A Production-oriented Approach in Electromagnetic Forming of Metal Sheets

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Abstract

In recent years, sheet metal forming shows tendencies to process a smaller number of parts per unit. Especially demands of modern lightweight design seem to be hard to satisfy by stretching conventional production methods. Thus, it is necessary to find new approaches. Adapting electromagnetic forming technology for the automotive industry would gain additional benefits like

- *less surface damaging owing to contact-less forming,*
- *the possibility of achieving smaller radii,*
- *focusing on low volume production through minimizing investment costs, and*
- *more manufacturing flexibility.*

An approach to start qualifying this technology under the aspect of production engineering has been attempted by establishing a high speed forming project. The Volkswagen AG, Siemens AG, H&T ProduktionsTechnologie GmbH together with Fraunhofer Institute of Machine Tools and Forming Technology started activities focusing on

- *clarifying the fields of research and development which are not resolved to date,*
- *developing necessary equipment, and*
- *a systematic research on the according technology.*

The analysis of available equipments brought up a number of questions with respect to production engineering requirements. It resulted in a 100 kJ pulse power generator. One of the core components to define the quality of the forming process of flat parts is the flat coil. A coil design is selected to transfer a maximum of stored energy into the sheet metal. A selection of basic and applied experiments had the aim to know the limits of the technique. The paper introduces some representative results of the project. It touches the challenges related to the process of bringing this technology to production

Keywords:

Forming technology; Electrical discharge machining, Production engineering

1 Introduction

Caught between the forces of international competition and an emerging trend towards individualization of customer requirements, today's companies are attempting to assert themselves and/or acquire new market shares by increasing their product range. The consequence is severe upward pressure on costs and production methods used to date are now being called into question. Possible solutions are to increase the efficiency of existing processes and to harness technologies which are new or which have, up until now, been somewhat neglected.

Electromagnetic flat forming is an example of one such technology. The primary field of application for flat forming is in postforming i.e. the process which follows the actual forming procedure in the process chain and in the opportunity for forming ancillary formed elements. However, many of the familiar challenges in this technology segment which have been known for decades have not yet been resolved, even with today's knowledge. New materials and advanced development of the technologies required for magnetic forming nevertheless present obvious possibilities in terms of overcoming the complex obstacles.

In the context of a project sponsored by the investment bank Sächsische Aufbaubank (SAB) and implemented in partnership with Volkswagen AG, Siemens AG, H&T Produktionstechnologie GmbH, and the Fraunhofer Institute for Machine Tools and Forming Technology, research is being carried out in the areas of current impulse equipment, magnetic coils, forming technology, and simulation. This project represents an attempt by the partners to highlight magnetic forming in terms of application-oriented research.

2 Technical installations for electromagnetic flat forming

2.1 The experimental equipment

In order to investigate electromagnetic forming under production engineering conditions, a suitable experimental plant was developed, consisting essentially of an energy storage equipment with appropriate switching technology to provide the energy, a flat forming coil with the necessary connectors and links to transfer the energy to the workpiece, and a tool holder to absorb the forming forces. As is required in forming technology production plants, the individual processes must be capable of being safely controlled and operated as well as important measurement and status parameters must be automatically recorded.

The design project focused on the safe integration of the pulsed current equipment and its connection to the forming coil inside the tool holder. The necessary development work was carried out in close collaboration with our joint venture partner Siemens.

The specifications for the tool holder were defined by the anticipated forces and the degree of flexibility required in accordance with the program of experiments. The objective of the investigations to be performed using the experimental plant is to qualify the technical and technological aspects of the installation for production engineering applications (see Figure 1).

