Design and Adaptation of EMF Equipment – From Direct Acting Multi-turn Coils to Separable Tool Coils for Electromagnetic Tube Compression

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Abstract

Since the electromagnetic forming (EMF) becomes more and more accepted within industrial manufacturing, the methods engineer has to deal with the choice of matching equipment as to perform the task of production in the best possible way. At the present time several manufacturers offer EMF-machines with different characteristics, whereby the machines consist of a pulse power generator and an exchangeable tool coil. The storable energy, the current capability and a high short circuit frequency enable the engineer to adapt tool coils for an optimised pressure course.

In the following some aspects of how to dimension direct acting tool coil properties for the EM compression process will be considered. Basically the use of multi-turn coils is advantageous for a good matching. But in a lot of cases the use of a fieldshaper is necessary. It will be shown how the design of a tool coil system including a fieldshaper influences the pressure course. A special case is the application of EM compression in closed spaceframe structures for which a separable tool coil is required. A separable compression coil with non-welding contact elements will be presented.

Keywords:

Electromagnetic forming, Tube compression, Tool design

1 Introduction

Investigations and developments in the field of electromagnetic forming (EMF) can be traced back to the early 1960s. But the increasing use of aluminium alloys in car manufacturing in the last ten years inspired a renewed and strong interest in the commercial application of this special high speed forming process. This forebodes the EMF process to become widely accepted within industrial manufacturing in the near future. At present, the most common application is the EMF of tubular aluminium components, especially for joining, but also for pre-forming or calibrating operations.

The most simple and well-known process type is the EM compression of tubular workpieces with good electrical conductivity: In this case the tool coil is located around a tubular workpiece and the sudden discharge of a capacitor bank through the tool coil causes a fast increasing axial magnetic field inside the coil. Due to the skin effect the magnetic field strength H decreases in the workpiece wall. Thus, it penetrates through the workpiece wall dependent on the frequency, the electrical conductivity, the wall thickness, and the radius of the workpiece [1]. The energy density of the magnetic field, which is equivalent to the acting magnetic pressure p (see equation (1)), is most efficient if the field is completely shielded by the current which will be induced in the workpiece wall.

$$p(t,z) = \tfrac{1}{2} \cdot \mu_0 \cdot H^2(t,z) \quad (1)$$

$$H(t,z) = w \cdot I(t) \cdot k_H(z)\ , \quad (2)$$

where w is the so called density of winding (number of turns per unit length) and k_H is a function describing the axial field distribution on the surface of the workpiece [2].

The principle of using the energy density of an extremely strong pulsed magnetic field for a non-contact type of forming operation places additional demands on the interdisciplinary understanding of the methods engineer: this includes a minimum fundamental knowledge of the Maxwell's theory to estimate the acting magnetic pressure, as well as some knowledge of the workpiece's forming behaviour under high speed conditions to determine the demands on the magnetic pressure. The strong dependencies and interactions between electrodynamics, acting forces, and forming behaviour of the workpiece complicate the choice of matching EMF equipment to fulfil a defined forming task in the best possible way. In the following, the design and dimensioning of EM compression coils will be treated more detailed under the aspect of an efficient energy use.

2 Significant characteristics of the EMF equipment

In general, the EMF process and its associated mechanisms are determined by the induced current in the workpiece, and therefore by the coil current as the responsible source. Figure 1 shows the equivalent circuit diagram including the core components of an EMF-system for tube compression which typically consists of a pulse power generator and an exchangeable tool coil. The pulse power generator, mainly consisting of a capacitor bank and a high current switch, has to be constructed in a low-inductive way (L_{inner} should be much smaller than the coil inductance) to realise an efficient use of the capacitors energy as a high current through the tool coil. The sudden close of the high current switch in this resonant circuit leads to a damped oscillating current $I_1(t)$ through the tool coil. The workpiece can be seen as a single shorted secondary turn of a transformer, in which the current $I_2(t)$ will be induced. Additionally, by the arrangement of tool coil and workpiece, especially by the gap volume in between, a leakage inductance L_{leak} will be caused.

