Industrial Application of the Electromagnetic Pulse Technology

Dr.-Ing. Ralph Schäfer, Dr.-Ing. Pablo Pasquale and Dipl.-Ing. Stephan Kallee
PSTproducts GmbH, Alzenau, Germany, www.english.pstproducts.com

The electromagnetic pulse technology (EMPT) provides non-contact processes for joining, welding, forming and cutting of metals. For EMPT processing electromagnetic coils are used, to which a short but very high-power electric current is applied from a pulse generator. The coil produces electromagnetic forces, which can for instance change the diameter of tubes by compression or expansion. Non-magnetic metals such as aluminium tubes can also be processed, as an eddy current is temporarily induced in the skin of the tubes.

EMPT processes can be used for joining, welding, forming and cutting of metals with particular success with those with high electric conductivity such as aluminium, copper and steel tubes. Non-symmetric cross-sections can also be expanded or compressed, resulting in a mechanical interlock, a solid phase weld or simply a geometry change if required. The procedure is so fast that it can produce solid-phase welds with a microstructure very similar to that of explosive cladding or explosive welding.

This article describes the technical possibilities of EMPT, suitable machines and the economics of the process. A German version is available on http://www.pstproducts.com/WhitePaper_PSTproducts_Juni2009.pdf

---

1 Fundamentals of the Electromagnetic Pulse Technology (EMPT)

An electrical conductor experiences a force when a current is applied to it in a magnetic field. This force is the Lorentz force after its discoverer. In addition, the current generates a magnetic field itself. Thus, two parallel, current-carrying conductors repel each other, if the currents flow in different directions.

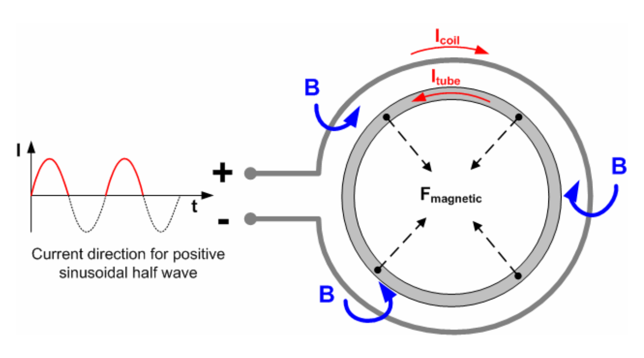

Fig. 1: Metallic tube inserted into an electromagnetic coil. Coil current, eddy currents and forces are shown for the positive half wave of the alternating current

If a tube is inserted into an electromagnetic coil, the coil can be seen as one conductor and the tube as the other. An eddy current is induced in the skin of the tube and flows according to Lenz's rule in the opposite direction to the current in the coil, if an alternating current is applied to the coil (Fig. 1). Therefore, the tube wall experiences a radial force acting inwards. If the coil current changes its direction, the current induced into the tube is also changed. Thus, the coil current and the current induced into the tube remain counterrotating with the direction of the magnetic force kept constant. The magnetic force compresses the tube radially within microseconds. However, because of the tube's inertia, the forming process is phase delayed to the pressure build-up. Figure 2 illustrates the forming process at five moments of time.

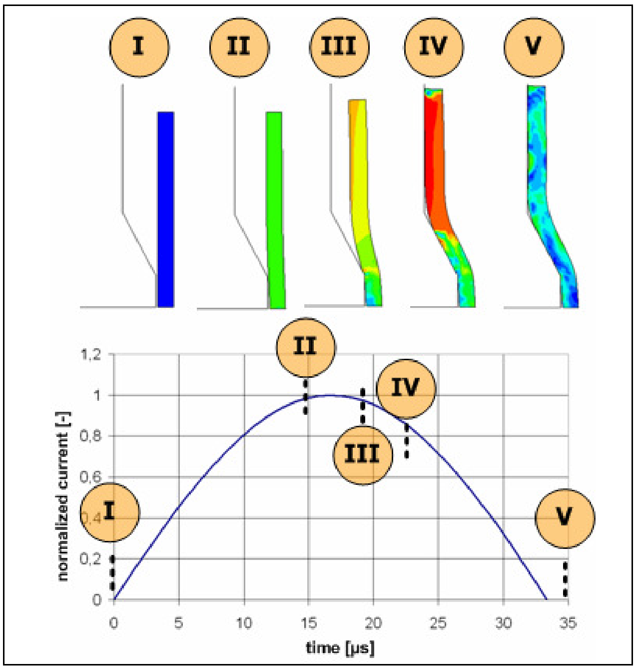

Fig. 2: Finite element analysis of crimping a tube onto an insert

During the rise of the magnetic pressure some microseconds will elapse before first material displacement of the tube is visible. During this time, internal stresses are built up inside the tube which first must overcome the material's yield strength and the inertial stresses. Subsequently the diameter reduction of the tube occurs. As the process continues, the the rate of diameter reduction is significantly increased with a final geometry reached prior to current direction change in the coil.

