pulsed magnetic fields to form metals with high electrical conductivity such as aluminum. Thereby, workpiece velocities of more than 300 m/s are achievable, which can cause difficulties when forming into a die. The kinetic energy, which is related to the workpiece velocity, must be dissipated in a short time slot when the workpiece hits the die; otherwise undesired effects, for example rebound can occur. One possibility to handle this shortcoming is to locally increase the stiffness of the workpiece. A modal analysis is carried out in order to determine the stiffness of specific regions of the workpiece so that an estimation concerning the feasibility of the desired geometry is possible in advance without doing cost and time consuming experiments. Thereby, the desired geometry of the workpiece will be fractionized in significant sectors. This approach has to define the internal force variables acting on the cutting edge, which are required to constrain the numerical model. Finally, a method will be developed with the objective of calculating the stiffness of each sector. The numerical results will be verified by experiments.

Keywords aluminum, electromagnetic sheet metal forming, modal analysis

1. Introduction

Research and development in the transportation sector focuses increasingly on the implementation of lightweight construction concepts. Therefore, the application of lightweight materials such as aluminum or magnesium also becomes more and more important. A further interesting aspect is the application of these materials in manufacturing processes, which are particularly suitable for forming these materials. Electromagnetic sheet metal forming—an energy-based high-speed process—represents one of these processes using pulsed magnetic fields to form metals with a high electrical conductivity, such as copper or aluminum.

2. Motivation and Forming Mechanism

A typical experimental setup for electromagnetic sheet metal forming is illustrated in Fig. 1 and 2a, which consists of a forming machine, a spirally wound tool coil, a form defining tool and a workpiece. The die as well as the blank are located above the tool coil. In this example, the die is assembled by the drawing ring and the cover plate, which is in this case a cylindrical cup. The forming machine is simplified represented by an equivalent circuit consisting of a capacitor c, an inner inductance L, and an inner resistor R. A detailed description of the process principle is given in (Ref 1, 2).

Due to characteristic forming mechanisms local workpiece velocities of up to 300 m/s are achievable, which can cause difficulties when forming into a die. This correlation and the associated importance of the geometrical stiffness of the workpiece in this highly dynamic process can be explained on the basis of the energy transfer during the process, which is represented in the diagram in Fig. 1b. When the charging energy E_c, which is stored in the capacitor of the forming machine, is transferred into a magnetic pressure pulse p, the deformation of the workpiece starts, namely in the area where the windings of the tool coil are located. The resulting workpiece velocity can reach values of approximately 180 m/s in this case (compare the intermediate forming states in Fig. 1a). This means that the magnetic pressure pulse is transferred into kinetic energy E_{kin}, which is reflected in the velocity distribution of the workpiece, on one hand, and into forming energy E_{def}, on the other hand. In this energy balance all energetic losses, for example friction, are neglected. At the moment t_1 when the pressure is decreased to zero the complete energy available for the remaining forming process is stored in the workpiece. In a free forming operation, this means without a die, the process ends as soon as the kinetic energy is completely transferred into deformation energy. Contrary, when forming into a die, the deformation is stopped as soon as the workpiece hits the die, for example at the moment t_{contact}. This contact is accompanied by a sudden decrease of the workpiece velocity. In this case the remaining kinetic energy E_{contact} in the workpiece has to be dissipated by the die. If this transfer cannot be entirely guaranteed, the remaining energy in the

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workpiece can cause further undesired effects, for example a rebound or other insufficient form filling (marked in Fig. 1a) (Ref 4). The last mentioned defect is caused by the fact that the middle part of the workpiece is too stiff, on the one hand, and on the other hand, the remaining kinetic energy in this part of the workpiece is deficient to fulfill the forming task successfully. In contrast, the occurring rebound is the result of the combination of several criterions: high kinetic energy and less geometrical stiffness of flat areas. Therefore, the geometrical stiffness is one important parameter, which has to be considered by analyzing the electromagnetic forming process beforehand.

