Recent Evolutions of Electromagnetic Pulse Processes in the Industrial Mass Production

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Abstract

Electromagnetic pulse processes used to be niche production applications. Apart from research and development (R&D) use, pulse generators were found in few production facilities and low production volume applications only. During the recent years, significant advances in certain key applications have been made.
For example, the crimping of cables and the welding of bus bar connectors are both high volume applications in the automotive industry. The machines (pulse generators and tool coils) as well as the processes have undergone extensive certification routines for quality assurance and meet the requirements for mass production. The manufacturers' specifications have been developed with regard to the particularities of electromagnetic pulse processes and machines. Enabled by the continuous development, it became even possible to enter markets with high production rates and volumes.
The success for these applications does not only result in an increased number of production machines, but also act as 'door opener' for further applications in and beyond their current field of application. Next steps are for example the development of a crimping and tube welding operation which joins a copper connector via an aluminium tube (welding) to an aluminium cable (crimping).

Keywords

cable crimping, welding, bus bar, industrial production

1 Introduction

Electromagnetic pulse processes are on their way to mass production. This was started in the late last century, when numerous more or less realistic applications have been thought of.

However, the necessary equipment was not at hand yet and the applications were too ambitious in many cases. Hence, this hype turned into disillusionment. As a consequence, electromagnetic pulse processes are stigmatized as not relevant for industrial (mass) production. This is why many production companies still have pulse generators from that era, but barely use them and don't invest in process research. Pulse process equipment has been almost exclusively used for university research and few funded industrial research projects. However, since then, many aspects have been improved:

Capable pulse generators with durable components are available. Switches, capacitors and cables have been vastly improved with regard to service life and stability, and need to be replaced far less frequently. Pulse switches can reach several hundred thousand pulses to more than one million pulses before they are replaced. They don't contain mercury, which was the case with certain types. The pulse cables and capacitors are capable of far more than one million pulses. This compensates the fact that these core components are very expensive and reduces the production costs per part.

The development of the tool coils aims for three goals: A more durable design, decreasing the costs, and a broad variety of geometries to fit a wide range of applications. They are usually designed so that the wear parts are small, cheap and easy to replace, whereas the rest is robust for a long service life. Sheet metal welding is possible with workpiece sizes between several millimetres and more than a metre. The part of the tool coil that actually induces the eddy currents into the flyer is the main wear part. The diameter for tube welding and crimping is in the same range as the length for sheet metal welding. Here, the field shapers are the main wear parts. Crimping and welding of a large variety of work piece geometries is possible. The geometry of the tool coil or field shaper is adapted correspondingly. Furthermore, tool coils for the industrial mass productions usually process more than one work piece per pulse to reduce costs.

The measurement of the pulse current is the most important parameter to monitor both pulse generator and process. With an adequate design of the equipment, the repeatability of the peak discharge current and the discharge current frequency can be as precise as ±0.15 %, including measurement errors. With careful design of the workpieces, the upstream processes (such as cleaning) and the automation system, the discharge current measurement and its evaluation alone are sufficient to monitor both the pulse generator and the process. The process capability of electromagnetic pulse processes can achieve more than the required threshold value for mass production processes in multiple applications and industry branches.

The knowhow regarding the design of automation systems, which are crucial for mass production, has improved greatly. Robust sensors, actuators and bus systems enable precise movements even in close vicinity to the tool coil.

2 Market overview

The progress of pulse generators, tools and auxiliary equipment enables more and more industrial products to be manufactured by electromagnetic pulse processes. Once one product of one manufacturer is processed using electromagnetic pulse technology (EMPT), other customers with identical or similar products follow. In many cases, the knowledge of the capabilities of electromagnetic pulse processes is spread within a company and adapted to other products. This may also involve the step from crimping a product to welding another.

This opens the markets and leads to an increasing demand for the machines. **Fig. 1** shows the delivered pulse generators within the given time periods by PSTproducts since the foundation in 2003. The number of tool coils is larger, because several customers have more than one tool coil for one pulse generator. As the value of tool coils has a very large margin and is usually lower than the value of the pulse generator (mostly about 20 %-50 %), the number of pulse generators provides a clearer picture. Furthermore, pulse generators with multiple tool coils are, without exception, mainly used for R&D purposes. It is worth mentioning that the share of production machines keeps increasing.