2 EMPT Machines

EMPT systems consist of three major parts; the pulse generator, a coil and, if appropriate, a field shaper.

2.1 Pulse Generator

The magnetic pressures for forming of metallic materials are in the range of 100N/mm². To generate these pressures, it is necessary to apply pulsed currents in the range from 100kA to more than 1000kA. The energy required has to be be stored in a pulse generator, consisting of a capacitor bank, a charging unit and a high current switch. The pulse generator and the coil of the EMPT systems create a resonating oscillating circuit, i.e. the energy $E=\frac{1}{2}CU^2$ which is stored in the capacitors is transferred into the coil with a magnetic energy $E=\frac{1}{2}LI^2$ and vice versa.

2.2 Coils and Field Shapers

Coils and field shapers are used to focus magnetic pressure onto electrically conductive work pieces. The coil consists of one or more electrical windings and is made from a highly conductive material, usually a special copper or aluminium alloy (Fig. 3). The coil cross-section is usually between 10 and several 100mm^2 depending on the required currents to transfer.

The field shaper is sectioned with at least one radial slot, and is electrically insulated against the work piece and the coil. The coil length and the field shaper length at its outer diameter are the same, with the gap between coil and field shaper kept as small as possible.

As the electrical pulse is transferred, the coil induces an eddy current in the skin of the field shaper, which flows to the inner surface of the field shaper bore by means of the radial slot. The inner diameter of the field shaper is similar to the outer diameter of the work piece. The length of the inner bore, however, is usually shorter than that of the coil and thus provides a concentration. This has two effects: firstly, the magnetic field lines are concentrated onto the ridge and, on the other hand, the non-uniform magnetic field of coils with multiple windings is homogenised [4].

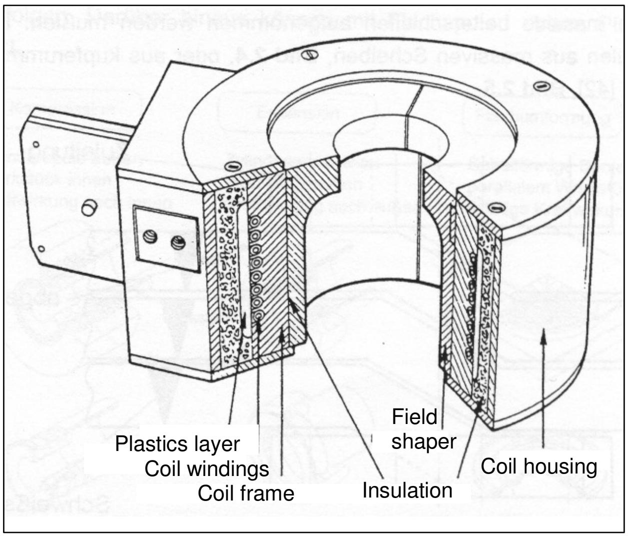

Fig. 3: Section of a multiple winding coil [5]

If a field shaper is used, the magnetic pressure that has to be reacted by the coil is smaller than the pressure that acts onto the work piece, thereby significantly increasing the service life of the coil compared to a direct-acting coil, leading to higher efficiency and more favourable costs. The state of the art coils developed by PSTproducts GmbH have been optimised using numerical methods, giving an average coil life time of 2,000,000 pulses.

A variety of work piece diameters and geometries can be processed with a standard coil and the addition of a suitable field shaper with minimal time and effort. A field shaper can be changed within two minutes. A field shaper is not a requirement with many part-specific systems using single purpose coils in service, but can add to plant and part flexibility on the shop floor.

3 Working Procedure

The sequence of operation is:

1. The workpiece is positioned in the coil.

2. With the high-power switch (Fig. 4) initially open, the charging unit charges the capacitors.

3. With charging voltage reached in usually less than 8 seconds, the charging switch is opened and the high-power switch of the coil circuit is closed, releasing the stored energy of the capacitors, providing a sinusoidal alternating current in the circuit of the coil and capacitors.

