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Experimental and numerical study on shaping of aluminum sheets with integrated piezoceramic fibers

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ABSTRACT

Force-fit integration of piezoceramic fibers in micro-formed structures is a new approach for function integration in structural sheet metal parts. In a first step, a micro-structured surface is formed in a planar semi-finished sheet metal part by micro-impact extrusion. Piezoceramic fibers are then assembled into this micro-structured surface with a small assembly clearance. The fibers and the structured surface of the sheet metal are joined by a forming process. In the next step, the sheet metal with piezoceramic fibres within a locally micro-formed substructure is shaped by deep drawing into a 3D-geometry. In this paper, results of the micro-impact extrusion and the joining by forming experiments are presented. Furthermore, the design constraints for assembly and joining due to the dimensional and form deviations of the piezoceramic fibers are discussed. Results of a numerical study of micro-forming, joining by forming and the global loading during a deep drawing process step were in good agreement with the experimental investigations. The direct comparison between experiment and numerical simulation increases the process knowledge and shows further improvement potential.

1. Introduction

With regard to lightweight design, the demand for increased performance and enhanced safety of passive sheet metal structures can be met by the implementation of integrated adaptronic systems. These adaptronic systems are characterized by function integration, miniaturization and electromechanical functions. To this end, new production technologies are required for the fabrication of structural sheet metal parts with integrated electrical and mechanical functions. Sensors and actuators as well as integrated circuits for signal processing are part of composite structures and provide both electromechanical and load-bearing functions.

The potential of functional integration for lightweight design has been described earlier for adaptronic microsystems, which have been applied by means of adhesive bonding (Gesang et al., 2000). Sensors in sheet metal structures are applicable for monitoring, detection and sensing of vibrations and mode shapes. Actuators enable static and dynamic excitation of the structure. Integration of sensing and actuating functionality in sheet metal allows for example health monitoring, collision detection or active vibration control and noise damping.

For production of active composite structures, adhesive bonding of laminar-type piezoelectric transducers on the surface of structural parts is state of the art (Nguyen and Kornmann, 2006). Mostly, the laminar transducers are composed of parallel piezoceramic fibers which are embedded in an epoxy resin and packaged between two layers of polymer foil (Sodano et al., 2004).

Adhesive bonding of packaged transducers on shaped sheet metal parts shows several limitations. Firstly, it is difficult to apply laminar-type piezoelectric transducers onto complex shapes. These limitations can be overcome, for example, by bonding the transducers on plane semi-finished sheet metal parts and subsequent deep drawing of the composite before the bonding adhesive is fully cured (Neugebauer et al., 2010). However, due to the packaging of the transducers, their potential for miniaturization is limited and the elastic polymer material becomes part of the structure, which is neither contributing positively to passive nor active functions of the adaptronic system. It is further important to note that packaging of laminar-type piezoelectric transducers accounts for approximately 95% of the cost of the transducer when compared to the cost of polarized piezoceramic plates of similar size and shape without packaging.

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The limitations of adhesively bonded pre-packaged transducers, namely, the limited miniaturization and the placement of passive and elastic polymer material into the structure, are overcome by force-fit integration of piezoceramic fibers in the metal without elastic interlayers. Recently, an approach has been developed for the direct integration of piezoceramic fibers in lightweight aluminum structures, in which piezoceramic/metal composites are produced by assembly of hollow piezoceramic fibers with a metal core into U-shaped cavities located on the surface of the aluminum sheet metal. Electrical and mechanical interconnection is achieved by hotpressing so that the fibers are embedded in a filler metal (Asanuma et al., 2009). However, this approach is limited to piezoceramic fibers with circular cross-section and manufacturing and handling of such fibers is less compatible with high-volume production than production of piezoceramic macro-fibers by dicing. This process is well known from the production of laminar piezoelectric transducers, which also facilitate piezoceramic macro-fibers with rectangular cross-section.