In order to vary the geometrical stiffness systematically, different forming elements are used in addition to the described experimental setup (compare Fig. 2a). These forming elements can be easily adapted to the cover plate. In order to keep as many parameters as possible constant, only the angle between cover plate and geometrical inserts and the depth of the geometrical insert have been varied, whereas the workpiece material, the sheet thickness, the depth as well as the tool coil geometry were the same throughout this investigation. Thus, the used die consists of flat bottoms and conical elements. The used material in all regarded experiments was aluminum (Al 99.5) with a thickness of 1.5 mm. The results of this investigation will be explained exemplarily on the basis of selected geometrical elements, shown in Fig. 2b.

3. Estimation of the Geometrical Stiffness of the Complete Structure

In order to compare different geometries in a simple way, the significant value K is introduced to define the geometrical stiffness of the desired workpiece geometry. The geometrical stiffness K of the workpiece can be roughly estimated with the knowledge of the first eigenfrequency via the following equation (Ref 5)

$$K = (2\pi f)^2 m \qquad \text{(Eq 1)}$$

thereby,the eigenfrequency f as well as the mass of the workpiece m were calculated with a modal analysis in the general purpose FE-program Ansys (version 8.1). The used method to determine the eigenfrequencies was Block Lanczos. In doing so, the FE-model exploits the axis symmetry of the investigated geometry so that only one cross section of the setup has to be modeled. But this assumption concerning the axis symmetry affects the analysis because some frequencies could not be calculated. Moreover, the undeformed flange area is neglected in the modeling of the workpiece because the flange increases the stiffness of the different geometries in the same manner.

4. Experimental and Numerical Results Regarding the Complete Geometry

The experimental as well as numerical results of the investigated geometries are summarized in Fig. 3. The photos, illustrated in Fig. 3a, show that, in general, a good form filling is achieved in both cases. Here, it is remarkable that the flat areas marked as B in case III and X in case II are achieved in good order. The main difference of the realized workpiece geometries is the geometrical stiffness (compare the table in Fig. 3b), which is higher in case III, although the added

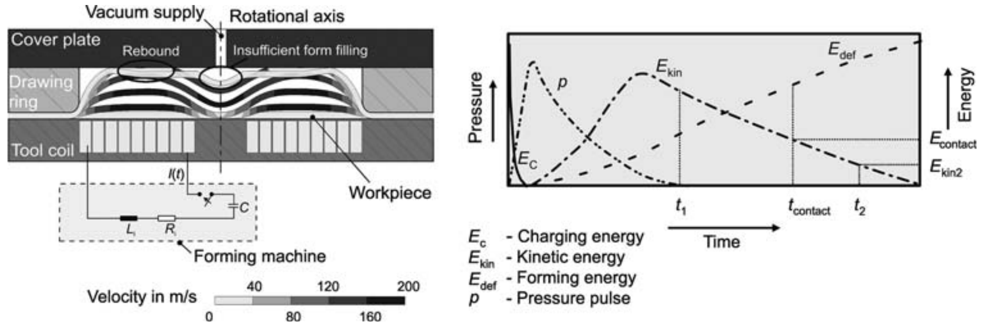


Fig. 1 (a) Process principle; (b) Energy transfer within the electromagnetic forming process (Ref 3)

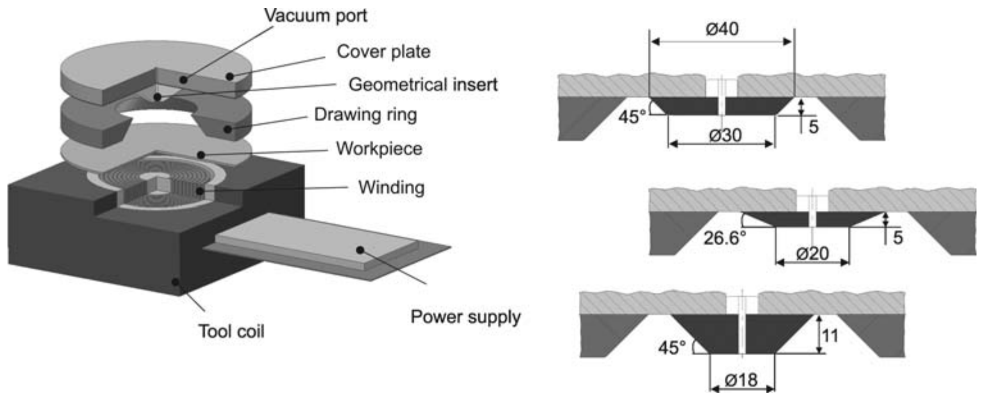


Fig. 2 (a) Experimental setup; (b) Selected geometrical inserts

geometrical inserts look quite similar. Regarding the achieved form filling in case II, a geometrical deviation can be observed in the ring-shaped area Y (compare the enlarged pictures). The desired contour could be achieved and no measurable geometrical deflection was detected, compare the enlarged pictures in Fig. 3a.