During the deformation process with the increasing volume of the gap, the leakage inductance increases. This results in an evident change of frequency of the coil current, as shown in Figure 1.

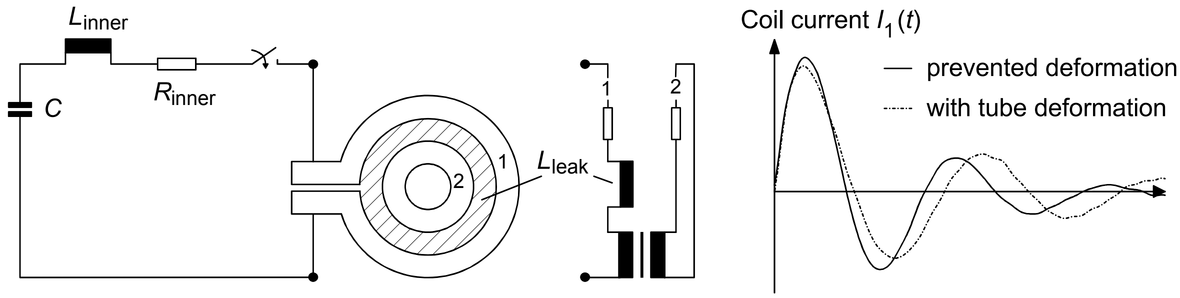

***Figure 1**: Equivalent circuit of an EMF machine with compression coil (1) and tubular workpiece (2)*

The parameters of the equivalent circuit diagram determine the frequency of the discharge, whereas the lower the inductance of the whole coil-workpiece-system, the higher the frequency. The maximum possible frequency is limited by the short circuit frequency which is mainly determined by the capacity and the inner inductance of the pulse power generator (without tool coil and workpiece). This is a significant characteristic of EMF-machines which is typically in the range of 20 to 100 kHz.

The other descriptive parameters of the machines are the maximum charging energy of the capacitors, which is defined by the capacity and the maximum charging voltage, and the maximum current, which is mainly limited by the capacitors and the high current switches. New developments in the field of high current switches are today of common interest because the well-known ignitrons, which are known as being robust against overload, are controversial due to the expected restrictions concerning the use of mercury [3].

The storable energy, the current capability, and a high short circuit frequency enable the engineer to adapt tool coils for an optimised current, field and pressure course (according to the relationship in equation (1) and (2). On the other hand, these characteristics of the pulse generator are dependent on the manufacturer and the machine costs (either as investment costs or as costs in consequence of wear lifespan).

3 Adaptation of direct acting multi-turn compression coils

Since the beginnings of working with the EMF process the design and realisation of durable and efficient tool coils, which have to resist magnetic fields of above 20 T, have been problematic. Up to now, the use of low efficient single turn coils is prevalent in order to obtain high mechanical stability. Their low inductance compared to the inner inductance of the pulse power generator leads to lower efficiency. This particularly concerns tool coils for small workpiece diameters, which hence should be realised as multi-turn coils.

The realisation of such multi-turn compression coils requires a strong reinforcement by a non-conductive high strength material with good damping quality. For these purposes we successfully use a composite that consists of para-aramid fibre (Kevlar) and an epoxy resin. Additionally, for the industrial use of these compression coils it is necessary to overcome the poor thermal conductivity of the composite. Therefore, copper parts are skilfully placed within the reinforcement and can be connected with a water cooling system. A more detailed description is given in [4, 5].

