Industrialisation of Electromagnetic Pulse Technology (EMPT) in India

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1 Introduction

The need for lightweight tubular structures becomes more and more evident, and PSTproducts GmbH offers therefore very advanced machines for joining, welding, cutting and forming of tubes. The electromagnetic pulse technology (EMPT) is now available for industrial applications in India and is also used by highly ranking Indian universities and R&D institutes. PSTproducts GmbH in Alzenau (Germany) is recognised as the leading equipment supplier in this field (Fig. 1). It is represented in India through Proteck Machinery Pvt Ltd.

Fig. 1: Pablo Pasquale and Wolfgang Schütz set-up PSTproducts in 2003 and developed the industrial application of the electromagnetic pulse technology. Their company operates now globally and is represented in India through Proteck Machinery Pvt Ltd

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 (Fig 2). Non-magnetic metal tubes such as aluminium and copper tubes can be processed, because an eddy current is temporarily induced in the skin of the tubes.

Fig 2: EMPT crimping of aluminium and steel tubes onto an aluminium node for an IP beam

Fig 3: EMPT welding of a pressure vessel for air condition systems (ø75mm dia. aluminium)

EMPT processes can be applied to various alloys with particular success with those with high electric conductivity such as aluminium, copper and steel. 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.

PSTproducts offers high-quality EMPT systems for the following applications:

- Automotive body and chassis components
- Tubes and valves for water, oil and gas
- Nuclear fuel rods from ODS alloys
- Pharma packaging (aluminium lids on vials)
- Aerosol and drink cans, shaped food tins
- Electrical components (e.g. batteries)
- Aluminium scaffolding tubes
- HVAC pressure vessels for CO_2 (Fig 3)
- Solar panels and their support frames
- De-icing tubes of air craft
- Aerospace mirrors and frameworks
- Automotive tow bars (dissimilar materials)
- Instrument panel beams (IP beams)
- Shock absorbers (aluminium or steel)
- Suspension struts (dissimilar metals)
- Next generation car crash boxes
- Seat structures for aircraft and cars
- Crashworthy automotive fuel lines
- Tube to node joints in space frames

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 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 4).

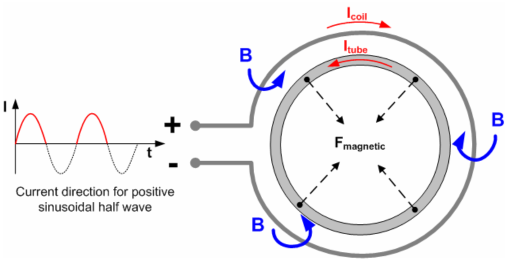

Fig 4: Forces onto a metallic tube in an electromagnetic coil

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. Therefore, the tube wall experiences a radial force acting inwards.

The magnetic force compresses the tube in a radial direction within microseconds. However, because of the tube's inertia, the forming process is phase delayed to the pressure build-up.

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 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 (Fig 5).

Fig 5: Integrated EMPT BlueWave system PS16-10 with 16kJ energy at 10kV voltage

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 stored in a pulse generator, consisting of a capacitor bank, a charging unit and a high current switch (Fig 6). 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.

Fig 6: PS112-16 BlueWave EMPT pulse generator with 112kJ energy at 16kV voltage

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. 7). The coil cross-section is usually between 10 and several 100mm² depending on the currents.

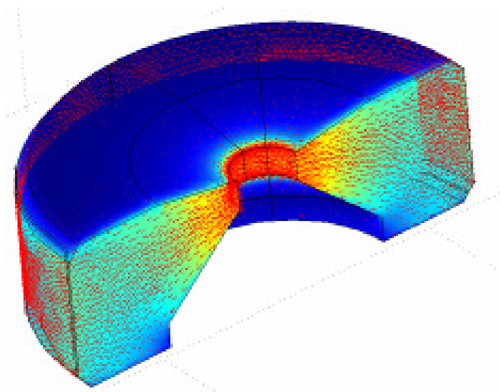

Fig 7: Concentration of the electromagnetic field in the field shaper

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 (Fig 8).

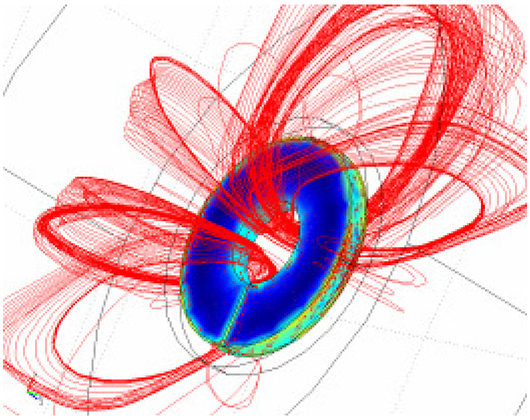

Fig 8: Finite Element Analysis (FEA) of the magnetic field inside a field shaper

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 (Fig 9). 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.