The results of the performed modal analysis regarding the eigenfrequency of the investigated geometries are summarized in the table in Fig. 3b. Thereby, the investigation starts with the analysis of a cylindrical cup (case I), followed by geometries consisting of conical as well as flat elements (case II-case IV). Although the investigated geometries look very similar, the corresponding eigenfrequencies are quite different. The results of this analysis substantiate that by increasing the geometrical stiffness the rebound effect and the geometrical deviations, respectively, exemplarily shown in Fig. 3a, could be reduced. Furthermore, due to preventing the middle part from deformation in case IV, a stretch-forming operation dominates in this area. This results in an extreme material thinning in the edge. Therefore, it is important to find a balance between the required geometrical stiffness to realize a component and the maximum formability of the used material, which is acceptable regarding technical as well as functional requirements.

However, in order to identify critical regions regarding the risk of insufficient form filling in advance, it is useful to determine local geometrical stiffness of specific workpiece areas. Therefore, a strategy in order to estimate the local stiffness of significant workpiece areas is applied.

5. Strategy to Estimate Local Geometrical Stiffness of Specific Workpiece Areas

The general idea to estimate the local geometrical stiffness of special workpiece sectors is shown in Fig. 4 on the basis of an example. At first, the structure is divided into part-dependent sectors of the workpiece followed by a modal analysis of each segment. Thereby, it is important to constrain the nodes on the regarded cutting edge. The simplest possibility is to constrain these nodes to a zero oscillation condition so that any "movement" of the nodes is avoided. With this strategy the calculation of the eigenfrequencies of each sector to obtain the local geometrical stiffness can be done by means of Eq. (1). Any discontinuity of the stiffness within the workpiece, which could cause difficulties with regard to achieving the desired geometry could be detected by the described strategy as discussed in the following.

6. Discussion of the Results

Using this strategy, the final geometry regarded in case III, shown in Fig. 5, is divided into four sectors, for which the local geometrical stiffness is calculated. The presented velocity distribution within the workpiece of different deformation states is obtained by means of a coupled electromagnetic-mechanical simulation (Ref 6). The results are summarized in the table in

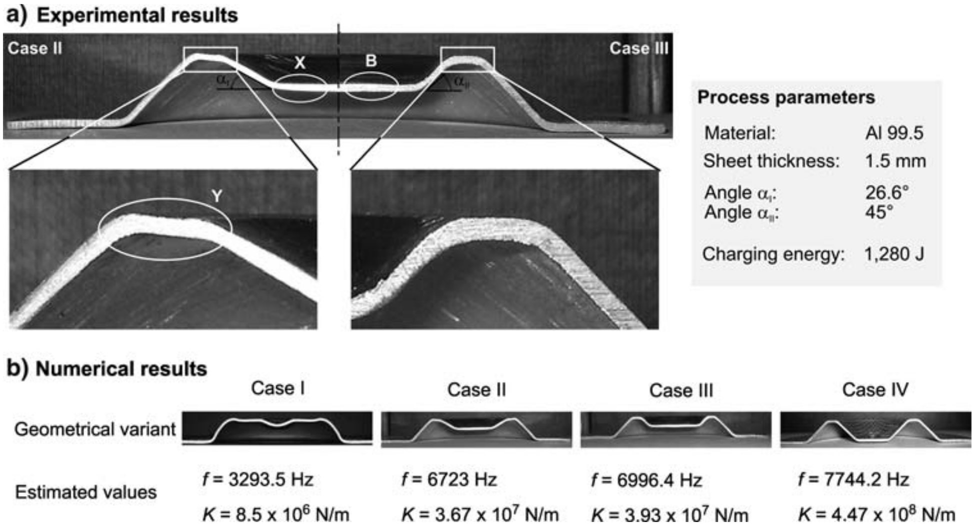


Fig. 3 Experimental and numerical results by using different geometrical inserts as forming elements