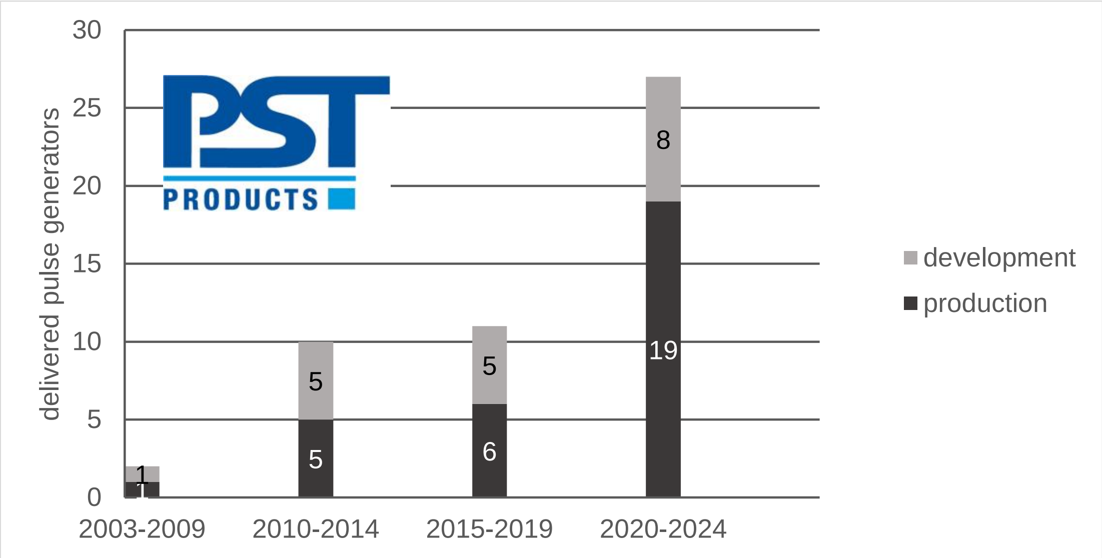

Figure 1: *Number of pulse generators delivered by PSTproducts during given time periods.*

The combination of a five-year time period was chosen because of its smoothening effect. Due to the low number of machines, their sometimes long production time and effects due to different accounting years, the resulting diagram on a yearly basis would require extensive explanation. Despite challenges, e.g., 2008 financial crisis, the number of delivered pulse generators keeps increasing. This is still due to a relatively small number of applications. However, this number keeps increasing, too.

After the foundation of PSTproducts in 2003, it took five years until the first pulse generator for mass production was delivered. At this early stage, most of the machines were bought by universities and labs for R&D purposes. Starting with 2009, more and more commercial enterprises became aware of and interested in the electromagnetic pulse technology. Whilst some of them started with pulse generators and tool coils for development purposes (with the option of upgrading the R&D machine to a production machine later), others started with mass production equipment right from the beginning after the trials.

The data shown here contains a delay which is worth mentioning: The time span between the first trials, either at PSTproducts' shop floor or at the customers' site with own equipment, and the delivery of the first machine ranges from two years up to nine years or more in rare cases. The reasons are manifold: economic factors, extensive tests (e.g., fatigue tests), complex development task, to name only a few.

3 Examples

Many applications and products are still under development and covered by nondisclosure agreements (NDA). In certain cases, this applies to parts in production, too. In this chapter, three undisclosed examples are described.

