Electromagnetic pulse forming technology. Keys for allocating the industrial market segment.

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Abstract

The electromagnetic pulse forming technology (EMPT) provides substantial technological benefits with respect to tube forming and joining operations. However, in the past this technology was mainly adapted in academics, military production and small batch size productions. Establishing this technology in the world of civil-industrial mass production demands for several key prerequisites to be fulfilled. This report lists these requirements and moreover provides answers on ways for their completion.

Keywords

Industrial, Forming,Metal

1 Introduction

Even if the technological possibilities of a new production method apparently are overwhelming, the major key for adoption of this process in today's industrial mass production is the provision of economical benefits. A measure for the economics is the manufacturing costs per produced component.

The electromagnetic pulse technology (EMPT) today is mainly used in mass production for forming, joining and cutting of tubular structures or closed profiles. In this sector, the EMPT is in a strong competition to well established production processes, for example by hydroforming or by fusion welding processes. Substitution of these processes by the EMPT is only possible, if the conventional method suffers on one of the following disadvantages:

a) technical problems solvable only by major efforts
b) need for high priced semi finished products
c) quality problems by process instability
d) low production rate
e) maintenance intensive conventional production process underlying major wear problems
f) need for expensive quality insurance tests

g) the conventional production process does not match properly to the process chain
h) need for replacement of high priced production equipment

If at least one of the above mentioned problems is related to a conventional manufacturing process, EMPT can play its benefits.

2 EMPT system requirements for industrial mass production

The major factors, governing the economics of the EMPT process with respect to industrial mass production are the component life time of pulse generator and coil, the repeatability of the process and the system’s control algorithms. Further, there are some technical aspects, being in strong relation to the EMPT system size and therewith to the prime costs.

2.1 Component life time

Industrial mass production means batch sizes of 100,000 to several million parts per year. The life time of the costly components of the pulse generator is therefore specified by the batch size per year. It should be at least in the range of a two year production. Costly components are the coil and the capacitors because of their purchase prize and even more because of the time which is essential for replacing those components. At a laboratory EMPT system, replacing the coil may be a task of some minutes. However, this changes if the system is integrated into a production line. Hence, coil life time is required to be in the range of some million pulses.

In the past, EMPT coils where commonly made of several windings of wire, embedded into an electrical insulator. This insulator was mainly made of plastics. The plastic insulator itself was surrounded by some metal or fiber reinforcement, enabling the coil to withstand the loads resulting from the magnetic pressure. This concept allows manufacturing multi-winding coils which can build up high magnetic pressure at relatively low discharge currents. This concept has one big pro but several contras:

The ratio of magnetic pressure to discharge current is high resulting in relatively small pulse generators and quite low electrical loads on all sensitive components, i.e. on capacitors and switches.

The biggest contra is the quite low coil life time. This is mainly due to the big discrepancy between Young’s modulus of the electrical conductors and the insulating plastics which causes high strains in the conductors during the pulse. Young’s modulus of copper is 115000 MPa, but that of fiber reinforced plastics is only round about 20000 MPa. The factor of 5.75 between the two material’s elastic properties means, that under elastic conditions the plastic will reach the same stress as the copper at 5.75 times the strain. Hence, there is no real reinforcement effect of the insulator. Figure 1 illustrates the magnetic loading of a coil made of 4 wire windings. The wire is a Ø 10 mm copper wire. The coil bore is 40 mm in diameter. Inserted into the coil bore is a tubular workpiece, made of aluminium. The coil is loaded by an altering current of 100 kA amplitude at 10 kHz frequency. The maximum pressure acting on the coil in radial direction is ~75 MPa. This will cause an expansion of the coil. In vertical direction, there is magnetic pressure, too. This pressure component causes a compression of the coil in vertical direction.