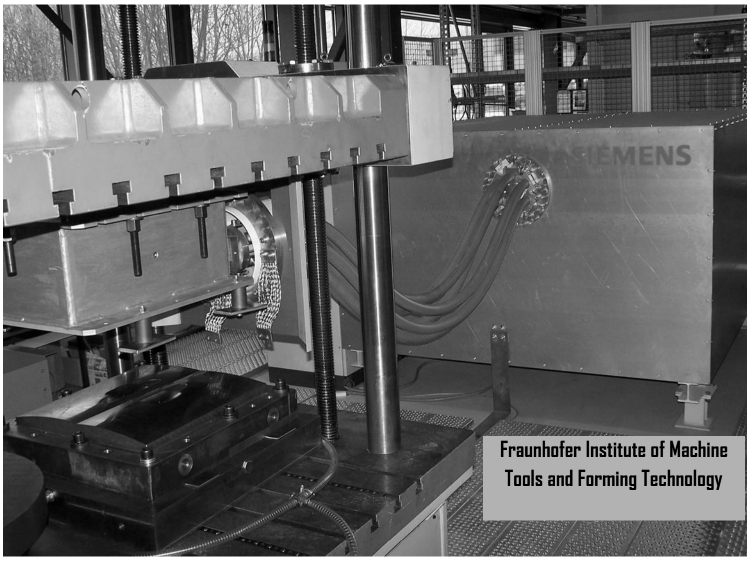


Figure 1: *Experimental electromagnetic forming plant*

The pulse magnetic field required to produce a pressure impulse on a sheet of metal to be formed is generated by a current impulse. Suitable current impulse equipment consists without exception, of a fast bank of capacitors with a charging voltage of some 100 V up to some 10 kV and the associated power circuit breakers. By closing the circuit breaker the energy is discharged from the bank of capacitors via the forming coil. A survey of commercially available pulsed current equipment for use in magnetic forming revealed that the equipment can be classified according to stored energy and that energy stores of up to 80 kJ are used. The selection and dimensioning of the components used is a function of the maximum voltage used, the maximum amount of energy to be stored, the peak currents and maximum increases in current arising in the oscillating circuit, and the mechanical and thermal load. In addition, when estimating the useful life of the equipment as part of the design of the experimental plant the shock load of all the components during the discharge process must be taken into account.

The design of the impulse equipment was essentially underpinned by the idea that the technological investigations into electromagnetic forming of flat components should concentrate initially on smaller structural elements. During the course of the investigations the results obtained were applied to flat geometries of more extensive size. As there is no reliable ratio between the amount of energy required and the area to be formed, taking account of geometric and materials parameters, it was decided - after consulting users and following extensive research in the literature - to specify 100 kJ as the electrical energy storage capability. The experimental plant was designed on the modular principle in order to permit replacement of selected components, if necessary.

In order to keep the capacity of the bank of capacitors low, given a specific energy requirement, and hence to keep the size of the impulse generating equipment to a minimum, the usable voltage level was set at 20 kV. In the voltage range envisaged vacuum switches (spark gaps), ignitrons (gas discharge tubes), and thyristors (semi-conductor switches) were used as circuit breakers and high-current switches. Previous current impulse plants have hitherto been produced almost exclusively with vacuum switches or with gas discharge tubes. The use of vacuum switches requires a higher level of maintenance, which ultimately makes them difficult to use in production engineering situations. Ignitrons, on the other hand, require no maintenance. The crucial disadvantage of ignitrons is that they consist of a liquid mercury cathode. In the event of a disastrous failure of the tube the ambient air may be contaminated with mercury. As this residual risk can not be completely excluded, in some countries the use of these switching elements is subject to the most severe restrictions or is prohibited altogether. Semi-conductor switches, by contrast, require no maintenance, nor do they carry the aforementioned risk. In the past, because their performance parameters were too low, these switching elements were only used for switching at low power levels or for switching processes in which the switching times were not critical. As a result of the development of GCTs (Gate Commutated Thyristors), it was possible to improve the switching characteristics of GTO thyristors (Gate Turn Off thyristors), given comparable load parameters. In addition, the characteristic values required, such as cut-off voltage, current carrier capability, and current rise time, are provided by the switching elements. Therefore the decision was, taken to opt for semi-conductor elements as circuit breakers (see Figure 2).

***Figure 2**: Arrangement of semi-conductor switches in the pulsed current plant*

In order to specify equipment requirements for electromagnetic forming plants in production engineering settings, it is essential to consider the handling of the tools and the workpieces. For this reason, a tool holder was chosen which is fitted with a spindle-driven lifting and tipping unit. After applying the electromagnetic setup approx. 650 mm of travel of the upper mounting plate is left. Since no masses (tools) have to be accelerated during the forming process the position of the working coil and the tool can be chosen arbitrarily. In the case of larger profiles it should be noted that the metal sheet to be formed flexes due to gravity, depending on the geometric and material parameters. This effect is further intensified by evacuating the space between the tool and the profile. This alters the distance between the sheet of metal to be formed and the working coil which, in turn, adversely affects the electromagnetic coupling and, hence, the degree of efficiency. This change in the process parameters must be taken into consideration when constructing the tool, the working coil, and the production plant and appropriate measures must be taken to compensate in certain circumstances.

