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The electromagnetic pulse technology (EMPT): forming, welding, crimping and cutting

Abstract: The electromagnetic pulse technology (EMPT) provides non-contact processes for joining, welding, forming and cutting of metals. 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. 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;

Introduction

The electromagnetic pulse technology (EMPT) provides non-contact processes for the joining, welding, forming and cutting of metals by the application of strong, short pulsed magnetic fields. This technique was developed 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 knowledge gained, the authors concentrated their efforts on the joining of tubes by positive locking, and consequently, a stronger joint could be made (*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 aluminium 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 behaviour, 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. analysed the influence of magnetic pressure, joint

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design and 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 researchers analysed the possibilities of joining 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 of using the EMPT 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 cover only a small percentage off all the research work conducted in the field of EMPT, but especially in the latter ones they are capable of predicting the substantial benefits of this technique. Nevertheless, EMPT did not find widespread application in industrial manufacturing processes. This was mainly caused by lowering life times of the EMPT system components, especially of the coils used for generation of magnetic pressure. Recent developments in EMPT system components provided substantial improvement of pulse generator and coil life-time. Pasquale and Schäfer report coil life times of 2.000.000 pulses for tube compression applications (*Schäfer, 2009*). These substantial improvements, conducted in 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.

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.

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.

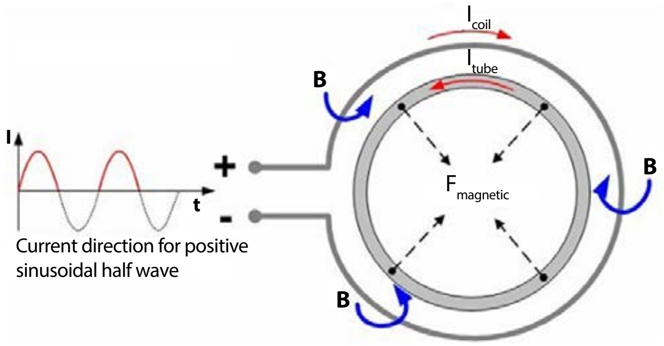

Fig. 1: Metallic tube inserted into an electromagnetic coil. Coil current, eddy currents and forces are shown for the positive half wave of the alternating current

If 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.

During the rise of the magnetic pressure some microseconds will elapse before the 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, 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.

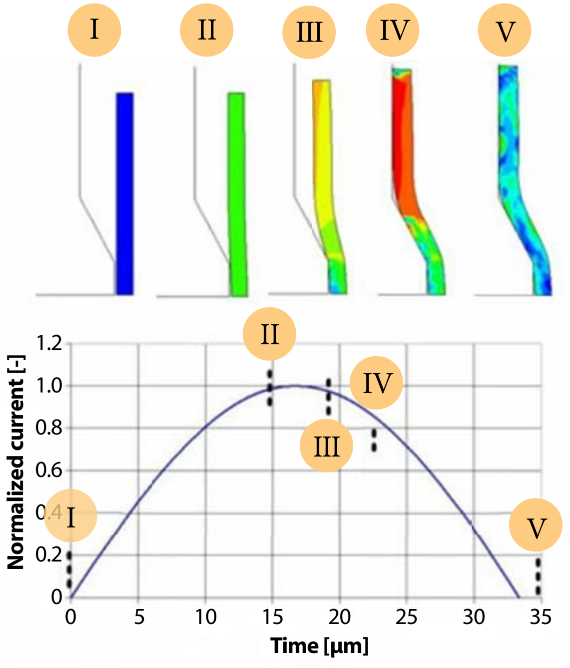

Fig. 2: Finite element analysis of crimping a tube onto an insert

EMPT Machines

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

Pulse Generator

The magnetic pressures for forming of metallic materials range in the interval of some 10 to some 100 N/mm². To generate these pressures, it is necessary to apply pulsed currents in the range from 100 kA to more than 1000 kA 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 field shaper.

Coils and Field Shaper

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 aluminium alloy. The coil cross-section is usually between 10 and several 100 mm² 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 centre bore of the field shaper. 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 also increased. (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.

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:

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. 3).

Fig. 3: 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. 4)

Fig. 4: 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 worldwide. 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.

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 noncontact process it can be used in sterile conditions, for example, for crimping aluminium lids onto pharmaceutical glass bottles (Fig. 5). 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. 5: EMPT crimping of a sterile aluminium lid onto a pharmaceutical glass bottle

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. 6). 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.