Regarding the efficiency of the process, it is necessary to design the tool coil according to the forming task, but also in accordance with the properties of the pulse power generator. The forming task defines the dimension of the workpiece to be formed and therefore the inner coil diameter and the coil length. The minimum gap width between tool coil and workpiece is defined by the required thickness of the insulation material and by a comfortable handling of the workpiece. Principally, it should be as small as possible to reduce the initial leakage inductance. If the coil diameter and axial length is fixed the number of turns is the essential parameter to determine the optimum inductance of the tool coil. The influence of this parameter is shown in Figure 2 for an aluminium tube ø12 mm x 1 mm, a coil length of 15 mm and a coil diameter of ø13.4 mm. To determine an optimised number of turns, the capacitor discharge in the equivalent circuit diagram has been calculated neglecting the workpiece deformation. This calculation has been performed for two different pulse power generators to show that the optimum number of turns is dependent on the generators characteristics. Interesting in this context is the obvious low efficiency of single-turn coils for both of the generators.

Furthermore, it is conspicuous that for a pressure maximum of 150 MPa with the optimum number of turns the generator with the higher short circuit frequency (generator A) needs less charging energy. Additionally, the required current maximum is less, because due to equations (1) and (2) a higher density of winding results in the same field strength and this means nearly in the same pressure maximum.

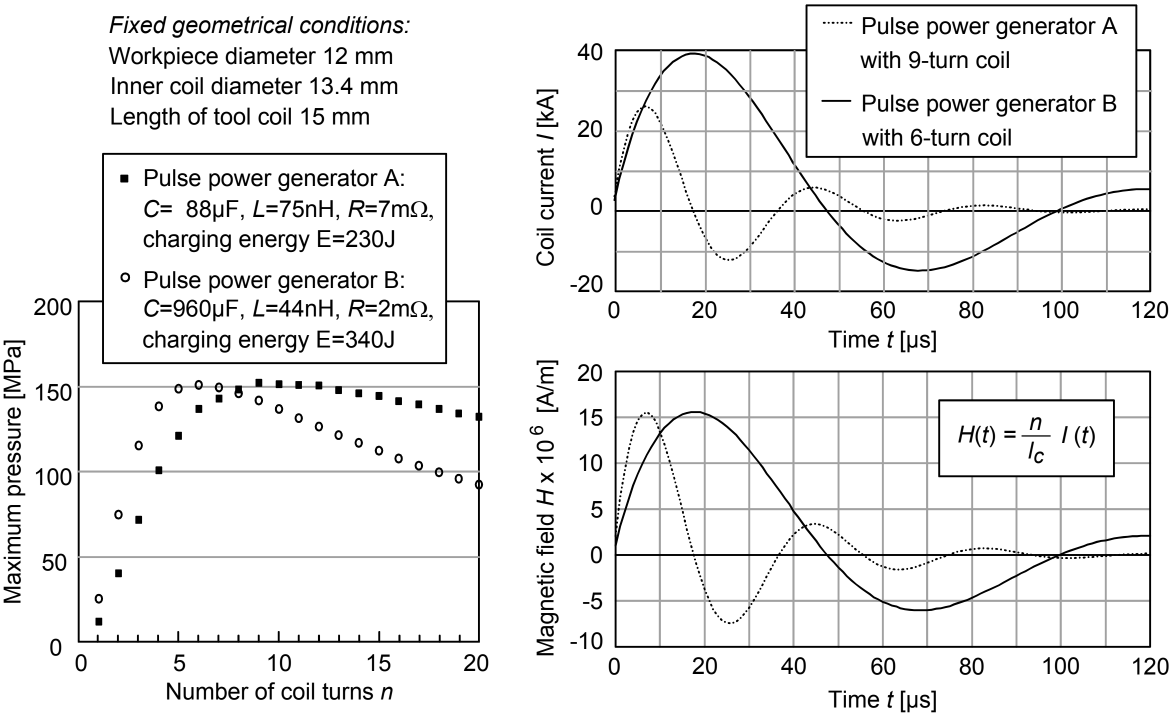

***Figure 2**: Adaptation of the coil turns dependent on the machine characteristics*

Which current course is most suitable depends on the forming task. The current course directly influences the pressure course, which is essentially described with the parameters pressure maximum, pressure rise time, and duration of the acting pressure pulse, resp. the working frequency. Investigations at the Chair of Forming Technology of the University of Dortmund have shown that in the case of EM compression of aluminium tubes the increase of stiffness due to the reduction of diameter during the forming process causes the compression process to be finished within the first pressure pulse. Therefore, the shape of the pressure over time curve influences the forming behaviour of the tubes. It could be observed that, for example, an increasing pressure rise time causes an increase of the forming velocity, and with an increasing forming velocity an improved roundness of the workpiece could be achieved [6]. Another advantage of a higher forming velocity can be seen in the case of joining operations, where a higher forming velocity of a tubular component results in a higher kinetic energy at the time of impact with an inner joining partner.