Investigations into position-dependent process characteristics require a mobile connection to the pulsed current equipment on the tool holder. Therefore, it is important to analyze the electrical properties such as contact resistances on the connecting elements and self-inductance of the cable and insulating sections. The chosen design fulfils the necessary criteria and can be mounted on both the rigid and the mobile mounting plate, thereby guaranteeing the flexibility in terms of assembly that is absolutely indispensable for the investigations.

In addition to the vertical positioning axis, the tool holder has a tilting axis permitting rotation of the upper plate through 360 degrees. This has proved to be particularly advantageous for installing the working coil on the upper plate. The connecting elements between the working coil and the energy chain must, however, be released manually before each rotation and fixed in place again after each coil change. An automated solution should be provided for the replacement and adjustment of the working coils in order to minimize tooling times.

Besides the availability of the main components such as capacitors and circuit breakers, it is essential to assess whether the selected voltage level and the resulting peak currents can be safely controlled in the installation as a whole. To this end, a safety and grounding plan was devised, based on a risk analysis. In addition to the usual mechanical dangers associated with forming machinery, electromagnetic forming plants carry risks resulting from high voltages and power outputs as well as from impulse magnetic fields. For this reason, the working area was galvanically isolated from the operator area. The power is supplied via a specially dimensioned contact separator. Control data and measurement data are exchanged via fibre optic cable between the autonomously operating control components. The experimental plant is controlled via a central operator console outside the protected zone. In case of an emergency an uninterruptible voltage supply ensures that the safe operational status of the installation as a whole can be restored. For the pulsed current equipment this means a complete discharge of the capacitors via rheostats specially designed for this purpose. All components within the protected zone are centrally grounded.

Measuring the forming process itself is made more difficult by the electromagnetic and mechanical properties of the setup and the expected high forming speeds. As has been shown in comparable applications, here, too, the current path and voltage path across the working coil are measured in order to determine the relationships between stored energy and the forming outcome. Although the measured results only reflect the global relationship between electromagnetics and structural mechanics, they nevertheless serve to verify coupled simulation models. In addition, the data provide information on the loading of the components within the pulsed current equipment. For the above reasons, experimental protocols containing both the measurement data and relevant parameters concerning the equipment are automatically generated.

2.2 Flat coils for magnetic forming

The tool and working coils must be adapted as closely as possible to the eventual form of the workpiece in order to create an efficient energy transfer and, hence, to apply the maximum possible amount of force to the workpiece. In sheet metal forming the working coils are constructed so they are flat (and are therefore also referred to as flat coils). Since all that is needed in the gap is space for the electrical insulation between coil and work piece the gap should be minimized in order to improve efficiency.

The natural frequency and maximum current of the oscillating circuit, consisting of the pulsed current equipment, transmission lines, and working coil, are determined with the electrical properties of the working coil – inductance and resistance. These parameters, in conjunction with the coupling characteristics of the sheet metal to be formed, define the forces between the working coil and the sheet metal. In addition to the definitive axial forces, however, comparable radial forces also occur between the turns. The calculation models drawn up in a joint project with Siemens are used to determine the electrical and mechanical characteristic values, which serve as input quantities for dimensioning and constructing the working coils.

In theory, a working coil consists of a conductor with corresponding connectors, a coil mount, possibly consisting of more than one section, and the power supply elements.