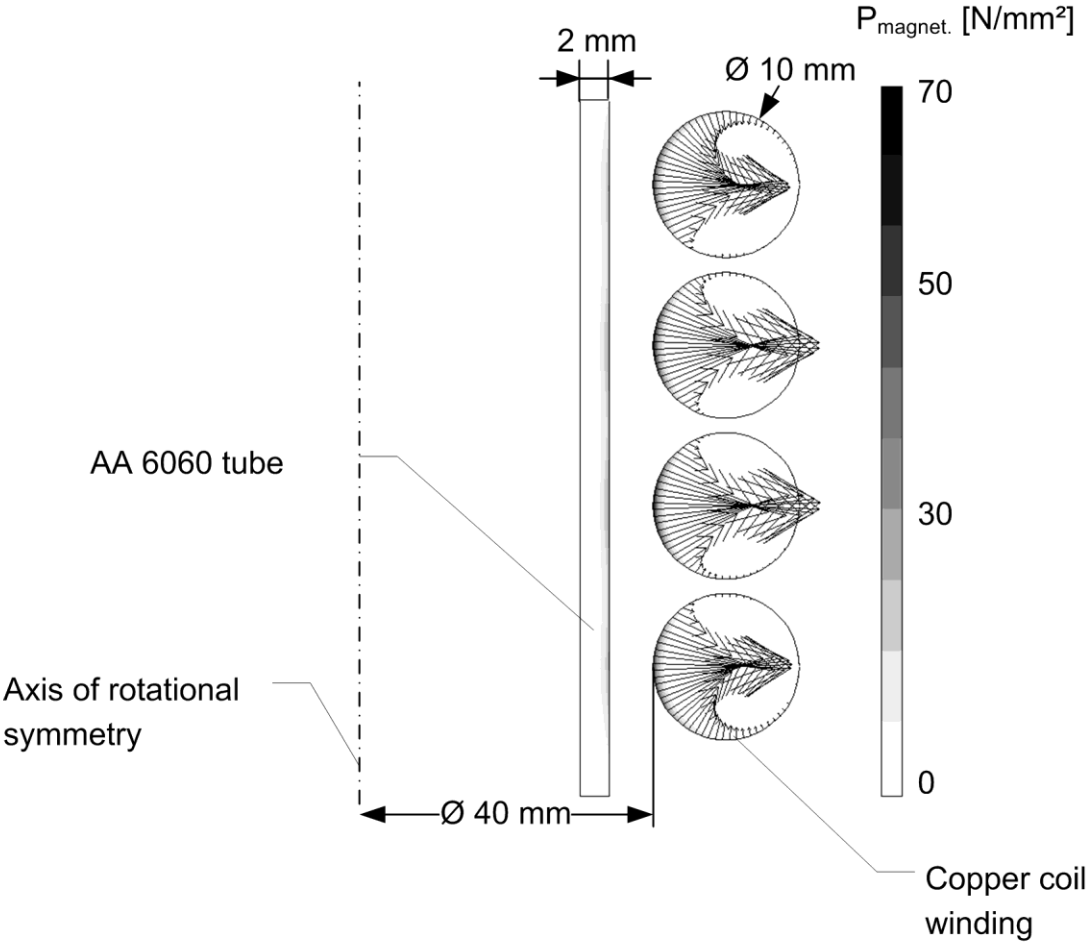

***Figure 1**: magnetic pressure loads at a 4 winding coil.*

The magnetic loading causes displacements inside the copper-insulation composite, resulting in fast ongoing micro fractures in the insulation. When the isolation is weakened by multiple cracks normally a shortcut between the coil windings or cracks in the electrical conductor will happen.

Building self reinforcing coils can help overcoming this problem. However, adding many windings to such a coil is more complex. Thus, self reinforcing coils normally are characterized by only some few windings, usually in the range between 1 and 5. As the number of windings is directly coupled to the magnetic pressure, these self reinforcing coils require elevated discharge currents. This disadvantage of the self reinforcing coils is more than balanced by their high life time, which is often 2 million pulses or even more [3].

Elevated discharge currents will lead to increased wear of cables, capacitors and switches. However, modern cables, capacitors and switches are capable to withstand electrical currents in the range of some 10 or 100 kA. Here, parallel use of these components helps to cope with currents in the range of some 100 kA to some 1000 kA. Proper component design leads to cable and capacitor life time of approx. 2 million pulses even with respect to pulse generators of the 100 kJ class [3]. The switch life time is above 200,000 pulses [3].