Furthermore, the duration of the pressure pulse, resp. the first half cycle duration of the coil current should not exceed the duration of the forming operation. In Figure 3, the measured coil currents of the adapted tool coil with 9 turns are shown as well as the current shape of an unfavourable coil with 27 turns. The latter demonstrates the case when the current still increases although the deformation is finished. In the diagrams the duration of the compression process is marked with grey columns, whereas the reduction of the diameter is limited by a mandrel with a diameter of 8 mm. This leads to an over-consumption of energy as well as to unnecessary high current loads of the generator components.

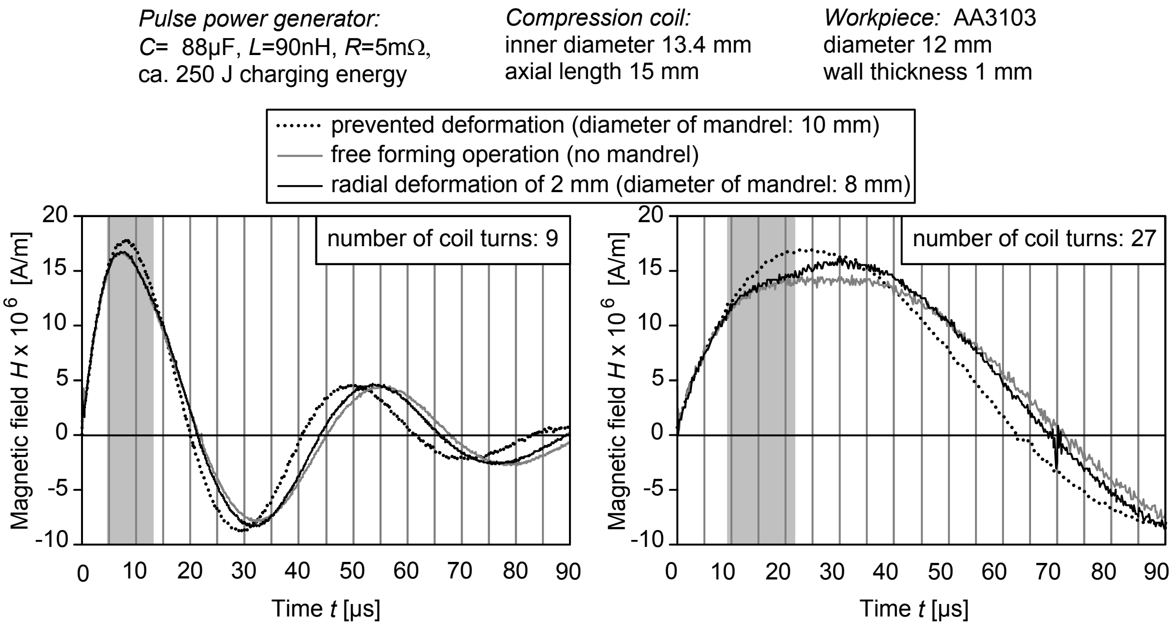

***Figure 3:** Different current over time curves for a joining example with different direct acting compression coils*

Recapitulating, from the point of view of the efficiency the dimensioning of tool coils has to be adapted with regard to the EMF machine properties, but within the limiting conditions resulting from the forming task. As the considered workpiece example shows, the required charging energy for such small tubes is very low. This is because the required energy depends on the dimension of the workpiece surface to be loaded with magnetic pressure. On the other hand, the required working frequency for the considered small tube should be comparable high, because the duration of the forming process is very short. Finally, it should be mentioned that also by the capacitance of the pulse generator the working frequency can be influenced. Thus, the methods engineer has the best chances to adjust a desired pressure course with the tool coil if the pulse power generator can be used in a modular way, with switchable energy segments.