4. After a few oscillations the alternating current is damped to zero with the tube shrinking to its final geometry during the first half wave of the alternating current (Fig. 5).

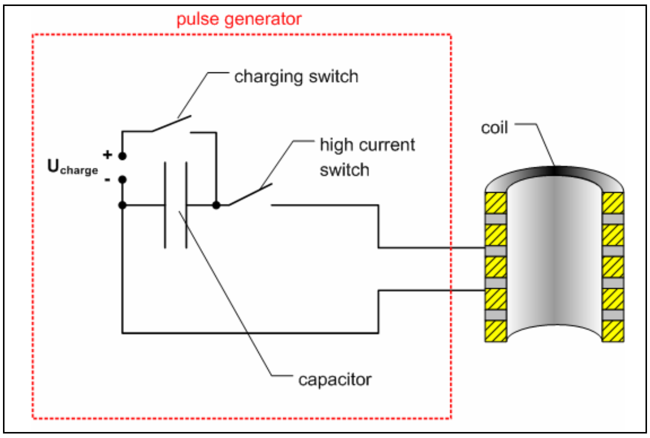

Fig. 4: Principle of the pulse generator and the coil

The EMPT systems used in industry generally have a discharging frequency in the range 6 to 30 kHz. EMPT systems developed by PSTproducts GmbH are characterized by very high discharging currents, high discharging frequencies, short cycle times and state of the art process monitoring and control algorithms. The life time of the capacitors is more than 2 million pulses, with scheduled maintenance intervals for the high power switches approximately every 500,000 pulses. The discharging currents are between 100kA and 2000kA at a voltage of 10kV to 16kV, depending on the model (Fig. 6).

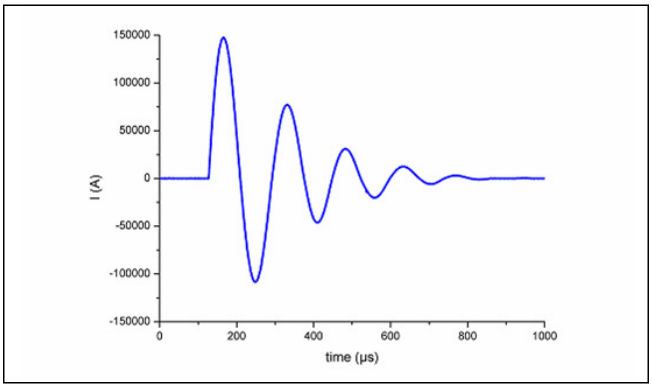

Fig.5: Oscillation of a typical discharging current

Fig. 6: PS45 EMPT pulse generator of PSTproducts at a leading German Tier 1 automotive supplier

A unique feature of PSTproducts pulse generators is a 100% process control system. This is provided by measuring, storing and analysing the current over time curve of each pulse. This rule-based algorithm ensures that the discharge energy is kept constant under various environmental conditions within a specified process window. The close loop control system of PSTproducts proves to be particularly useful for the integration of EMPT systems in fully automated production lines (Fig. 7).

Fig. 7: PS45 EMPT crimping system of PSTproducts with a double coil concept for making two joints with one pulse in automated high-volume production at a leading German Tier 1 automotive supplier

4 Industrial Applications

Some industrial applications of EMPT for crimping, welding, forming and cutting follow:

4.1 EMPT Crimping

EMPT crimping represents a technical and economic alternative to mechanical crimping processes. The non-contact process that EMPT offers, creates a more uniform pressure over the circumference with none of the variation nor tool marks inherent in mechanical processes. Thus the EMPT crimp is more uniform with no radial nor longitudinal misalignment, e.g. when joining metal fittings to rubber hoses (Fig. 8).

Fig. 8: EMPT crimping of steel fittings onto rubber hoses

The application of EMPT is not limited to soft alloy structures, but high-strength steel parts can also be processed. Truck wing holders can be manufactured from mild steel St 52-3 N (= S355J2+N) with 50mm diameter and 3mm wall thickness (Fig. 9).

Fig. 9: EMPT crimping of a steel truck wing holder

EMPT crimping of electrical cables and contacts leads to a very high and uniform compression. The electrical resistance of EMPT crimped cable connectors is up to 50% lower than of those produced by mechanical crimping [3].

EMPT crimping requires minimal set-up times between different workpiece geometries and offers excellent repeatability. The industrial use of EMPT crimping is widespread with approximately 400-500 EMPT machines installed world wide. EMPT crimping is often used for joining dissimilar materials such as aluminium or magnesium tubes to steel or plastic inserts. EMPT is used for making very lightweight structures in the transport industry, e.g. for seats of cars and aircraft (Fig. 10).

