The Electromagnetic Pulse Technology (EMPT): Forming, Welding, Crimping and Cutting

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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 aluminum, 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 welding.

This article describes the fundamentals of the EMPT process, suitable machines and the economics of the process. Industrial applications of the technique are shown.

Keywords: Electromagnetic forming, solid state welding, joining, cutting

1. Introduction

The electromagnetic pulse technology (EMPT) provides non-contact processes for joining, welding, forming and cutting of metals by application of strong, short pulsed magnetic fields. This technique came up in the 1960's and was adopted by many researchers within the following decade. The research work covered the fundamentals of the EMPT as well as its applications. Dietz et. al. derived a scheme for calculation of the magnetic pressure acting on the workpiece by use of the energy balance equation (Dietz, 1967). Later, the same authors could validate their theoretical considerations by experimental analysis. Within these, they used Hall-sensors to gain the magnetic flux density distribution data inside a compression coils bore (Dietz, 1969). Bühler and v.Finkenstein manufactured shrink-fit connections between copper tubes and steel rods with the help of the EMPT. However, the bearable force of these connections was quite low (Bühler, 1968). Based on the gained knowledge, the authors concentrated their efforts on joining of tubes by positive locking. Here better strength of the joint could be established (Bühler, 1971). Winkler gives a comprehensive overview of the Research work conducted in the late 1960's and the early 1970's. However, the research work of this time interval was primary concentrated on tube forming and tube joining by crimping with respect to soft and electrical good conducting materials like aluminum and copper. Further developments in the process where temporarily hindered by only small machine sizes available, which were not capable to provide high magnetic pressure amplitudes -for example for forming steel.
After some years of apparently little scientific interest, research activities in EMPT again began being increased. However, the field of applications was quite widespread. Beneath further work in fundamentals, like materials behavior, the field of sheet metal forming by EMPT became more and more of interest. In addition to this, the possibility to accomplish solid state welding with the help of the EMPT began to wake academic interest. Kojima, et. al. analyzed the influence of the magnetic pressure, the joint design and the collision angle in three consecutive reports (Kojima, 1985; Kojima, 1988 and Kojima 1989). With respect to EMPT welding of aluminium, they found that single tapered cores are very well suited for this process if their taper angle is between 10° and 15° (Kojima 1989).
Other researches analysed the possibilities to join hard to weld material combinations with the help of the EMPT. Zhang had effort in establishing an EMPT welding between an aluminium AL6061 tube to

an tungsten K7100 rod. Moreover, he successfully joined a Ti-3Al-2.5V tube to an Inconel 625 core (Zhang, 2003).

McGinley analysed the feasibility to use the MEPT for welding of nuclear fuel rods. Tubes and rods were manufactured of high strength alloys PM 2000 ODS (ODS = oxide dispersion strengthened) and T91 ferritic-martensitic steel (McGinley, 2009).

The cited reports are covering only a small percentage off all the research work conducted in the field of EMPT, but in especially the latter ones are capable to depict for the substantial benefits of this technique. Nevertheless, EMPT did not found widespread application in industrial manufacturing processes. This was mainly caused by to low life times of the EMPT system components, especially of the coils used for generation of the magnetic pressure. Recent developments in EMPT system components provided substantial improvement of pulsegenerator and coil life-time. Pasquale and Schäfer report coil life times of 2.000.000 pulses for tube compression applications (Schäfer, 2009). The bespoke substantial improvements, conducted in the recent years, allowed for an economic industrial application of the EMPT. Within the scope of this paper, industrial applications with respect to tube forming and joining are shown.

2 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 called 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.

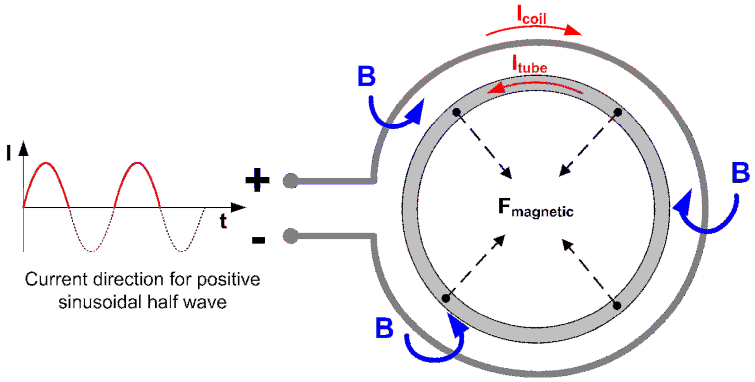

Fig. 1: Metallic tube inserted into an electromagnetic coil. Coil current, eddy currents and forces are shown for the positive half wave of the alternating current

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 counter rotating with the direction of the magnetic force is 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.