4 Energy considerations in the use of fieldshapers

Many forming tasks require the use of a fieldshaper, for example if a tube is to be assembled on both of its ends with fittings like shown in Figure 4. The geometry of the fittings does not allow the use of a matching direct acting tool coil, because the minimum required coil diameter is contrary to the requirement of a small gap between tool coil and workpiece. A possible solution consists in a two-part fieldshaper. Due to the skin effect the induced current in the fieldshaper flows near to its surface, so that in both fieldshaper parts there are closed loop currents as it is indicated by the arrows in Figure 4. The current at the inner edge of the field shaper, which is close to the workpiece, determines the acting magnetic pressure.

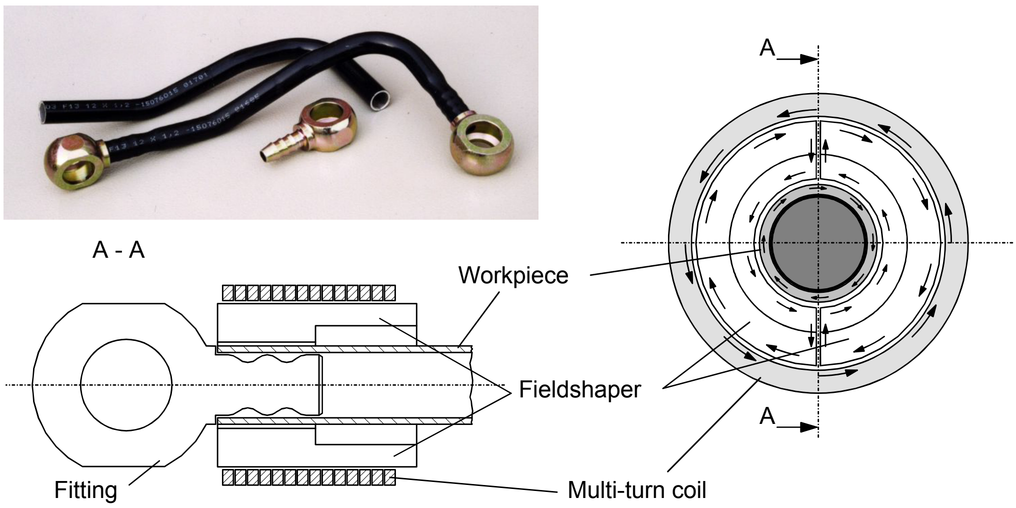

***Figure 4**: Joining example requiring the use of a multi-part fieldshaper*

Regarding the multi-turn coil and the fieldshaper together as the tool coil system, the gap volume to be filled with magnetic field energy leads to an additional leakage inductance in comparison to a direct acting coil. Consequently, more charging energy is needed and the current over time curve changes to lower frequencies.

Nevertheless, to achieve a high pressure pulse in the forming zone by low charging energies, normally the effect of field concentration by the geometrical design of the fieldshaper will be used: the current per length H at the outer surface of the fieldshaper is determined by the coil turns per length and will be concentrated at the inner surface of the fieldshaper by the length of an edge which is close to the workpiece, while the residual length is far away from the workpiece. If there are no restrictions concerning the dimensions of the multi-turn coil, it is possible to achieve very high concentrating factors for the magnetic field as well as for the acting magnetic pressure. But the higher the concentrating factor the higher the local mechanical load on the inner edge of the fieldshaper, and this leads to a more massive construction finally resulting in a larger coil diameter.