Fig. 10: EMPT crimping of dissimilar materials for lightweight seat structures of cars and aircraft

Gas or hydraulic tightness of closed containers can be produced with EMPT by means of sealing elements such as rubber O-rings. Since no consumables are required and because EMPT is a non-contact process it can be used in sterile conditions, for example, for crimping aluminium lids onto pharmaceutical glass bottles (Fig. 11). PSTproducts has recently developed and patented a special multiple joining coil, with which up to 50 joints can be made simultaneously.

Fig. 11: EMPT crimping of a sterile aluminium lid onto a pharmaceutical glass bottle

4.2 EMPT welding

In some cases, it is desirable to make solid phase welds, also called atomic bonds as the joint is made on an atomic level. The method is very similar to explosive welding and works because atoms of two pure metallic work pieces are pressed against each other at high pressure until a metallic compound by electron exchange occurs (Fig. 12). This is done without raising temperature and therefore also without microstructure changes, i.e. there is no heat affected zone. 'Rolling' of one pressurised contact partner on the other is achieved during EMPT welding by a V-shaped gap between the work pieces, e.g. due to a conical preparation of the insert. EMPT welding has particular benefits, if there are product specific requirements regarding leak tightness or electrical conductivity.

In the bottom of the V-shaped gap appear contact normal stresses in the scale of approximately 1000 N / mm² with a significant strain. These occur essentially at the point of contact between a continuously re-forming bow wave with a wavelength of a few 10µm in front of the joint area of the two work pieces. The resulting near-surface plastic deformation causes a break-up of the oxide layers of both contact partners and leaves a wavy microstructure very similar to explosive welding. Finite element calculations show deformation speeds above the speed of sound in air, but far below the speed of sound in metals. The air gap between the workpieces is compressed and accelerated towards the end of the angled gap. The resulting jet carries dirt and resolved oxide particles from the joint area.

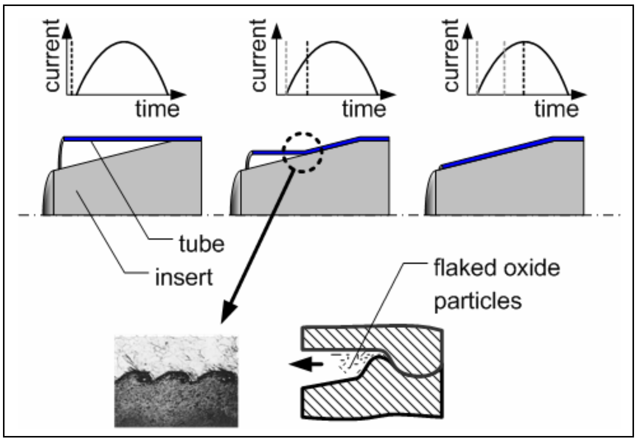

Fig. 12: Schematic representation of the EMPT welding process

The advantages of EMPT welding are on the one hand the high strength of the joint, because the joint strength is equal to the strength of the softer work piece. In addition EMPT welding can produce helium-tight connections of different metallic materials without creating a heat affected zone. Stainless steels, which are often difficult to weld by fusion welding, can be welded by EMPT and even dissimilar welds between steel and aluminium, steel and copper, as well as copper and aluminium are feasible and can be manufactured in commercial production (Fig. 13).

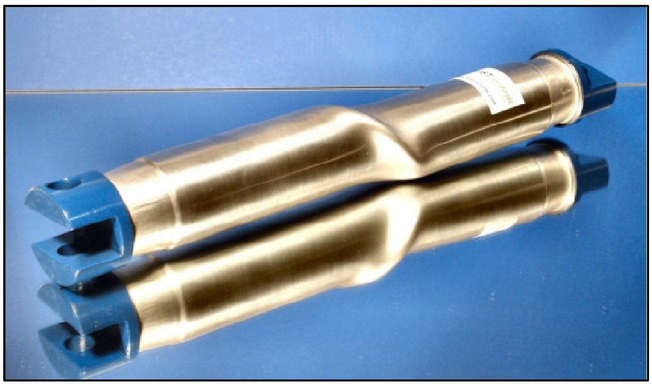

Fig. 13: EMPT welding of steel end pieces into a lightweight aluminium drive shaft

The necessary magnetic pressure and hence the deformation of the work pieces can be offset by better surface preparation and higher material quality. In many cases the work pieces have to be precision machined, ground or polished prior to degreasing and EMPT welding.