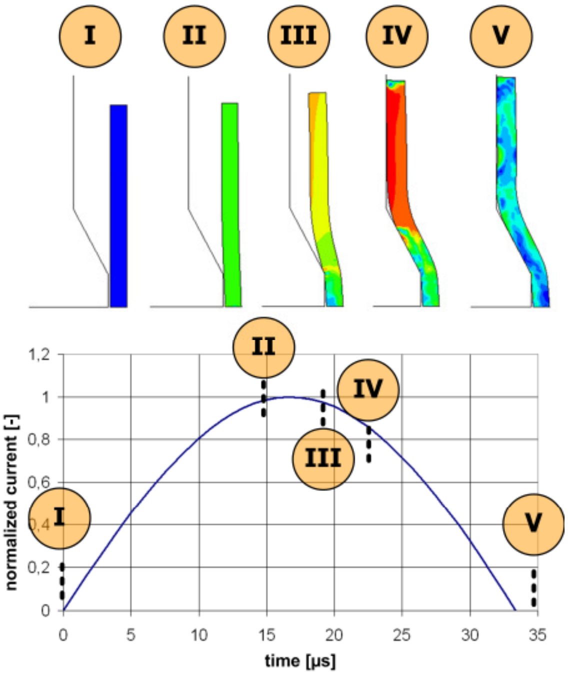

Fig. 2: Finite element analysis of crimping a tube onto an insert

During the rise of the magnetic pressure some microseconds will elapse before first material displacement of the tube is visible. Within 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 takes place. As the process continues, the rate of diameter reduction is significantly increased with a final geometry reached prior to current direction change in the coil.

Fig.3 illustrates the correlation between current-time history and displacement-time history for the above given tube compression example. The displacement data are related to the tube's tip point. After 7 µs first displacement is identifiable. Only 15µs later, the forming operation is accomplished.

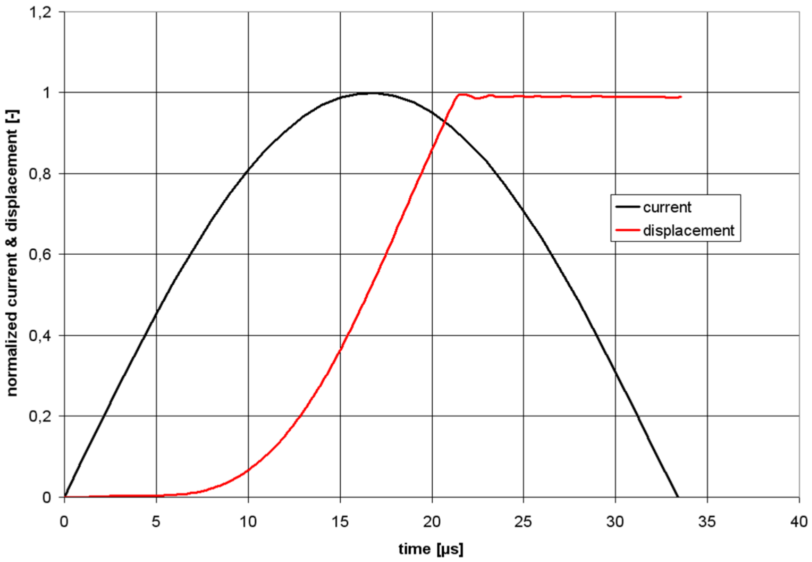

Fig. 3: current and correlating displacement –time history for a tube compression

Fig. 3 depicts for a beneficial correlation between current and displacement characteristics. A significant displacement of the workpiece begins at approx. 80% of the current maximum. The deformation ends, when the current has only slightly excessed its maximum. In this case, nearly the complete magnetic energy is applied to the moving workpiece. The correlation between discharge frequency and degree of efficiency is caused by 3 fundamentals:

1. The magnetic pressure is dependent on the width of the air gap between coil (or field shaper) and workpiece. When the gap distance increases to more than 1mm, significant magnetic pressure losses are identifiable. Hence, the main portion of magnetic pressure should be applied to the workpiece, before the air gap becomes bigger than 1mm
2. Maximum magnetic pressure is build up, when the induced current builds up a magnetic field in the same magnitude as the coil's field. I.e. if a single winded coil is used, the current, induced into the workpiece should equal the coil current. For this, the skin depth should be smaller than the work piece wall thickness. Only in this case, inductive coupling losses are minimized. Figure 4 illustrates the correlation between discharge frequency, skin depth and magnetic pressure for an aluminum Al6060 tube of 1mm wall thickness.

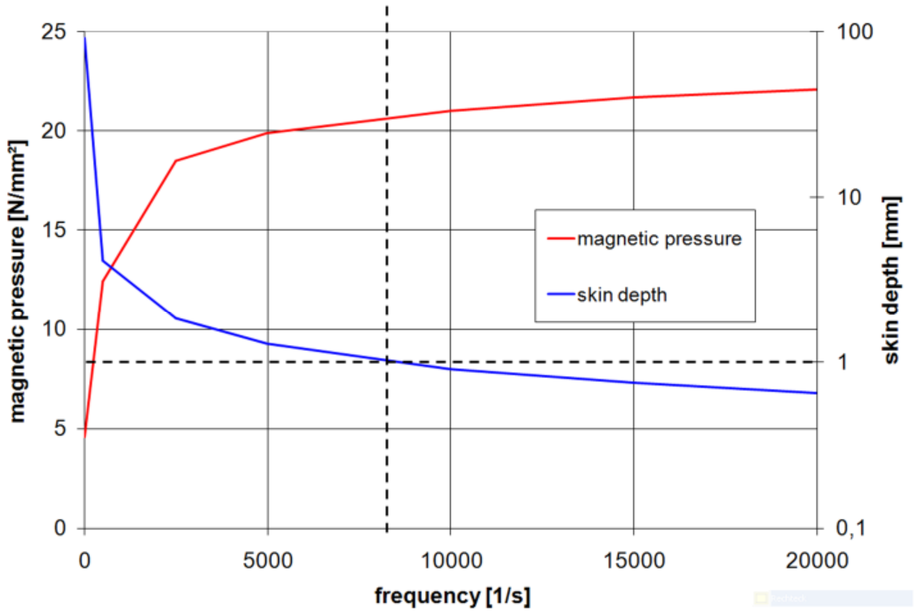

Fig. 4: Correlation between discharge frequency, skin depth and magnetic pressure for an 1mm wall thickness aluminum Al6060 tube

The skin depth in a component is dependent on frequency and electrical conductivity of the component's material:

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

δ denotes for the skin depth, χ for the electrical conductivity, *f* for the discharge frequency, μ_0 for the magnetic permeability of vacuum and μ_R for the relative magnetic permeability. Because of the high magnetic flux densities in EMPT coils, the relative magnetic permeability is nearly negligible due to saturation effects.
Hence, for forming of steel parts a higher discharge frequency is mandatory than for aluminum parts with the same wall thickness. Figure 5 gives values of magnetic pressure for a 1mm wall thickness structural steel tube and a 1mm aluminum AL6060 tube. Additionally, the skin depth of the structural steel tube is given.