2.2 Matching system settings to the EMPT process requirements

As the price of the EMPT System significantly governs the economics of the process, choosing the proper system configuration is mandatory. The EMPT System is related to the following characteristics of the product:

a1. Cross-sectional dimensions of the tube or profile
a2. Workpiece material properties
a3. Magnetic pressure essential to accomplish the forming, cutting or joining operation
a4. Length of the pressure loaded area

The combination of these four aspects defines the characteristics of the EMPT System:

b1. Coil & field shaper
b2. Discharge current
b3. Discharge frequency

2.2.1 Choosing the appropriate discharge frequency:

For crimping and forming operations the discharge frequency is directly governed by the workpiece's wall thickness and its electrical conductivity. This correlation is caused by two mechanisms, based on the skin effect and the correlation between magnetic pressure build up and the magnetic flux density distribution at the inner and outer circumferential face of the tubular workpiece. The skin effect is the characteristic of altering currents to locate in a thin layer near the workpiece surface. The thickness δ of this layer is given by

$$\delta = \sqrt{\frac{1}{\chi \pi f \mu_0}} \tag{1}$$

In case of EMPT, χ denotes for the workpiece electrical conductivity, f for the discharge frequency and μ_0 for the magnetic permeability of the vacuum.

The dependency between the magnetic pressure and the difference of the magnetic flux inside and outside the tubular workpiece is given by the following equation:

$$P_{mag} \sim B_{inside} - B_{outside} \tag{2}$$

In case of a tube compression, equation 2 computes for the highest magnetic pressure, if there is no magnetic flux density at the tube's inner wall. This is roughly estimated true, when the skin depth is smaller than the tube's wall thickness. A skin depth exceeding the wall thickness of the workpiece, will cause significant losses in magnetic pressure. Figure 2 illustrates the numerically computed relation between frequency, skin depth and magnetic pressure build up for an Ø50 mm aluminium AA6061 tube with a wall thickness of 1 mm.

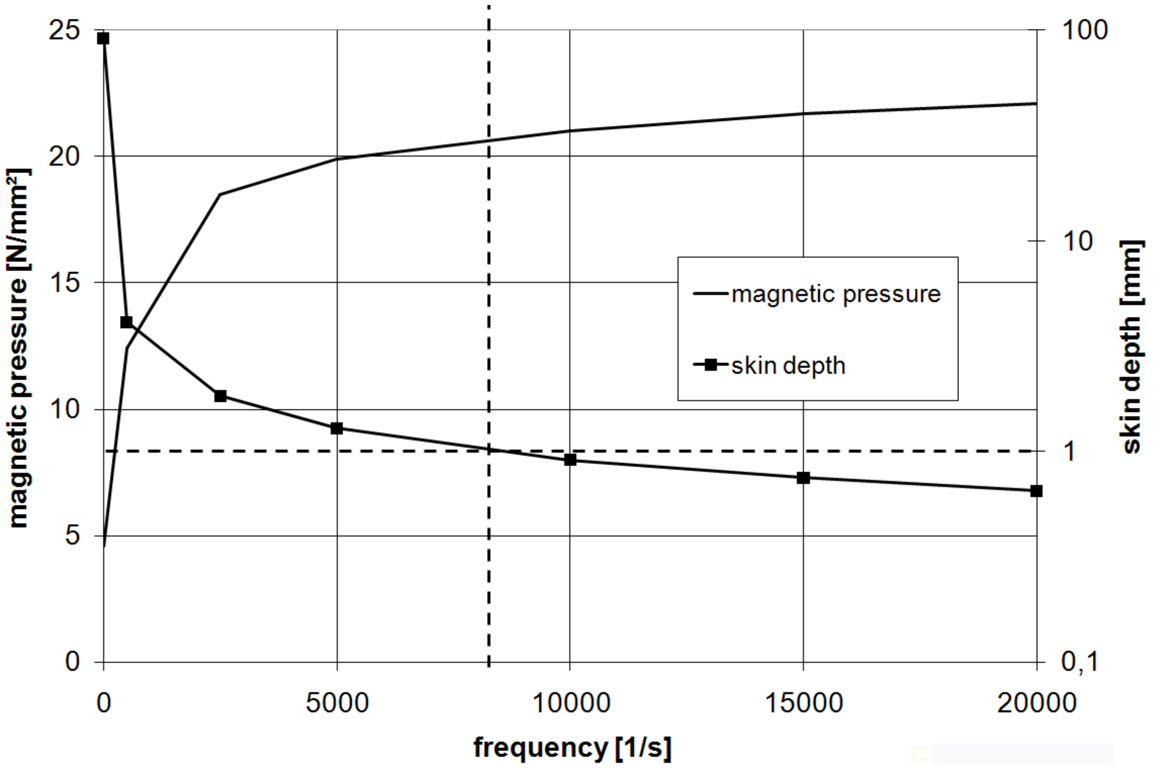

Figure 2: *numerically computed relation between frequency, skin depth and magnetic pressure build up for an Ø50mm aluminium AA6061 tube with a wall thickness of 1 mm.*

A rule of thumb for estimating the discharge frequency for sufficient build up of magnetic pressure is therefore given by:

$$f = \sqrt{\frac{1}{\chi \pi t^2 \mu_0}} \tag{3}$$

χ denotes for the workpiece electrical conductivity, f for the discharge frequency, μ_0 for the magnetic permeability of the vacuum and t for the workpiece wallthickness.

