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Analytical methodology for the process design of electromagnetic crimping

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ABSTRACT

Modern lightweight design concepts, like the space frame design and multi-material structures, have complex demands on joining technologies, and conventional processes are often pushed to their technological limits. An interesting alternative for connecting extruded aluminum profiles without heating or penetration is joining by electromagnetic crimping. Compared to adhesive bonding and welding, the process also requires a less extensive joining zone preparation. However, existing process design methodologies require either extensive experimental studies or sophisticated numerical modeling. Therefore, an analytical approach for the determination of process parameters, like the applied charging energy, is presented in this article. Besides groove geometry and workpiece properties, the model also considers the electrical characteristics of the electromagnetic forming equipment. Experimental studies of the joining process are performed to verify the developed model. Additionally, the electromagnetic crimping operation is numerically modeled for a more detailed analysis of this process.

1. Introduction

A current trend to decrease the weight of a structure is the application of multi-material designs in combination with newly developed and more sophisticated materials. For example, the mass proportion of light metals, such as aluminum and magnesium alloys, has greatly increased in comparison to steel in the automotive industry and will continue to increase in the coming years (Schürmann, 2007). In this lightweight design concept, materials are selected in accordance with the local requirements of a structure, such as the acting mechanical stresses. Another innovative lightweight design concept, which is especially suitable for low volume production, is the so-called space frame design. According to Chatti (2004), extruded aluminum profiles are particularly suitable for manufacturing such lightweight frame structures. The high freedom in the cross-sectional design is a major advantage of these profiles. As a result, load adapted and functional cross section shapes can be manufactured and parts with a high stiffness, but a low mass can be achieved.

The high weight reduction potential of multi-material designs and space frame structures is opposed by the very complex demands on the joining technology for these kinds of structures (Mori et al., 2013). Due to the different material properties of the workpieces which are to be combined, conventional and widely used joining techniques often reach their technical limits. For instance, if there is a significant difference in melting temperature and thermal conductivity of the joining partners, fusion welding cannot be applied. Pure aluminum space frame structures can sometimes also be very challenging for conventional welding techniques. For example, the formation of the so-called heat-affected zone (HAZ) during thermal welding leads to a reduction of the strength of a connection. To achieve joint strengths in the range of the base material strength, an additional heat treatment of the joining zone is necessary (Barnes and Pashby, 2000).

Hence, this kind of structures can often only be joined by mechanical fastening or adhesive bonding (Mori et al., 2013). But a lot of the conventional processes have significant disadvantages, which exclude them for particular applications. For example, main drawbacks of mechanical fastening are the need for supplementary connection elements, like screws, bolts or rivets, and the often necessary pre-punch operations. Additionally, the required penetration of the joining partners can lead to an inhomogeneous stress distribution and thereby to critical notch stresses. As a result, the transferable loads might be reduced. The major disadvantages of adhesive bonding are the often very intensive surface preparation and the typically very long process times (Schürmann, 2007).

An interesting joining technique to overcome some of these disadvantages, especially in the case of profile-to-profile connections, is the application of joining by forming processes (Mori et al., 2013). Due to its ability to manufacture multi-material joints

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without additional connection elements very rapidly, electromagnetic crimping is particularly suitable for this kind of connections (Psyk et al., 2011).

2. Fundamentals of electromagnetic crimping

Electromagnetic crimping is a process variant of electromagnetic forming (EMF), which is an energy-based impulse forming technique (Winkler, 1973). Within this process, pulsed magnetic fields are used to form highly conductive metals such as aluminum. Depending on the arrangement of tool coil and workpiece, electromagnetic forming can be used for the compression or expansion of profiles with a closed cross section as well as for forming sheet metal (Psyk et al., 2011). Since the mechanical strength of tool coils for electromagnetic expansion is relatively low and their lifetime is very limited (Belyy et al., 1977), electromagnetic compression is the most common application of forming profiles. In addition to forming operations, tubular workpieces and sheet metal parts can be joined by EMF.

According to Weddeling et al. (2011), connections generated by electromagnetic forming can be classified into three categories depending on the dominating mechanism against an external load: interference-fit connections, form-fit joints and adhesive bonds. All three mechanisms and any combination of them can be applied for tubular workpieces (Psyk et al., 2011). According to Mori et al. (2013), an interference-fit joint is based on a difference in the elastic recovery of two workpieces being joined, leading to an interference pressure between the parts after deformation. Form-fit connections are manufactured by forming the material of one joining partner into an undercut (e.g. a groove) of the other joining partner. Thus, an interlock between the workpieces is formed and they are locked against external loads. In this article, the manufacturing of this bonding mechanism by electromagnetic forming is referred to as electromagnetic crimping. Fig. 1 shows examples of this connection type. Adhesive bonds can be manufactured by impulse welding processes like magnetic pulse welding, which is a process variant of electromagnetic forming (Mori et al., 2013). These solid-state welds are generated by impacting the joining partners at very high velocities of up to several hundred meters per second.

