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Electromagnetic forming—A review

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ABSTRACT

Electromagnetic forming is an impulse or high-speed forming technology using pulsed magnetic field to apply Lorentz' forces to workpieces preferably made of a highly electrically conductive material without mechanical contact and without a working medium. Thus hollow profiles can be compressed or expanded and flat or three-dimensionally preformed sheet metal can be shaped and joined as well as cutting operations can be performed. Due to extremely high velocities and strain rates in comparison to conventional quasistatic processes, forming limits can be extended for several materials. In this article, the state of the art of electromagnetic forming is reviewed considering:

- basic research work regarding the process principle, significant parameters on the acting loads, the resulting workpiece deformation, and their interactions, and the energy transfer during the process;
- application-oriented research work and applications in the field of forming, joining, cutting, and process combinations including electromagnetic forming incorporated into conventional forming technologies.

Moreover, research on the material behavior at the process specific high strain rates and on the equipment applied for electromagnetic forming is regarded. On the basis of this survey it is described why electromagnetic forming has not been widely initiated in industrial manufacturing processes up to now. Fields and topics where further research is required are identified and prospects for future industrial implementation of the process are given.

1. Introduction

Electromagnetic forming is an impulse or high-speed forming technology, which uses pulsed magnetic fields to apply forces to tubular or sheet metal workpieces, made of a material of high electrical conductivity. The force application is contact free and no working medium is required. The principle is based on physical effects described by Maxwell (1873). Maxwell explained that a temporarily varying magnetic field induces electrical currents in nearby conductors and additionally exerts forces (the so-called Lorentz forces) to these conductors. Northrup (1907) reported accordingly that "in passing a relatively large alternating current through an non-electrolytic, liquid conductor contained on a trough, that the liquid contracted in cross-section and flowed up hill lengthwise of the trough, climbing up upon the electrodes" was observed. With increasing current a contraction of the cross-section and a depression in the liquid was found. The first one who generated magnetic field strengths which were sufficient to deform solid conductors was Kapitza (1924). Thus, he provided the foundation for the electromagnetic forming process. However, the earliest work on technologically exploiting this principle for a target-oriented forming of metals began in the 1950s with the patent of Harvey and Brower (1958). A more detailed description including examples of applications is given in Brower (1969).

Depending on the arrangement and the geometry of the coil and workpiece, different applications of electromagnetic forming are achieved: compression and expansion (also called bulging) of tubular components or hollow profiles as well as forming of initially flat or three-dimensional preformed sheet metals (see Fig. 1). According to these three different variants of the process, different types of coils for the electromagnetic forming process can be distinguished. During tube compression the coil encloses the workpiece, while in the setup for the expansion it is the other way around. According to Belyy et al. (1977) tubes with a diameter in the range of 3 mm up to 2 m and with thicknesses of up to 5 mm can be processed. For electromagnetic sheet metal forming flat coils are used. Here, the area of the formed workpiece can be in the range of 10^{-4} up to 0.02 m^2 and the sheet thickness can be up to 5 mm (Belyy et al., 1977). However, the charging energy depends on the area to be formed, so that a machine with higher maximum charging energy is required if large tubes or sheets shall be processed.

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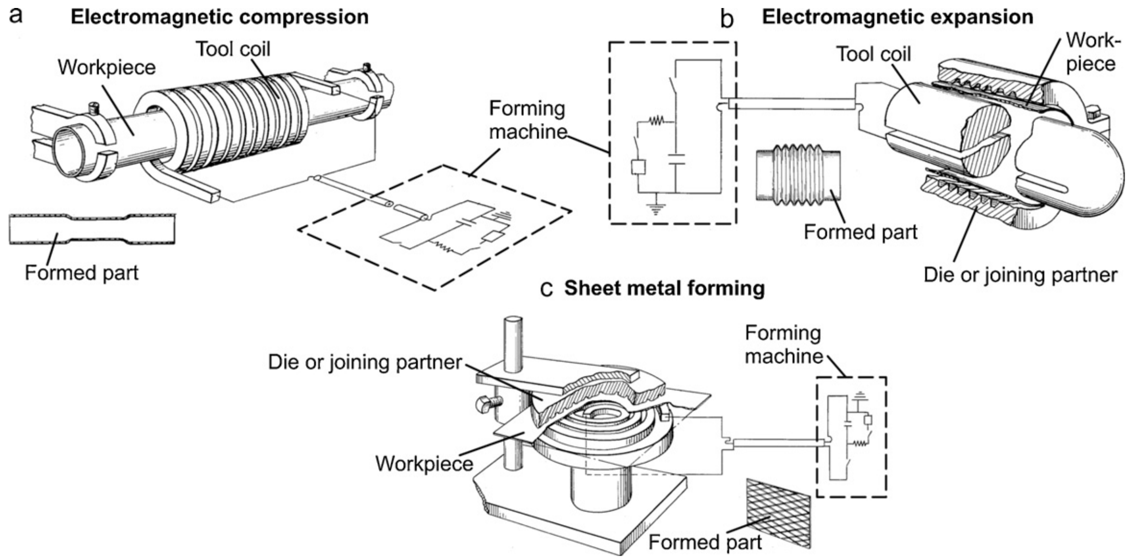

Fig. 1. Different coil types for the electromagnetic forming processes according to Harvey and Brower (1958).