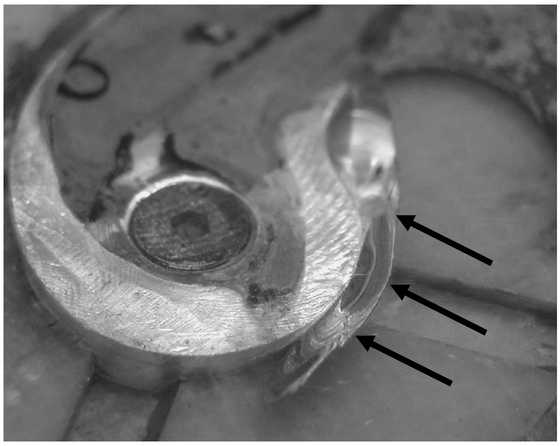
a)  b) 

Figure3: *Flat coil with spiral turns a) flat coil after casting, b) crack formation along the turn*

If the conductor is shaped in the form of an Archimedes screw (see Figure 3a) special structural measures are required to connect the inner end of the conductor. The coil is incorporated in a coil mount which must be capable of withstanding the high shock loads. If the turns are very tight care must be taken to provide good electrical insulation between them. Depending on the design of the coil, voltage differences can arise corresponding with the maximum useful voltage. If the voltage insulation is provided in the form of a cast resin this will be subjected to the pulse-like radial forces. For this reason, selection of the cast resins must take account of their impact strength, rupture strength, and elongation at fracture. As shown in Figure 3b, an increase in crack formation along the turns was observed when cast resins with a very high E-modulus were used.

Depending on the design, established manufacturing processes such as milling and water jet cutting can be used to produce the working coils. If the current-carrying elements consist of several parts the contact resistance must be minimized. Abutting or arced connections are subject to electrical forces that must be taken into account at the design stage. If the individual components are connected to one another by means of hard-soldered connections, the execution of the joints must be optimized with regard to contact resistance and mechanical stability. The turns are mildly annealed due to the increased application of heat and their strength is thereby reduced. In order to be able to withstand the radial load, the turns must be supported by additional constructional measures, for example the selective choice of casting material.

The load on the working coil is also determined by the position of the sheet metal to be formed in relation to the working coil. If the sheet metal completely covers the coil and at a minimal distance a good coupling should be guaranteed. If the sheet metal is smaller than the coil or is no longer homogeneous (with sections cut out or formed areas) then the initial inductance of the oscillating circuit is determined by the position of the workpiece in relation to the coil. A poorer electromagnetic coupling means an increase in the mechanical load on the coil. It was observed during investigations in connection with this aspect that the coils fail in the vicinity of poor electromagnetic coupling. This must be taken into account in particular where the sheet metal is formed in several stages without adjusting the working coil properly and restoring the coupling. These special operating conditions must be considered during the design process of the working coil.

In addition to the increased mechanical load on the working coil, poor coupling conditions also affect the components inside the pulsed current equipment. The increased inductance accompanying the diminished coupling results in an increase in the load current integral (I^2t). The thermal ageing process triggered as a result reduces the anticipated serviceable life of the components. In order to be able to estimate the load on all the components, it is necessary to calculate the expected current flow. Since under production engineering conditions it is not possible to launch a full-length coupled simulation before every forming process a simplified calculation should be used at this point, based on the initial values and end values for inductance of the working coil. The measuring technology required for this determines the inductance of the coil before and after each forming process, without interrupting or affecting the timing of the process. The measurement results are continuously evaluated and can be used both for technological process control and for ensuring the safety of the installation components. A measurement model of this kind is currently being developed at the Fraunhofer Institute for Machine Tools and Forming Technology.

3 Technological investigations into electromagnetic flat forming

In the trio comprising installation, coil, and technology, all efforts are concentrated on providing optimum conditions for the forming process. This does not mean, however, that any of the aspects carries more weight than the others. On the contrary, a particular feature of electromagnetic forming is the need for mastery of the interaction between all three aspects. In the project, the potential of the technology is analyzed in experimental investigations both on a theoretical level and in applications using real components.

3.1 Basic investigations

The primary aim of the design and implementation of series of experiments on the technological theories is to be able to put forward fundamental propositions regarding the behavior of a blank under the conditions of electromagnetic forming.

The tool geometry used in the investigations already exhibits characteristics of the eventual components and permits a generalized extrapolation of the knowledge acquired from the experiments. Careful consideration of the design of a tool that would meet all these requirements resulted in the dish with a conical body, shown in Figure 4, and the illustrated tool design.

The tool consists of the actual matrix and a universal base plate. Several air ducts are incorporated in the base plate to enable a vacuum to be created via additional ducts in the matrix. The connections for the suction hoses of the pump and various fixing options are also provided in the base plate. The change in depth of the basic form is achieved by means of tool inserts and subsequent mechanical processing is envisaged for the variation in other parameters.