4.3 EMPT Forming

Tubular structures can be compressed or expanded by electromagnetic pulse forming (Fig. 14). In most cases mandrels or dies are used to ensure geometric tolerances in both compression and expansion, but die-less forming is also possible. Occasionally split mandrels or dies are used to separate these and the work piece after forming.

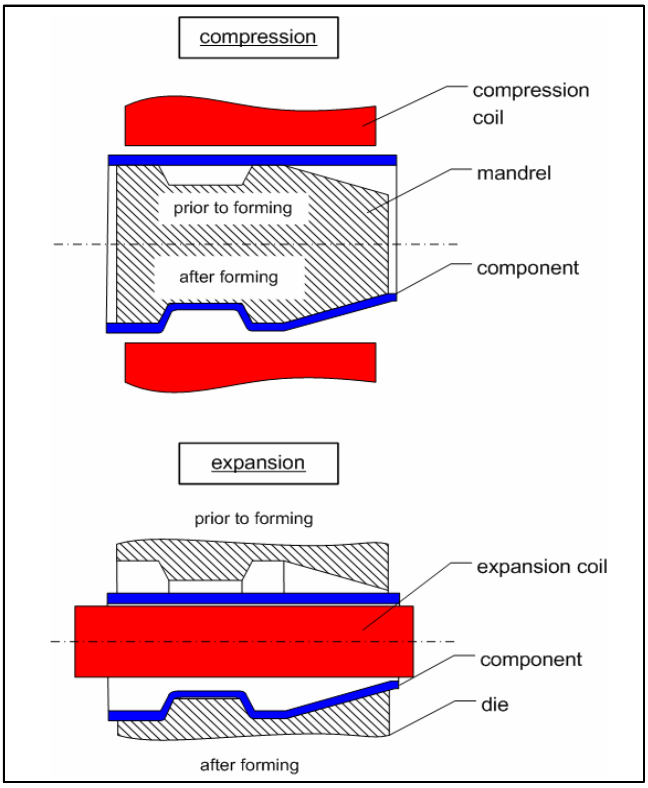

Fig. 14: Tools for EMPT compression and expansion

EMPT forming of tubular structures shows numerous benefits over conventional tube forming processes. EMPT can compress non rotational symmetric tube cross sections and due to the high velocities and forces, springback effects are minimized. Moreover, analyses made by Daehn emphasize, that under certain circumstances, the forming limits are shifted towards higher strain values [1]. To analyze the benefits of high strain rate forming with respect to potential increases of the forming limits Daehn et al. conducted ring expansion tests of aluminium alloys. Under quasistatic conditions, plastic straining of 26% in circumferential direction was possible without material failure. During high strain rate expansion by EMPT at a radial expansion velocity of up to 170m/s plastic straining in circumferential direction of up to 60% has been accomplished without material failure [1].

The process limits of EMPT are mainly caused by the electrical conductivity of the workpiece. Table 1 represents the electrical conductivity characteristics of some technically relevant materials.

Material	Elecrical conductivity $[1\ m/(\Omega \cdot mm^2)] = [10^6\ S/m]$
Copper Cu99,9	>58,0 [2]
Aluminum Al 99,9	36,89 [2]
Aluminum 6082	24-28
Magnesium Mg 99,9	22,7
Magnesium AZ91	6,6-7,1
Structural steel	9,3
Titanium Ti 99,9	2,56 [2]
Stainless steel 1.4301	1,6 [2]

Table 1: Electrical conductivity of some technical relevant materials

At present, the conductivity of structural steel represents the minimal value for accomplishing direct EMPT. If the material’s conductivity is below that of structural steel, ohmic losses will cause an undesired heat generation iside the workpiece. This, with a significant decrease in the amplitude of the magnetic pressure can create some challenges for EMPT. To overcome this, a “driver” is used. This is a thin walled aluminium or copper ring, placed in the forming zone.

With a driver, non conductive material is also formable by EMPT. Structural steel is applicable for driverless EMPT. However, for EMPT forming of stainless steels today the use of driver rings is preferred.

The potential applications of EMPT forming are not limited to tubular products, but the forming of flat sheets and plates is practically still limited by the insufficient availability of flat spiral coils, often dubbed pancake coils, that could be used in industrial high-volume production

4.4 EMPT Cutting

The acceleration of the work piece material is so fast, that the EMPT can be used for cutting holes into metal tubes or sheets (Fig. 15). The process has successfully been demonstrated on aluminium and steel sheets, and even high strength steels can be processed. The tooling is comparatively cheap in comparison to mechanical cutting processes, because a cutting die is only needed on one side of the work piece. One of the greatest advantages is that very little burrs occur.