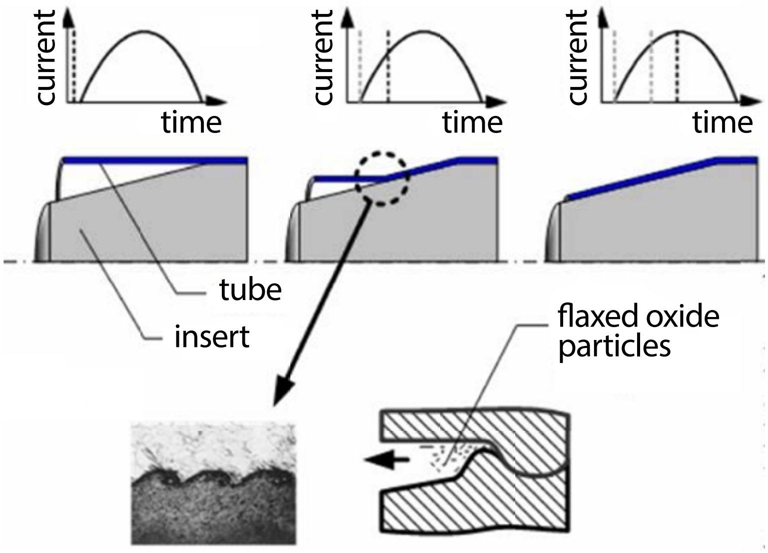

Fig. 6: Schematic representation of the EMPT welding process

In the bottom of the V-shaped gap appear contact normal stresses in the scale of some 1000 N/mm^2 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.

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. 7).

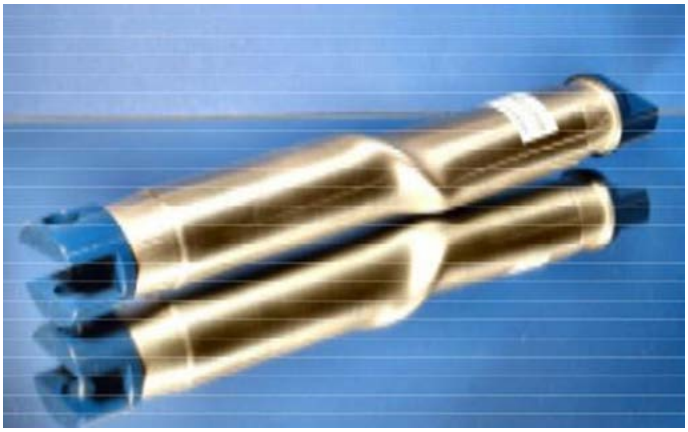
Fig. 7: EMPT welding of steel end pieces into a lightweight aluminium drive shaft

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.

EMPT Forming

Tubular structures can be compressed or expanded by electromagnetic pulse forming (Fig. 8). 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.

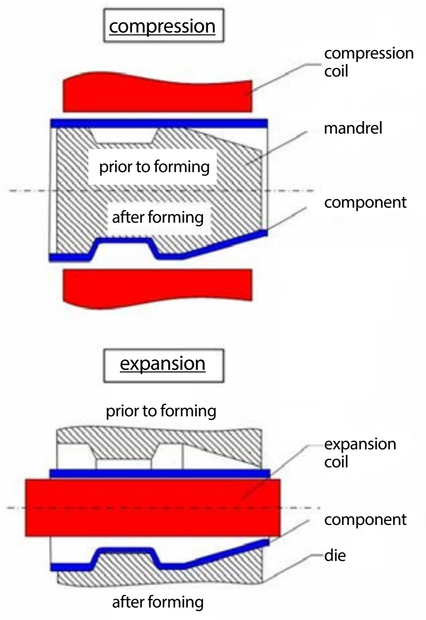

Fig. 8: Tools for EMPT compression and expansion

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. analysed 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 analyse 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 a circumferential direction was possible without material failure. During high strain rate expansion by EMPT at a radial expansion velocity of up to 170 m/s plastic straining in a 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.

Table 1: Electrical conductivity of some technical relevant materials

Material	Elecrical conductivity [mS/m]
Copper Cu 99,9	>58,0
Aluminium Al. 99,9	36,89
Aluminium 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
Stainless steel 1.4301	1,6

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, which with a significant decrease in the amplitude of the magnetic pressure can create some challenges for EMPT. To overcome this challenge, a "driver" is used, 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

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. 9). 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 few burrs occur.

Fig. 9: Simultaneous EMPT forming and EMPT cutting of a crash box

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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