While the optimum energy efficiency depends on geometrical boundary conditions of the application, a desired pressure rise time and pulse duration depend on the electrical properties of the EMF machine and on the total inductance of the system consisting of multi-turn coil, fieldshaper, and workpiece. As an example, the setup of Figure 4 shall be considered in the following:

Because of the geometry of the fitting, a minimum coil diameter of 25 mm is required. The fieldshaper has to transform the magnetic field to the tube diameter of 12 mm and a length of 15 mm (similar to the forming area considered in chapter 3). Here, the multi-turn coil should be as small as possible and has been chosen at a winding diameter of 26 mm and a winding length of 27 mm. According to the dimensioning of a matching direct acting compression coil as shown in chapter 3, an inductance of about 0.225 µH should be realised with the fieldshaper setup. The dimensioning can be executed, for example with the help of the simulation software FEMM, a free finite element code for magnetic field analysis [7]. Here, the resulting number of coil turns was 7. To compare this tool coil setup with the direct acting tool coil, nearly the same diameter reduction has been performed as with the magnetic field which is shown in Figure 3 (left diagram). Instead of 250 J with the 9-turn direct acting coil, a charging energy of 750 J was necessary with the fieldshaper. The measured coil current is shown in Figure 5. Due to the reduction of the workpiece diameter during the forming operation, the gap volume increases, but will not influence the coil current as much as in the case of direct acting coils. Additionally to the higher charging energy, the required coil current is about 45 kA (instead of 28 kA with the direct acting coil). With regard to the current load of the switch and the capacitors of the pulse generator, the number of turns has been increased to 14 (corresponding total inductance: 1.14 µH). As shown in Figure 5, the current maximum then is clearly reduced, but on the other hand the duration of the first half wavelength seems almost too long relative to the duration of the forming process.

Pulse power generator:
C= 88µF, L=90nH, R=5mΩ,
ca. 750 J charging energy

Compression coil:
inner diameter 26 mm
axial length 27 mm

Fieldshaper:
inner diameter 13 mm
length of inner edge 15 mm

Workpiece: AA3103
diameter 12 mm
wall thickness 1 mm

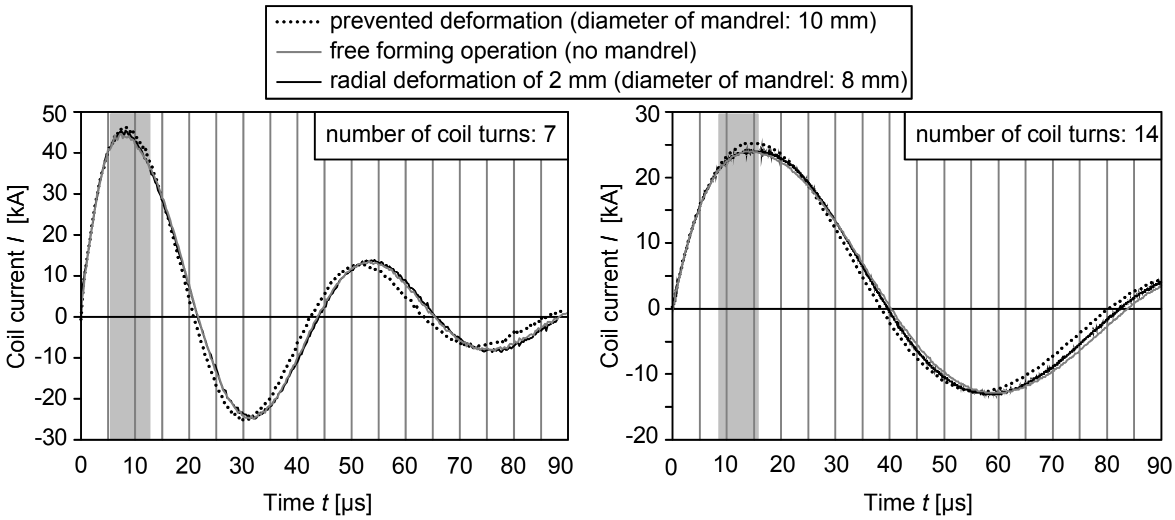

Figure 5: *Coil currents of different tool coils combined with the same fieldshaper*