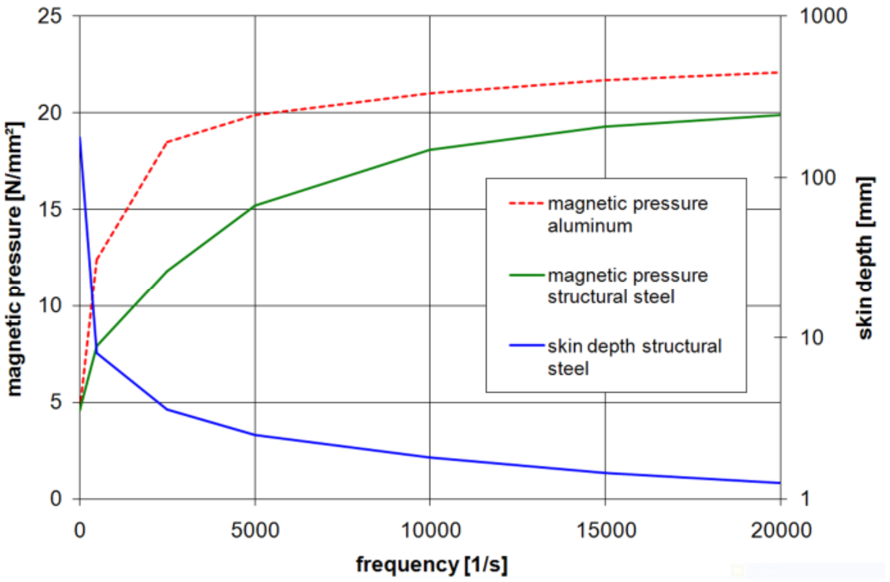

Fig. 5: Correlation between discharge frequency, skin depth and magnetic pressure for an 1mm wall thickness structural steel tube

3. However, there is a frequency dependent damping counteracting the beneficial effects of higher frequencies given in point 1&2. According to Winkler, in free tube compression, the radial displacement increases first with increasing frequency. After exceedance of an optimal frequency, the radial displacement decreases again (Winkler, 1973).
   To analyze this effect, numerical modeling of a free aluminum tube compression test is conducted. The tube dimensions are 40 mm in diameter, 1mm in wall thickness and 50 mm in length. The outer circumferential face is loaded on an area of 20 mm length, 15 mm away from each tube end, by a magnetic pressure of 60 N/mm² in amplitude. The pressure shows a sinusoidal time-history behavior. Plastic yielding is computed with the help of the Johnson-Cook equation. The coefficients for aluminum Al6082 T6 are derived from Lee, 1998. All variables except the discharge frequency are kept constant. For discharge frequencies of 1, 5, 10, 15 and 20 kHz, the maximum radial displacement of the tube material is monitored. As the frequency increases, the strain rate of the material is increased, too. Because of the strain rate dependent hardening behavior, the radial displacement is nearly inverse proportional to the discharge frequency, see figure 6.

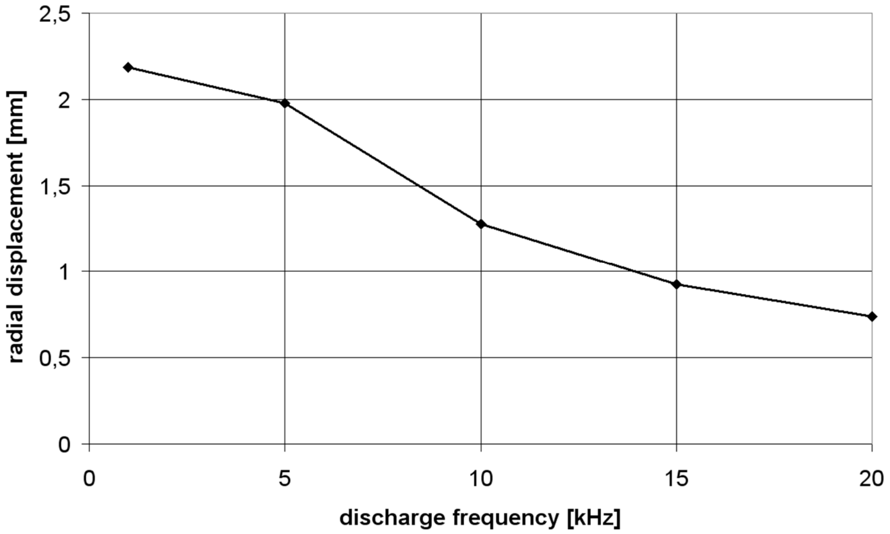

Fig. 6: Strain-rate dependent plastic yielding: Numerically computed correlation between discharge frequency and radial contraction of an AL6082 aluminum tube

Because of the above mentioned three effects, the discharge frequency should be adjusted to reasonable values. The rule of thumb for frequency adjustment is to use this frequency, which ensures the skin depth being smaller than the tube's wall thickness. This case, the magnetic energy is nearly completely transformed into mechanical pressure loading the component to be formed. Discharge frequencies above this value may cause counterproductive results.