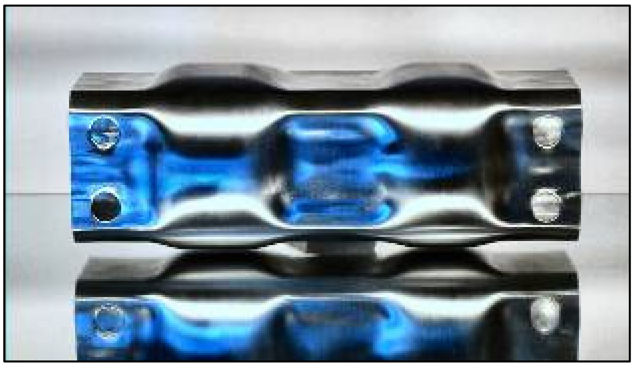

Fig. 15: Simultaneous EMPT forming and EMPT cutting of a crash box

5 Economic considerations

When looking at the high currents used during EMPT processing, the layman occasionally thinks there were high electricity costs and a need for a special power supply. However, this is far from the truth, because the pulsed currents are supplied by the capacitors of the pulse generator (Fig. 16). To load the capacitors of a powerful pulse generator only a conventional industrial mains connection with 3~400V, 50Hz, 32A is required (or in the USA 3~208V, 60Hz, 50A). Small EMPT pulse generators can even be connected to a normal household wall plug with 1~230V, 50Hz, 16A (or in the USA 1~120V, 60Hz, 20A). The electricity for a pulse of a 60kJ pulse generator costs currently less than € 0.0025 (0.25 cents US).

A multiple joining coil, trademarked MJo Coil, has been developed and patented by PSTproducts. It enables the simultaneous processing of multiple components with the power equivalent to a single forming operation. By using this special coil, it is possible, to decrease cycle time significantly. Consequently, the component-related forming or joining cost can be drastically reduced. The production of several components with one pulse also leads to a significant extension of the maintenance intervals of the pulse generator and the coil, because the wear and tear of those components is depends on the number of pulsed used.

PSTproducts offers customers in addition to the traditional purchase of an EMPT system also the possibility to install this on a ‘pay per pulse’ basis. Billing depends on the actual number of pulses delivered per year, although a minimum number of pulses is required. This concept includes all the maintenance cost for the pulse generator and can thus be used to indicate a price per joint. The cost of an EMPT joint (including electricity costs in July 2009) for a typical steel-to-steel assembly of an automotive supplier with 400.000 pulses per year, is approximately € 0.33 (33 cents US).

Fig. 16: A PS100 pulse generator by PSTproducts with 100 kJ power for Europe’s most powerful EMPT welding machine in a leading German R&D centre

6 Summary

The electromagnetic pulse technology (EMPT) is based on the contact-less deformation of electrically conductive materials using strong magnetic fields. It can be used for joining, welding, forming and cutting of sheet metals and tubes. In industrial applications, however, joining and forming of tubes outweigh other process variants. A special feature of the EMPT in this context is the ability to compress almost any tubular cross-sections.

The life expectancy of pulse generators and coils has been extended through the use of appropriate materials and design methods, and the maintenance intervals have been increased to 500.000-2.000.000 pulses. The cost for a joining or forming operation of solid steel or aluminium parts has therefore been decreased to a few cents. The availability of PSTproducts systems meets today's industrial requirements with 100% process control and the proven implementation in fully automated production lines.

7 Literature

[1] Daehn, G. S. et al.: Opportunities in High-Velocity Forming of Sheet Metal. Metalforming magazine, January 1997

[2] Lide, D. R.: CRC Handbook of Chemistry and Physics: 87th Edition, B & T, 2006 to 2007

[3] Belyy, I.V., Fertik, S.M.; Khimenko, L.T.: Electromagnetic Metal Forming Handbook. A Russian translation of the book: Spravochnik po Magnitno-impul'snoy Obrabotke Metallov. Translated by Altynova M.M., Material Science and Engineering Department., Ohio State University, 1996

[4] Winkler, R.: Hochgeschwindigkeitsumformung [High-speed forming]. VEB Verlag Technik, Berlin, 1973

[5] Miracle, D. B. et al.: ASM Handbook: Composites. Edition: 10, ASM International, 2002

Further information: www.english.pstproducts.com