4 Working Procedures

The workflow can be described as follows: After the work piece is positioned in the coil, the charging of the capacitors begins while the high current switch of the pulse generator is open. The resonant circuit is thus initially interrupted. The capacitors reach the selected voltage within a period of usually less than 8 seconds. Once the charging voltage is reached, the charging switch is opened and the high current switch closed. The energy stored in the capacitor is then released and causes a sinusoidal current flow into the electromagnetic coil, which ceases after a few oscillation cycles (Fig. 10). The discharge frequency of industrially used EMPT systems is in the range between 6 and 60 kHz.

Fig 9: EMPT hemming of a pressure vessel for aluminium shock absorbers

EMPT facilities of PSTproducts GmbH are characterized by an optimised tool life, high discharge currents, short cycle times and advanced process monitoring and control algorithms. The lifetime of the capacitors of modern BlueWave pulse generators is more than 2 million pulses. Service intervals are at about 500,000 pulses. The discharging currents vary, depending on the model, between 100 and 2000 kA.

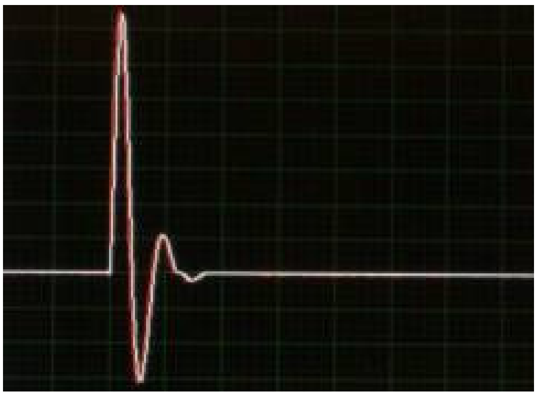

Fig 10: Plot of a typical discharging curve

A unique feature of the BlueWave pulse generators of PSTproducts is the close-loop process monitoring system. Here, the current profile of each pulse is analyzed and stored. It will then be processed by rule based algorithms, which guarantee that the discharge currents are kept within a specified process window even if the ambient conditions change. The control systems of PSTproducts thus allow the integration of these pulse generators in fully automated production lines.

5 Industrial Applications

The EMPT is used industrially for forming, joining, welding and cutting:

5.1 EMPT Forming

During EMPT forming it is possible to compress or expand tubular structures. This can be achieved at room temperature [3] and the resulting deformation is greater than with conventional methods. Free forming is also possible, but a mandrel or die is commonly used to ensure small geometric tolerances in both compression and expansion respectively. Often it is necessary to split these tools, so remove the finished component from its tools.

The applications of EMPT forming are not limited to splines as they are used in telescopic drive shafts (Fig 11). It is also possible to form flat structures (sheets) by specifying suitable coils and tools.

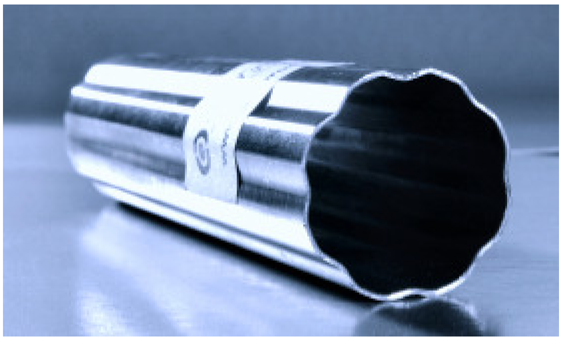

Fig 11: EMPT formed spline (ø40mm)

5.2 EMPT Crimping

EMPT crimping with a mechanical interlock represents a techno-economically attractive alternative to conventional mechanical crimping. The contact pressure is applied electromagnetically over the entire circumference without touching the tubes or rings (Fig 12).

Fig 12: EMPT crimped air suspension

Axial positioning errors of the components can be compensated for by EMPT assembling. Since no filler materials or additives are necessary, the EMPT processes can also be carried out in clean rooms or under sterile conditions, for example, for crimping lids onto glass and ceramics (Fig 13).

Fig 13: Aluminium lid EMPT crimped onto pharmaceutical glass vial

EMPT crimping of electrical contacts results in a very uniform compression of the cable strands (Fig 14). The electrical resistance of EMPT crimped cable connections is sometimes 50% lower than that produced by mechanical crimping [4].

Fig 14: EMPT crimped high current cable: copper-copper and copper-steel-copper joints

EMPT crimping is in widespread industrial use with some 400-500 EMPT machines worldwide. It can be used with rubber O-rings to seal fluid and gas tight containers or filter housings (Fig. 15).