3 EMPT Machines

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

2.1 Pulse Generator

The magnetic pressures for forming of metallic materials range in the interval of some 10 to some 100N/mm². To generate these pressures, it is necessary to apply pulsed currents in the range from 100kA to more than 1000kA to the coil. The energy required is 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 $E=½CU^2$ which is stored in the capacitors is transferred into the coil with a magnetic energy $E=½LI^2$ and vice versa. Here, C accounts for the circuit's capacitance, U for the charging voltage, L for the inductivity and I for the discharge current.
The discharge frequency f is governed by the complete EMPT system's inductivity L and its capacity C. The complete EMPT system consists of the pulse generator, cabling, coil and fieldshaper.

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

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 high-strength copper or aluminum alloy (Fig. 3). The coil cross-section is usually between 10 and several 100mm^2 depending on the required currents to transfer.

With respect to compression coils, the so called field shaper is an insert of electrical good conductive material, placed inside the coil. The work piece itself is place inside the center bore of the fieldshaper. The field shaper is sectioned with at least one radial slot, and is electrically insulated against the inlaying work piece and the enclosing 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. According to Winkler, the current density increases at the inner bore surface and hence, the magnetic pressure is here increased, too. (Winkler, 1973). 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. Figure 7 illustrates the numerically computed current density distribution on the fieldshaper's surface as well as the current direction. At the inner bore, the current density and therewith the magnetic pressure is significantly increased in comparison to the outer circumferential face. Blue color denotes for low current density, red for high. The small arrows are illustrating the current direction.

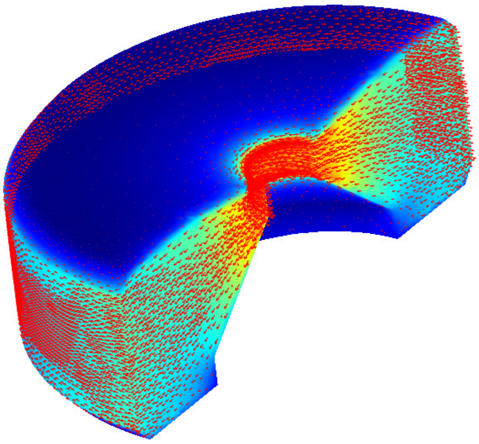

Fig. 7: Current density distribution at the field shapers surface

4 Industrial Applications

With the help of an adapted EMPT system even sophisticated forming, cutting and joining operations are feasible. 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. Belvy et. al. found the electrical resistance of EMPT crimped cable connectors being up to 50% lower than of those produced by mechanical crimping (Belvy, et.al, 1996)

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 aluminum 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 aluminum lids onto pharmaceutical glass bottles (Fig. 11). Recently, Pasquale has developed a special multiple joining coil, with which up to 50 joints can be made simultaneously within one pulse. The current consumption is only little higher compared with a normal single bore coil (Pasquale, 2007). Hence, the costs for an EMPT operation with respect to the single component are nearly divided by the number of coil bores.

Fig. 11: EMPT crimping of a sterile aluminum 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 pressurized 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 some 1000 N / mm² The interfacial zone is additionally severely plastically strained. The maximum contact normal pressure occurs 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 chipped oxide particles from the joint area.

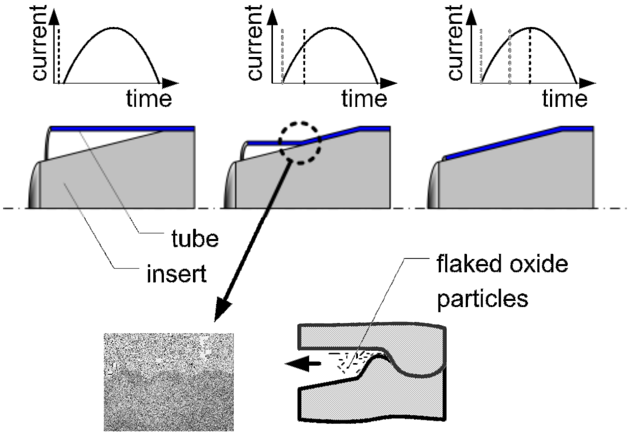

Fig. 12: Schematic representation of the EMPT welding process

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 aluminum, steel and copper, as well as copper and aluminum are feasible and can be manufactured in commercial production (Fig. 13).