Apart from these three major process variants, which are frequently discussed in the literature, some special variants are mentioned in Furth and Waniek (1962). These are electromagnetic forming with direct electrode contact. While in most cases a required current in the workpiece is realized via induction, Furth and Waniek (1962) suggest passing the current directly to the metal through electrodes. They claim this method to be more efficient than the conventional procedure and they recommend using electrodes with flexible extensions in order to prevent sparking or erosion. A second idea presented in Furth and Waniek (1962) deals with electromagnetic forming by pulling. While in typical applications the workpiece is always pushed away from the tool coil, here a special setup including two different coils is suggested in order to establish pulling forces, which allows forming bulges on hollow objects or large sheets, where a force application on the inner or reverse side is not possible.

Another special process variant is suggested in Brower (1966) for the first time. In this variant the electromagnetic forces act on the workpiece via an elastic medium. For this purpose the setup for electromagnetic sheet metal forming illustrated in Fig. 1 is supplemented by a pressure concentrator and an elastomeric punch, which is positioned between the tool coil and workpiece. In contrast to the more conventional electromagnetic forming variants, this process is not limited to workpieces made of an electrically conductive material. In Livshitz et al. (2004) a comparison between direct electromagnetic forming and electromagnetic forming through an elastic medium is given. It is pointed out that using the elastic medium the current oscillation frequency should be lower then in case of direct electromagnetic forming (a frequency of 5 kHz is advised, here). Furthermore, information about the suitability of elastomers of different modulus of elasticity are given. It is said that an elastomer of higher modulus of elasticity allows using an open die while in case of an elastomer of lower modulus of elasticity has to be applied in a closed system in order to achieve good efficiency.

Bühler and von Finckenstein (1971) claimed the joining of tubular workpieces to be the most widespread and economically promising field of application. Bauer (1980) even stated that only the process variant of the electromagnetic compression has advantages compared to conventional forming processes at all. However, according to Beerwald (2005) a kind of renaissance of the electromagnetic forming can be observed over the last years, which is related to the increasing trend of implementing lightweight construction concepts especially in the automotive industry. As recently stated by Schäfer and Pasquale (2010) as well as by Zittel (2010), at the moment joining operations are still the most relevant ones, but according to Löschmann et al. (2006), the significance of the electromagnetic sheet metal forming can be expected to increase within industry until 2012.

The electromagnetic forming process has several advantages in comparison to conventional, quasistatic forming processes. The major ones are summarized in the following:

- Due to the contact-free force application, it is possible to form covered semi-finished parts without destroying the layer as stated by Bertholdi and Daube (1966). No mechanical contact between the tool coil and workpiece exists, so that no impureness or imprint occurs on the workpiece surface.
- According to Erdösi and Meinel (1984) the process is environmentally friendly, because no lubricants are used. Additionally, this results in a simplification of the workpiece processing, because there is no need to clean the workpiece.
- A high repeatability can be achieved by adjusting the forming machine once. According to Daube et al. (1966) the adjustment of the applied forces via the charging energy and the voltage, respectively is very accurate. Belyy et al. (1977) quantify that the forming energy can be dosed precisely up to 1%. According to Bertholdi and Daube (1966) reworking operations are usually not necessary.
- Joining of dissimilar materials including material combinations of metals and glass, polymers, composites or different metals is possible. This is shown in Al-Hassani et al. (1967) on the example of a metallic cap joined to a glass bottle and in Rafailoff and Schmidt (1975) for the example of a joint between a metallic tube and a porcelain component.
- In contrast to the conventional sheet metal forming the electromagnetic sheet metal forming process uses only one form defining tool. Hence, the tool costs can be decreased significantly (Plum, 1988).
- Springback is significantly reduced in comparison to conventional quasistatic forming operations. This simplifies the die design significantly.
- According to Saha (2005) high production rates can be achieved. In the case of manual feeding the production rate is limited by the time required for loading and unloading of the part. As mentioned in Brower (1969) production rates of 350–400 parts per hour can