If the frequency is increased above the value computed by equation (3), no further significant pressure build up will be possible. However, an increase in discharge frequency boosts the velocity of the workpiece and therewith the strain rates. The strain rate influences the yield stress of the tube material. Herzig et. al. found that for steels, the difference between the yield strength under quasistatic conditions and at high strain rates differs by a factor of two, see Figure 3 [1].

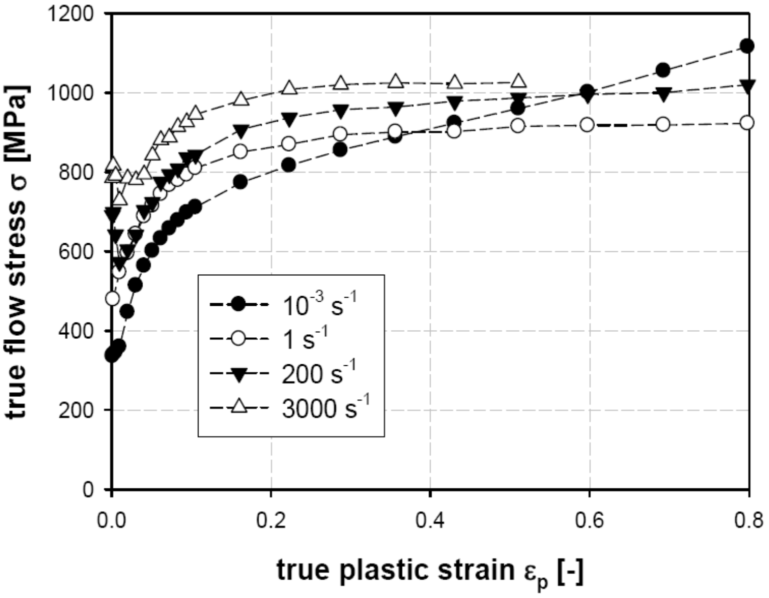

Figure 3*: Flow stress behaviour of AISI 1045 steel at different strain rates [1].*

Increasing the discharge frequency also enlarges the tube accelerations and therewith the inertial forces. Hence, even if the correlation between strain rate and initial yield strength is negligible (i.e. for many aluminium alloys), a higher magnetic pressure will be essential when the forming result should be constant, but the discharge frequency is increased. An example for this is represented by the following described free compression experiment: An aluminium tube, diameter $Ø_{out}$ 50 mm, wallthickness 2 mm and tube length of 30 mm, material AA6082-T6 is compressed to a diameter of 40 mm. At 1 kHz discharge frequency a pressure about 50 MPa is essential for accomplishment of this. When increasing the frequency, the essential pressure for keeping the diameter reduction constant increases linearly. So at 20 kHz discharge frequency, the magnetic pressure amplitude required for decreasing the tube diameter to 40 mm is 130 MPa.

2.2.2 Coil

The inductance of a long coil (it's length must be significantly bigger than it's diameter) is approximately given by

$$L = 2\pi r \mu \frac{N^2}{l} \tag{4}$$

L denotes for the inductance, µ for the magnetic permeability, *r* for the coil's radius, N for the number of coil windings and *l* for it's length. The discharge frequency is given by

$$f = \frac{1}{2\pi\sqrt{LC}} \tag{5}$$

where C denotes for the capacity of the pulse generator, *L* for the inductivity of pulse generator and coil. Normally the inductivity of the pulse generator is far below that of the coil. Equation (4) shows, that an increase in coil diameter and the number of coil windings boosts the coil's inductance. However, according to equation 5 an increase in inductance decreases the ringing frequency.