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

The essential magnetic pressure and hence the deformation of the work pieces can be decreased 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.

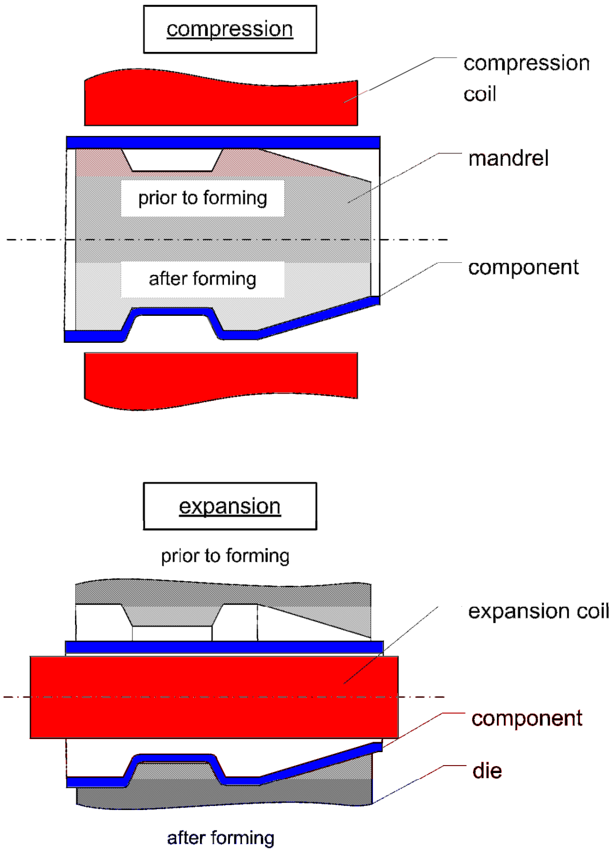

Fig. 14: Tools for EMPT compression and expansion

EMPT forming of tubular structures shows numerous benefits over conventional tube forming processes. EMPT can compress non rotational symmetric tube cross sections. Moreover, springback effects are minimized. Yamada et. al. analyzed the fundamentals of springback calibration by high velocity forming processes. They found, that during the impact of the workpiece on the die, some kind of ironing becomes effective. I.e., significant stresses in wall thickness direction are induced, leveling the residual stress distribution in the component to a homogeneous distribution. Thus, springback is minimized (Yamada, 1981).Moreover, analyses made by Daehn et. al emphasize, that under certain circumstances, the forming limits are shifted towards higher strain values (Daehn et. al., 1997). 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 aluminum 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 (Daehn et. al., 1997).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/(Ω·mm²)] = [10^6 S/m]
Copper Cu99,9	>58,0 (Lide,2006)
Aluminum Al 99,9	36,89 (Lide,2006)
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 (Lide,2006)
Stainless steel 1.4301	1,6 (Lide,2006)

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 inside 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 aluminum 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.

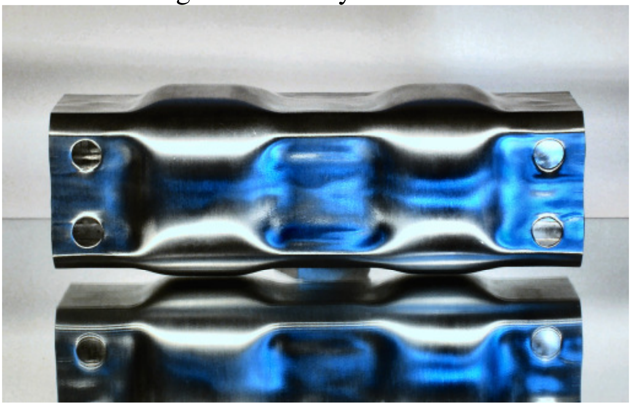

Fig. 15: Simultaneous EMPT forming and EMPT cutting of a crash box

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 (Schäfer, 2009). 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 EMPT-systems meets today's industrial requirements with 100% process control and the proven implementation in fully automated production lines (Schäfer, 2009).

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