3.1 Pressure vessels for heat pumps

In contrast to heat pump systems with conventional refrigerants such as R-134A, new systems with CO_2 operate at far higher pressures (max. 2 MPa vs. more than 100 MPa), thus requiring all components to be far stronger, for example by increasing the wall thickness. This stands in contrast to the requirement of being lightweight in mobile applications such as cars. Electromagnetic pulse welding offers the great advantage of not weakening the workpieces, for example by heat affected zones. This allows for a decrease in wall thickness and thus weight. **Fig. 2** shows a pressure vessel which consists of a tube and two lids. The tube is welded onto the lids with two individual but sequential pulses. The diameter is usually in the range around 80 mm.

pressure vessel

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start of first trials:	2014
first production machine:	2016
machines sold by mid-2025:	3

Figure 2: *Pressure vessel for CO_2 heat pumps.*

During the development phase, the wall thickness could be reduced due to the better dynamic strength properties of EMPT welded joints. The geometry of the joint was adapted for a further improved (fatigue) strength.

3.2 Power bus bars

Due to the electrochemical requirements, rechargeable Lithium-Ion batteries usually have a (nickel coated) copper connector and an aluminium connector. Irrespective of the design of the cell pack, these two metals need to be connected at some place. This is can be realized by hybrid power bus bars, which exist in a large variety of geometries. **Fig. 3** shows an example. The thickness of the metals is typically between 1 mm and 3 mm, but may be up to more than 5 mm. Conventional joining processes, such as screws and bolts, have disadvantages regarding electrical resistance, creep strength, cycle time or joint costs. An electromagnetic pulse weld offers excellent mechanical and electrical properties.

power bus bar

start of first trials:	2013
first production machine:	2015
machines sold by mid-2025:	7

Figure 3: *Power bus bar (example, not an actual production part).*

The bus bars are comparably small with a typical width of some tens of millimetres. At the same time, they are mass products which need to have low manufacturing costs. The solution are sheet welding tool coils which weld more than one bus bar during one pulse. Depending on the bus bar geometry, more than ten individual welds can be produced per pulse. The capacity of the pulse generator needs to be increased only moderately, typically less than 10 % per additional welding.

3.3 Cable crimping

The mechanical crimping of cables is trivial for small cross sections of 10 mm^2 and less, but becomes increasingly challenging with larger cross sections. The friction between the individual wires prevents the crimping force from the outside from reaching the centre. The compression shock wave from electromagnetic crimping however reaches the whole cross section, resulting in a homogeneous and good compression of the cable. Hence both the mechanical pull-out strength as well as the electrical resistance show superior values, even after many mechanical and temperature cycles. As a result, these connections can be smaller than conventionally crimped cables.

EV cable

start of first trials:	2019
first production machine:	2021
machines sold by mid-2025:	13

Figure 4: *Two different cable cross sections: 150 mm^2 (left, before crimping) and 70 mm^2 (right, after crimping).*

Besides the crimping of the cable core, the shield connection is also produced by electromagnetic pulse crimping. The tool coil and the pulse generator are the same, but a different field shaper and a lower discharge current are used.

In this particular case, the electromagnetic pulse technology enables a new development: In order to save weight, aluminium cables are preferred over copper cables. Still, the connector needs to made from copper. Crimping a copper connector to an aluminium cable is possible, but after only a few thermal cycles the joint becomes ineligible. The solution is provided by an additional aluminium-copper weld. One portion of an additional aluminium sleeve is welded to the copper connector. The other portion of the sleeve is crimped onto the aluminium cable. Depending on the diameter and geometry, both crimping and welding are be possible during one pulse with one field shaper only.

4 Summary and outlook

The development of the equipment for electromagnetic pulse processes has enabled a wide spread of this manufacturing technology. Three exemplary products and processes in mass production have been described: tube welding, sheet metal welding and crimping. They prove that pulse generators and the joining processes have made their way into high volume manufacturing.

The described mass production examples have in common that there is no online process monitoring, except for the measurement of the discharge current. In some applications, even inline non-destructive testing after joining is omitted. Instead, random samples are taken for destructive testing. Hence the upstream processes (e.g., cleaning), the discharge current measurement and the stability of the tool play an important role for quality assurance. This is why the equipment has to undergo extensive certification routines to make sure that all components meet the high quality requirements for mass production.

As a conclusion it can be stated that although electromagnetic pulse processes and equipment are used in mass production, there are still open tasks left for future development, especially regarding online and inline monitoring and testing.