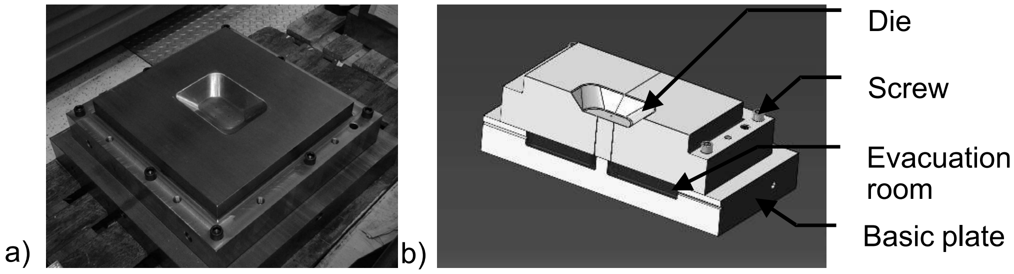


Figure 4: *Experimental tool for basic investigations*
a) top view b) cross-section through the CAD model

Since the development of an innovative impulse power installation and the basic technological investigations started almost at the same time in this project initial experimental investigations were carried out in collaboration with the University of Applied Science in Zwickau. The variables in these investigations included the energy, the vacuum, the forming depths, and the materials. The coil was positioned centrally.

Figure 5 shows the effect of various different energy quantities. The material used is AA5182 and the forming depth is 15 mm. It is evident that higher energy levels do not necessarily result in better forming results. Two points can be made to summarize this:

- As the amount of energy increases, there is an improvement in the forming of the corner radii,
- and as the energy increases, so does the central “indentation” because the acceleration of the areas subject to applied pressure increases and the inertia of the unaccelerated central areas has greater effect.

Part order

22,2 KJ	15,24 KJ
18,18 KJ	30,22 KJ

Material: AA5182

Figure 5: *Influence of varying energy levels*

Another important point is the investigation into the effect of the vacuum. The forming process takes place so quickly that air cushions are created if the tool is not adequately evacuated. This has a detrimental effect on the forming result (Figure 6).

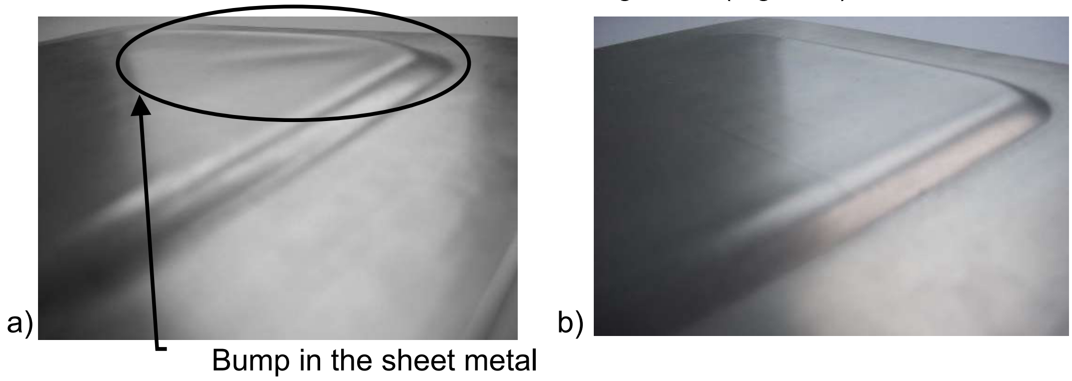


***Figure 6**: The effect of an inadequate vacuum*
a) vacuum approx. 78.5% b) vacuum approx. 95%

As can be seen from Figure 7a, in magnetic forming the blank is drawn in. In order to achieve greater depths in the component, as envisaged by the investigations, drawing in of the sheet metal is indispensable. The possibilities and the challenges resulting from this knowledge have not yet undergone comprehensive analysis at this stage of the project.

Inclusion of steel materials is also the subject of the investigations. The mechanical and electrical properties are less advantageous compared with those of aluminum. However, it seems sensible to consider the possibility of using steel materials in electromagnetic forming in terms of subsequent forming operations for the manufacture of ancillary formed elements, for example in doors. Differences in the forming of various sheet metal materials are shown for the purpose of illustration in Figure 7b.