Additionally to the geometric boundary condition of each case of application, the properties of the pulse power generator significantly influence the optimum design of the tool coil system. While the forming velocity and the duration of the forming process determine the optimum inductance of the tool coil system (maximum number of turns, coil diameter, and coil length), the current capability limits the minimum permissible number of coil turns. Furthermore, the efficient use of fieldshapers requires a pulse generator with a sufficient high short circuit frequency. The worst case concerning the efficiency would be if the temporal demands lead to a use of a single turn coil, because the concentrating effect mainly bases on the possibility of using multi-turn coils.

5 Example of a realized separable compression coil

A special case is the application of EM compression for joining operations in closed spaceframe structures as often required in the automotive industry. Therefore, the use of a separable tool coil is unavoidable.

To understand the difficulties in the realisation of a separable compression coil, let us consider a single turn coil consisting of two parts which are directly coupled to the high current pulse generator: a desired magnetic pressure inside the coil of about 200 MPa requires a magnetic field strength of 18×10^6 A/m (= 18 kA/mm). With the skin depth in copper of about 0.5 mm for the typical impulse length of 10 to 40 µs, the current density in the coil will be more than 30 kA/mm^2. This would certainly cause a welding procedure in the contact zone of the two coil parts. Our experimental investigations with CuBe-springs have shown that it is possible to avoid welding at a current per unit length lower than 5 kA/mm. But this corresponds only to a magnetic pressure of 15 MPa, which is too low for the forming process. So it is necessary to realise a current carrying geometry which concentrates the field strength in the forming zone.

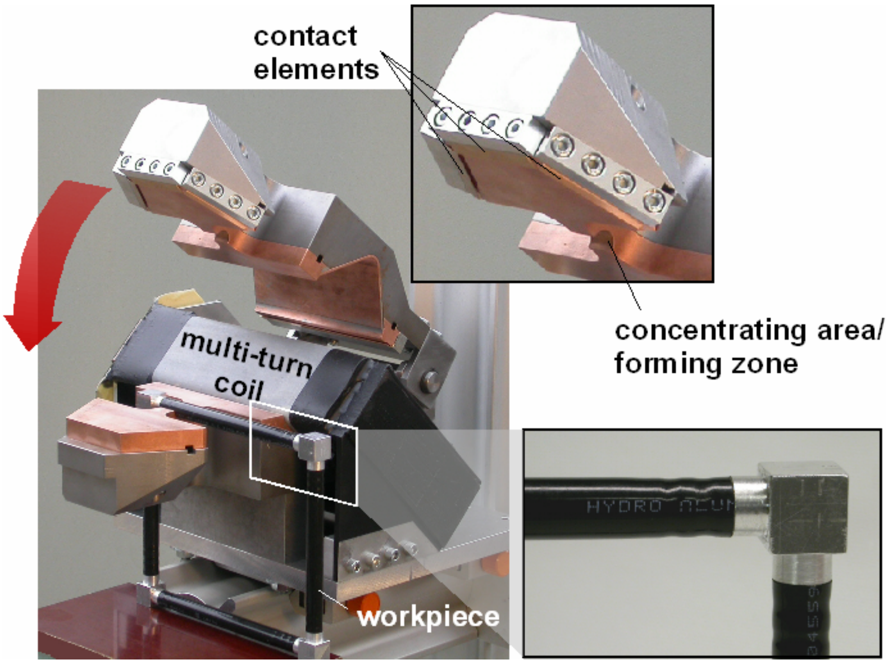

Figure 6: *Separable compression coil with non-welding contact elements and joining example (closed frame structure)*

Figure 6 shows such a separable coil with non-welding contact elements [4, 8]: the single turn coil consists of two parts which are inductively coupled to a long multi-turn coil. The length of this multi-turn coil is nearly the same as the minimum required length of the contact elements. Due to the increasing amount and complexity of the current-carrying geometry an unavoidable additional leakage inductance occurs. It is therefore very important to adapt the number of turns as good as possible to the pulse generator and to compensate the corresponding energy losses with a concentrating factor.