The highest joint strengths can typically be achieved by impulse welds or electromagnetically jointed form-fit connections. Aizawa et al. (2007) show that impulse welding can lead to connection strengths high enough to cause a failure in the base material and not in the joining zone. Park et al. (2005) observed a joint failure by base material fracture also for form-fit connections. But compared to electromagnetic crimping, magnetic pulse welding requires higher input energies to supply magnetic pressures high enough to reach the necessary impact velocities (Weddeling et al., 2014). This leads to much higher loadings of the tool coils and a promotion of the wear of the EMF equipment by the increased discharge currents. Hence, form-fit joints should be preferred if no other demands like gas-tightness exist.

In comparison to other widely used joining techniques, like mechanical crimping, electromagnetic crimping features very homogeneous bond characteristics, which result from a uniform forming pressure distribution. Additionally, various materials show increased forming limits under impulse loads (Balanethiram and Daehn, 1995). Since deeper undercuts can be filled without damaging the deformed joining partner, higher connection strengths can be achieved by electromagnetic forming than by quasi-static joining techniques (Bühler and von Finckenstein, 1968). According to Daube et al. (1966), the applied forces can be adjusted very accurately via the charging energy and, therefore, the process is highly reproducible. Another advantage of electromagnetic crimping is that there is no physical contact between tool and workpiece during the joining process (Psyk et al., 2011). Thereby, a large variety of different profile cross sections can be formed. In addition, already coated workpieces can be formed without damaging the coating.

A major disadvantage of electromagnetic joining is that at least one of the joining partners has to be made of an electrically conductive material (Psyk et al., 2011). Otherwise, so-called drivers have to be applied to produce the required plastic deformations (Weimer, 1963). Furthermore, only overlap connections can be manufactured by this method as with all other joining by forming processes (Mori et al., 2013).

The earliest reported applications of electromagnetic crimping are from the electrical industry, like swaging of copper tubes to coaxial cables (Birdsall et al., 1961). Rowland (1967) introduces some applications for the automotive industry, e.g., the sealing of rubber protective boots to ball joint housings and the assembly of air brake hoses.

2.1. Determination of the acting loads

In Fig. 2(a) the general setup of electromagnetic crimping by compression consisting of the EMF machine, the tool coil, and the workpiece is displayed. The setup can be represented by a *RLC* circuit. Here, the forming machine is symbolized by the inner resistance R_i, the inner inductance L_i, and the capacitance C.

The capacitance represents a number of capacitors, which are used to store the energy needed for the workpiece deformation before the discharge. This charging energy E can be calculated from the capacitance C and the applied charging voltage U.

$$E = \frac{1}{2} C \cdot U^2 \qquad (1)$$

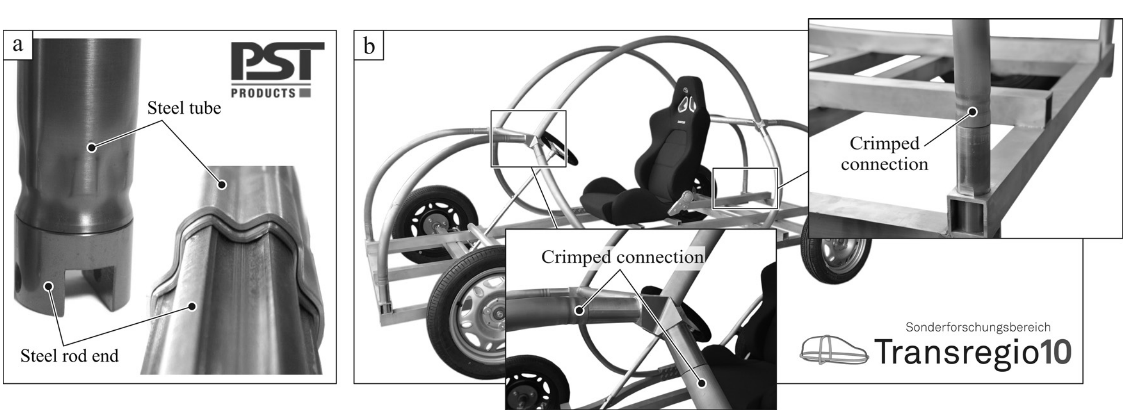

Fig. 1. (a) Electromagnetically crimped driveshafts; (b) demonstrator space frame of the collaborative research center SFB TR10.