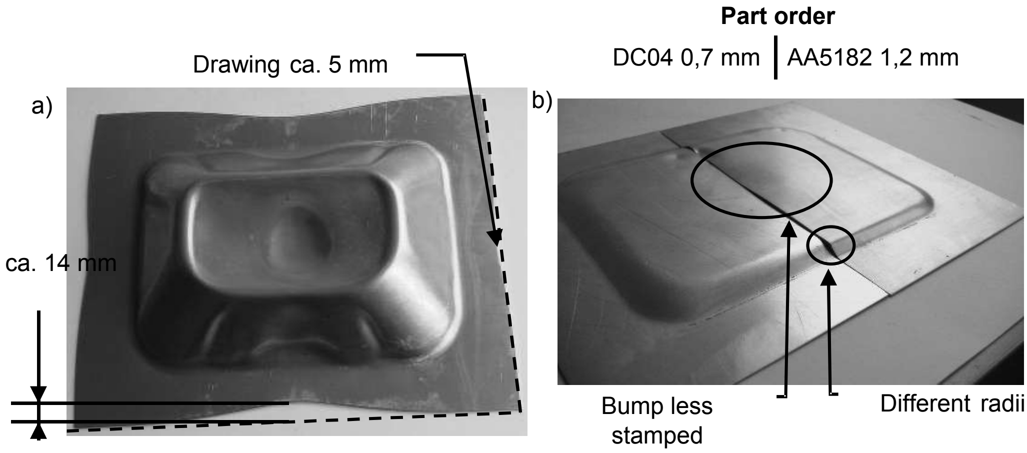


***Figure 7:** Experimental results from the basic investigations*
a) illustration showing how the blank is drawn in b) comparison of components made from different materials

3.2 Component-related investigations

As the second step in the technological investigations, the knowledge acquired from the basic investigations was applied in the project to a real component. An additional experimental tool was used as an intermediate step in relation to the real part geometry of the depression in a door to accommodate a door handle. This tool contains the geometry of the door handle depression and its immediate vicinity and is intended to enable preliminary investigations to be carried out.

The results of experiments to date are encouraging (Figure 8). The crease that is still present is due to the necessity of repositioning the coil, which is currently too small. The surface damage occurred as a result of persisting inadequacies in the process sequence.

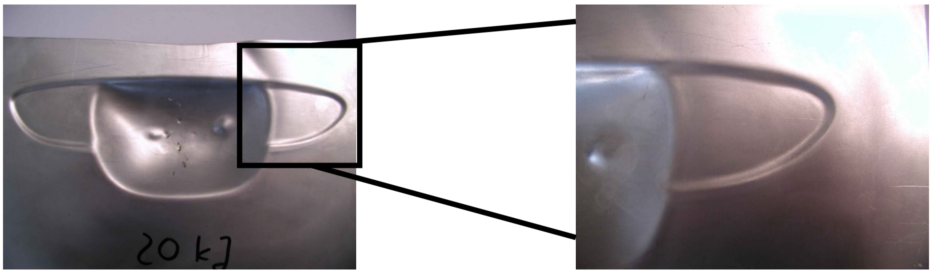


Figure 8: *Experimental results from the door handle depression*
a) forming with 3 kJ b) forming with 5 kJ

4 Summary and prospects

The experimental installation, which has been developed for the electromagnetic forming of flat components, represents a further step towards qualifying appropriate plant and equipment for production engineering. Rather than focusing primarily on maximizing the known parameters of the equipment, development of the installation was geared to the technical adaptation of the equipment from the point of view of production engineering. The knowledge acquired, in conjunction with the results of technological investigations, will influence the development of future magnetic forming installations.

Overall, interesting aspects have emerged from the basic investigations, which will have a bearing on future investigations. Particularly noteworthy are the following:

- drawing in of the sheet metal at greater drawing depths;
- the theoretical possibility of achieving good results with steel as well as other metals, and
- initial encouraging results from the experimental forming of a depression for a door handle, which was central to this project.

Additional tasks have been identified for inclusion in future investigations, for example optimized process control for greater drawing depths. Similarly, the inclusion of the electromagnetic forming process in process chains and the further improvement in economic viability by means of additional process integration will also play a role in this connection. In the future, too, investigations will continue to focus on practical applications of electromagnetic forming of sheet metals.

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