On the other hand, the number of coil windings is directly related to the magnetic pressure. Hence, choosing the appropriate number of coil turns is some kind of optimization problem. However, the bigger the coil diameter, the less windings should be used, because of the therewith ongoing significant increase in inductance. Thus, often, in case of workpiece diameters above 100 mm the use of a single winding coil and a pulse generator, capable to supply high discharge currents is beneficial.

2.2.3 Field shaper

The field shaper focuses the magnetic pressure on the area to be deformed [4]. It is not a must for EMPT, however, it is beneficial because of several reasons:

- In case of changes in work piece diameter, only the field shaper and not the coil must be replaced
- The field shaper provides possibility to manufacture undercut joint geometries
- The field shaper locates the pressure on the workpiece. Hence, the coil is loaded with minor pressure than the workpiece, which results in improved coil life time.

When a field shaper is inserted into a compression coil, the coil induces surface currents in the outer circumferential face. These currents run via at least one slot of the field shaper to the field shaper bore. Figure 4 provides a schematic of a field shaper inserted into a coil.

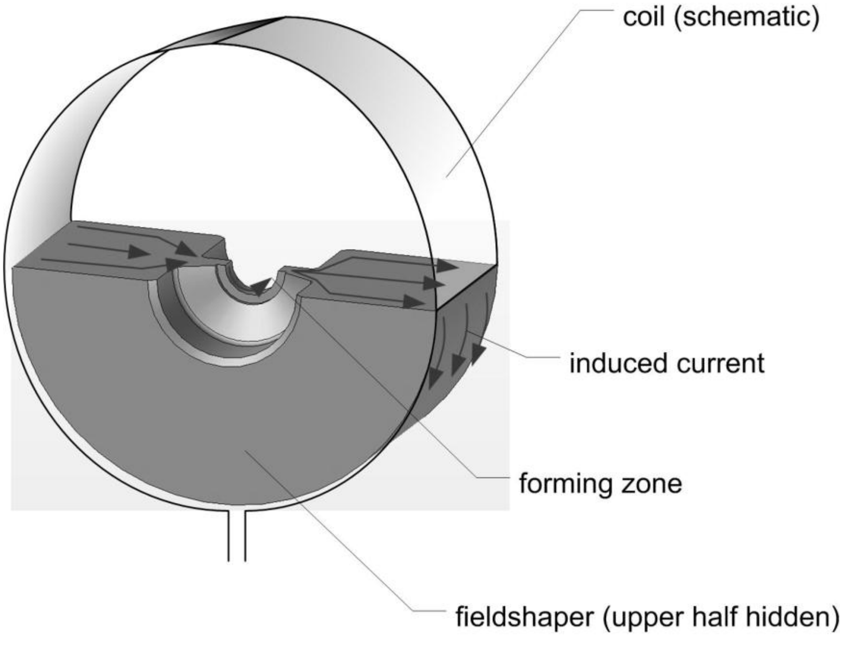

Figure 4: *Schematic of a field shaper inside a compression coil.*

The bore length is usually smaller than the field shaper length. Hence, the current density is increased. This causes a local elevated magnetic pressure. Figure 5 illustrates the current density distribution at a field shaper half.

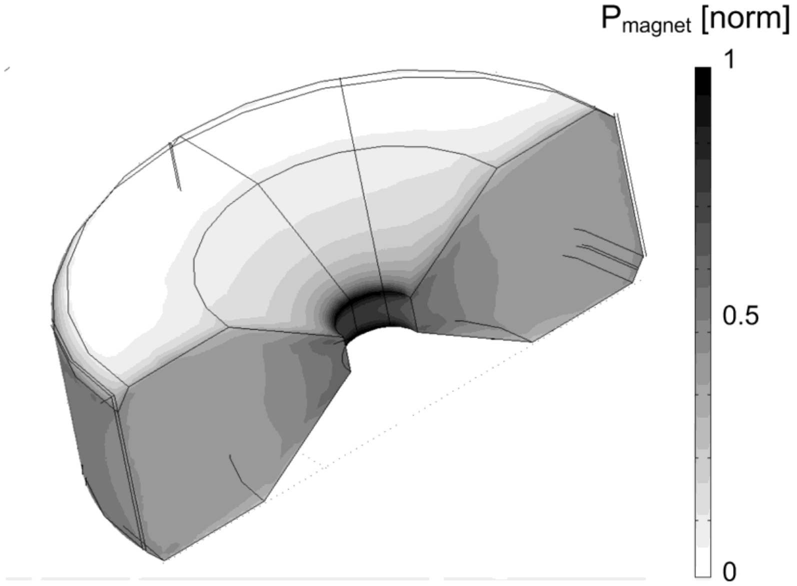

Figure 5: *Current density distribution at a field shaper half. Red colour denotes for high current density, blue for zero.*