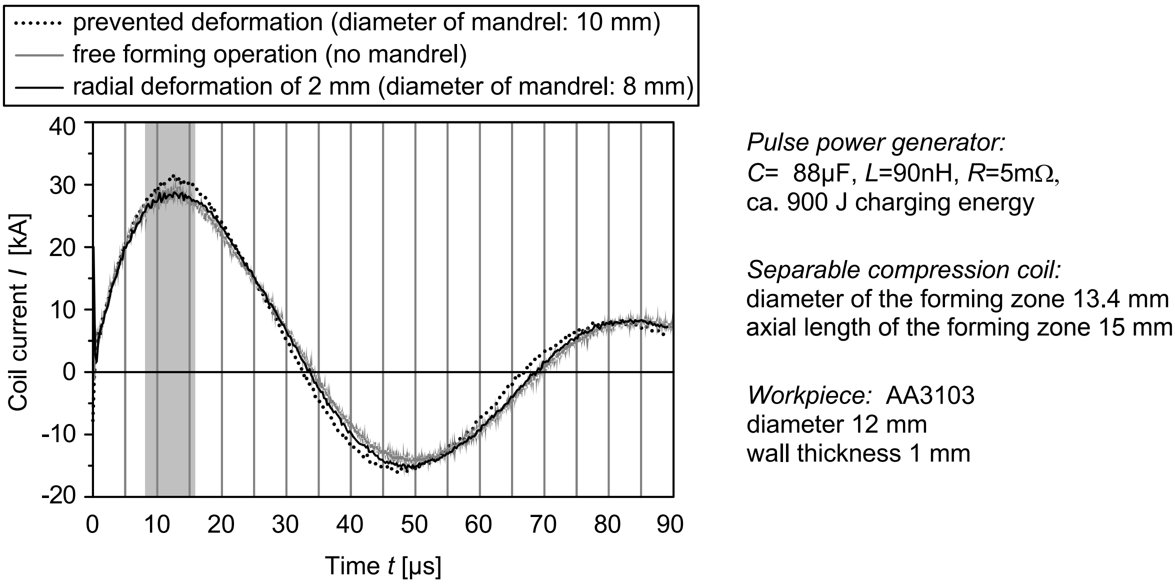

Figure 7: *Measured current over time curves of the separable compression coil*

Figure 7 shows that it is possible to achieve an adapted current over time behaviour with the same pulse generator as it has been used with the matching direct acting coil (chapter 3) as well as with the coil-fieldshaper-tool (chapter 4). For a similar diameter reduction of the abovementioned 12 mm x 1 mm aluminium tube 900 J charging energy is necessary and the current is within the required specifications (described in chapter 4).

6 Summary

As the most common and well suited application of the EMF process the compression of tubes has been considered. It can be used e. g. for joining, calibrating, or pre-forming operations. Due to the forming task the optimum pressure pulse has to be defined and then to be realised by the EMF equipment. In the case of tube compression the pressure maximum and rise time influence the forming velocity as well as the desired final geometry and properties of the workpiece. Additionally, the engineer should turn attention to the efficient use of the pulse generators energy by a good matching between the duration of the deformation process and the duration of the pressure pulse.

The shape of the pressure over time behaviour is directly related to the course of the magnetic field strength which finally is determined by the current through the tool coil. The latter depends strongly on the parameters of the EMF equipment consisting of the pulse power generator and an exchangeable tool coil. In most cases it should be possible to adjust a desired pressure course by the coil design, more precisely by its number of turns.

The limiting factors are the short circuit frequency and the current capability of the pulse generator. Vice versa, a pulse generator with switchable energy segments can be used to match the pressure pulse for a given coil-workpiece arrangement.

This is regardless of the tool coil being a direct acting multi-turn coil or a single-turn coil coupled to the generator by a multi-turn coil, like in the case of using a fieldshaper or a separable compression coil.

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