Fig 15: EMPT crimped aluminium-plastic fuel filter with two O-rings (ø75mm)

5.3 EMPT Welding

EMPT welding (also known as magnetic pulse welding) is used to achieve metallurgical bonds, e.g. if pressure or vacuum vessels needs to be helium tight (Fig 16).

Fig 16: Successful peel test of a EMPT welded pressure vessel

The EMPT welding process can be conducted without creating a heat affected zone and this leads to excellent strength, especially in artificially aged aluminium alloys (Fig 17).

Fig 17: Small pressure vessels for automotive air condition systems (ø50mm dia.)

EMPT welding is similar to explosive welding because the atoms of two work pieces are brought into intimate contact by applying high pressures. During the process, on surface rolls and rubs on the surface of the other, while an initially V-shaped gap is being closed. An the contact area of the V-shaped gap stresses normal to the surface and at the level of approximately 1000 N/mm² occur at considerable strain rates (Fig 18). The contact line between the two work pieces creates a continuously re-forming bow wave whose wavelength is in the range of tens of microns. The plastic deformation in the joint line leads to a disruption of the oxide layers resulting in a solid phase weld.

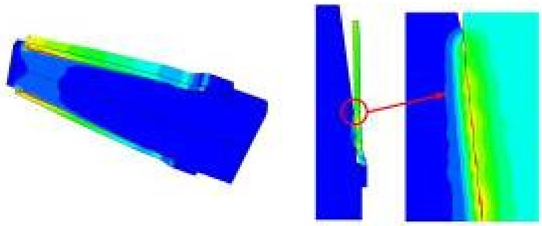

Fig 18: Finite Element Analysis of the stress distribution during EMPT welding

The benefits of EMPT welds are related to high strength and the possibility to join advanced materials which are often difficult or impossible to weld by fusion welding. Difficult to weld high-strength steels, oxide dispersion strengthened alloys (ODS) and metal matrix composites (MMC) can be welded by EMPT [5] (Fig 19).

Fig 19: EMPT welding of the ferritic-martensitic steel T91 for nuclear fuel rods (ø8mm)

It is also possible to EMPT weld dissimilar materials with very high integrity, e.g. aluminium or stainless steel tubes onto copper inserts (Fig 20). This leads to excellent electrical conductivity and thermal conductivity. Many suppliers of parts for electric and hybrid cars are now investigating the properties of these joints.

Fig 20: EMPT welded aluminium-copper transition joint (ø25mm dia.)

5.4 EMPT Cutting

The body of motor vehicles must be sufficiently rigid, to provide crashworthiness, and thus processing the high-strength steels involved – for example punching holes into these – can prove challenging. EMPT cutting procedures are now being developed and will save time, energy and money in the future (Fig 21)).

Fig 21: EMPT cutting of automotive sheets at Fraunhofer IWU in Chemnitz using a PSTproducts BlueWave coil

The strength of the steels that are used throw up their own challenges, for example when automobile manufacturers have to punch holes in them for cable routing. During conventional punching of high-strength steel mechanical cutting tools rapidly wear out. And because mechanical processes leave some burrs on the lower surface of the sheets, additional time has to be spent for de-burring. One possible alternative is to use lasers as cutters, but these require a great deal of energy, which makes the entire process time-consuming and costly. Therefore heavy duty EMPT cutting systems are now being developed and used (Fig 22)

Fig 22 Heavy-duty EMPT BlueWave system PS103-25 with 103kJ energy at 25kV voltage

Working together with a number of partners including Volkswagen, researchers at the Fraunhofer Institute for Machine Tools and Forming Technology IWU in Chemnitz have come up with an innovative way to make holes in press-hardened steel bodywork. The new method is based on electromagnetic pulse technology (EMPT), which was previously used primarily to expand or compress aluminium tubes (Fig 23).

Fig 23: EMPT crimped seat structure by PSTproducts using Sapa extrusions

6 Cost-Value 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 24). 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).

Fig 24: Heavy-duty PS96-16 BlueWave System by PSTproducts with 96kJ at 16kV for use in the industrial environment of the world's largest aluminium extrusion company Sapa

A multiple joining coil, trademarked MJo Coil, has been developed and patented by PSTproducts (Fig 23). 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.

Fig 23: BlueWave Multiple joining coil MJo2 for simultaneous joining of two work pieces

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 (Fig 24). 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.

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.

Fig 24: Modular packaging of an industrial PS96-16 BlueWave system by PSTproducts

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 R&D environments and fully automated production lines (Fig 25).

Fig 25: Heavy-duty EMPT BlueWave system PS100-10 with 100kJ energy at 10kV voltage

8 More Information

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