2.3 Mjo coils: Increasing the production rate and the component life time, as well as decreasing the production costs

An appropriate chosen EMPT-System using field shapers is capable for economic forming cutting or joining of components up to medium batch sizes. However, in mass production situation it is often inevitable to increase the production rate. Adding a second EMPT system is not a choice because of the additional cost and the additional space requirements. Using one pulse generator to process several parts within one pulse is an option to increase the production rate at minor costs than by using several EMPT systems in parallel. This can be done best by use of a so called multiple joining coil (Mjo-coil). This coil is characterized by several bores, each usable for processing one part [2]. The current consumption of this coil is nearly the same as a single bore coil [2]. Hence, the EMPT process costs per manufactured part are divided by the number of parts manufactured within on pulse. Moreover, the maintenance interval is multiplied by the number of coil bores, too. If for example a Mjo coil is used, which can process two parts within one pulse, twice as much parts can be manufactured before the first system maintenance in comparison to a conventional single bore coil EMPT system. Figure 6 shows a Mjo coil for parallel processing of two workpieces.

***Figure 6**: Multiple joining coil for parallel processing of two work pieces (MJo2).*

2.4 Control algorithms

Today, economical mass production requires the application of online quality insurance systems. Often, these systems save relevant process data in a common database which provides possibility to retrieve information on any process, the manufactured part had undergone.

The result of an EMPT process is mainly related to the magnetic pressure applied to the specimen. So if there are only minor deviations of the material parameters within a workpiece batch, it is essential to keep the current and therewith the magnetic pressure constant. For this, on the one hand a constant charging voltage of the capacitors is essential, which is a question of the charging device's quality. On the other hand, parallel firing of all high current switches of the pulse generator within some nanoseconds is mandatory. Non parallel firing of the switches will result in deviations of the first current amplitude and the discharge frequency.

Additionally to this, a 100% control of the discharge current history of every pulse helps providing useful data for the quality insurance system. By monitoring the current amplitude and the frequency, the integrity of the machine is verified. In many cases these two characteristics can be even used to identify whether a workpiece is inserted in the coil bore or not.

Moreover, an appropriate pulse generator control algorithm can ensure the process stability by increasing the charging voltage, i.e. when one capacitor fails at the end of its life time. However, in case of a capacitor failure, the discharge frequency will also be changed. Hence, an automatic disconnection of the failed capacitor and an increase of the charging voltage for the working capacitors to reach the same discharge current as before the fail is not the appropriate solution. The better way is the use of a process window, which correlates discharge current and frequency to the result of the EMPT process.

Control algorithms for mass production EMPT systems should additionally provide the possibility for remote software maintenance and remote hardware diagnosis to minimize machine down times.

3 Conclusion

In mass production, EMPT is in a strong competition to conventional forming and joining processes. Hence, the technological benefits of EMPT will only be taken in account, if there are at least non economical benefits. However, in most of the cases, this new technique will only be adopted in mass production when technical and economical benefits are given.

For gaining economical benefits, EMPT system life time must be in the range of a two year component production. This can be accomplished by high quality switches, capacitors and cables. An additional use of multiple joining coils can further increase the maintenance interval and decrease the costs per manufactured component.

References

[1] *Herzig, N.; Bleicher, F.; Puschitz, F.; Dorn, C. et al*.: Collective Research for High Performance Manufacturing; 15th International Working Seminar on Production Economics, Innsbruck; 03.03.2008 - 07.03.2008; in: 15th International Working Seminar on Production Economic, p. 163 – 172, 2008

[2] *Pasquale, P*.: Mehrfachfügespule. German Patent application, 2007

[3] *Schäfer, R.; Pasquale, P*.: Die Elektromagnetische Puls Technologie im industriellen Einsatz. Whitepaper PSTproducts GmbH; http://www.pstproducts.com/downloads.htm, 2009

[4] *Winkler, R.:* Hochgeschwindigkeitsbearbeitung – Grundlagen und technische Anwendung elektrisch erzeugter Schockwellen und Impulsmagnetfelder. VEB-Verlag Technik, Berlin, p. 307-333, 1973.