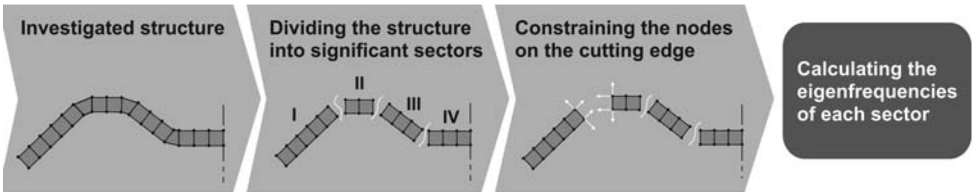
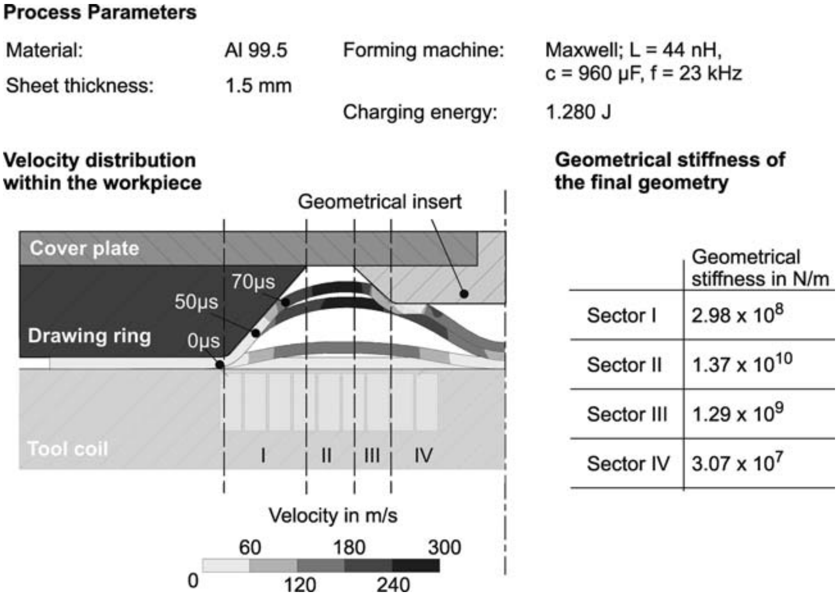


Fig. 4 Strategy for local stiffness estimation



Process Parameters

Material: Al 99.5
Sheet thickness: 1.5 mm
Forming machine: Maxwell; L = 44 nH, c = 960 µF, f = 23 kHz
Charging energy: 1.280 J

	Geometrical stiffness in N/m
Sector I	2.98×10^8
Sector II	1.37×10^{10}
Sector III	1.29×10^9
Sector IV	3.07×10^7

Fig. 5 Local stiffness distribution and corresponding velocity distribution of the investigated example

Fig. 5. It is remarkable that the calculated geometrical stiffness of sector II and sector III are very high compared to the other sectors. As described in the previous chapter the critical area of this geometry where undesired deformations can occur is situated near the crossing between sector II and sector III. The velocity of the corresponding workpiece area is about 200 m/s, whereby the resulting kinetic energy is also high.

Comparing these facts, it could be seen that the workpiece zones which have the highest local geometrical stiffness in the final geometry are also the fastest ones during the forming process. Thus, it is possible that the kinetic energy resulting from the workpiece velocity could be completely transferred into forming energy. Consequently, no rebound occurs in this example (case III) and the desired geometry was achieved.

7. Summary and Outlook

The influence of the geometrical stiffness on the electromagnetic sheet metal forming process has been presented and a method to determine the geometrical stiffness has been introduced. Furthermore, the importance of the process knowledge to interpret the results concerning the local workpiece stiffness has been pointed out. Therefore, this process knowledge has to be taken into account in the analysis of the geometrical stiffness. For this purpose an investigation of the geometrical stiffness of different intermediate forming states has to be carried out so that stiffness over time curve can be developed to evaluate the feasibility of the desired geometry.

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