This paper introduces a new alternative to adhesive bonding based on the force-fit integration of piezoceramic fibers in the sheet metal. The aim is the fabrication of free formed parts with integrated piezoceramic fibers. Piezoceramic fibers are placed in micro-formed cavities on the surface of the sheet metal and are subsequently joined to the sheet metal by forming process. The fibers are thereby mechanically interlocked within the micro-structured surface. Due to the resulting force-fit between the piezoceramic fiber and the base metal both normal and shear stresses can be transferred between the fibers and the metal. In this setup the fiber is surrounded by the base metal on three sides. An additional layer on the remaining side to seal the composite is possible but not essential. The resulting composite can be regarded as a graded composite with bulk aluminum as a carrier and a local piezoceramic/metal composite as a cover layer. The thickness, weight and stiffness of the sheet metal are not significantly altered by the partially embedded piezoceramic fibers on the sheet metal.

To attain a comprehensive functionality of the composite, piezoelectric effects in the longitudinal, transversal and tangential direction are possible depending on electrode arrangement, polarization direction and ceramic insulation layers applied on the fiber. In principle, the integrated piezoceramic fibers could be applied as sensor, actuator, ultrasonic transducer and energy harvester, depending on the particular design and applied piezoceramic material. The electromechanical function and design of prototypes with longitudinal piezoelectric effect have been discussed and proven earlier where piezoceramic fibers have been used as directly integrated sensors for the stress and strain in the structure (Schubert et al., in press). Further, the use as an ultrasonic transducer within the structure is seen as a future application, which is currently under investigation.

2. Scope of the study

Earlier investigations of the proposed design principle unveiled challenges with regard to the mechanical integration of ceramic macro-fibers in a micro-structured metal surface and the joining of the fibers by forming. These challenges are: the manufacturing of micro-structured surfaces and macro-fibers with appropriate dimensions and tolerances, fiber-fracture due to mechanical joining by forming and degradation of the mechanical joint during shaping of the metal sheet. To overcome these challenges this paper focuses on the manufacturing process steps of the integrated piezoceramic/sheet metal composite. However, functional aspects of the piezoceramic macro-fibers, such as polarization, electrical insulation and electrical contact are outside of the scope of the study. The basic understanding of the phenomena during the process steps for production of aluminum sheets with integrated piezoceramic macro-fibers is fundamental for the design of future applications of parts with integrated piezoelectric functions.

Fig. 1 shows the process steps required for the manufacturing of metal sheets with integrated piezoceramic macro-fibers. First, surface structuring of the aluminum sheets is carried out by a micro-impact extrusion process. Second, prefabricated piezoceramic macro-fibers are integrated using a micro-assembly unit. After joining by forming, the fibers are mechanically clamped in the aluminum sheet. This results in a sheet with integrated piezoceramic/metal composite substructures. In the last step, this part is shaped by deep-drawing. The study compares experimental and numerical investigations of the most challenging process steps required to manufacture shaped aluminum sheets with integrated piezoceramic macro-fibers. This includes experiments for micro-impact extrusion, fabrication of piezoceramic macro-fibers, micro-assembly, and joining these sheets to create interlocking of piezoceramic macro-fibers and sheet metal. Finally these parts are shaped into a geometry with a degree of complexity similar to typical structural parts for automotive and aerospace applications. Due to the complexity of the process chain (Fig. 1), numerical simulations are required to understand the forming processes, where a close connection between experiment and simulation is necessary.

The challenge of the numerical simulation of the manufacturing process lies in the combination of process steps at the micro and the macro scales. Simulations of the forming processes are therefore carried out using a submodeling technique able to consider the local cavity geometries of the micro-forming and joining by forming processes, as well as global loading of the sheet with integrated macro-fibers during final shaping step. In the numerical study, several aspects of the experimental process steps can be studied in detail. Global strains, which are not critical to the global structure, could be critical to local micro-cavities. Tolerances need to be ensured in the generation of micro-cavities, which must be able to withstand the loads of the subsequent global forming step. In particular, the evaluation of the local material flow conditions,

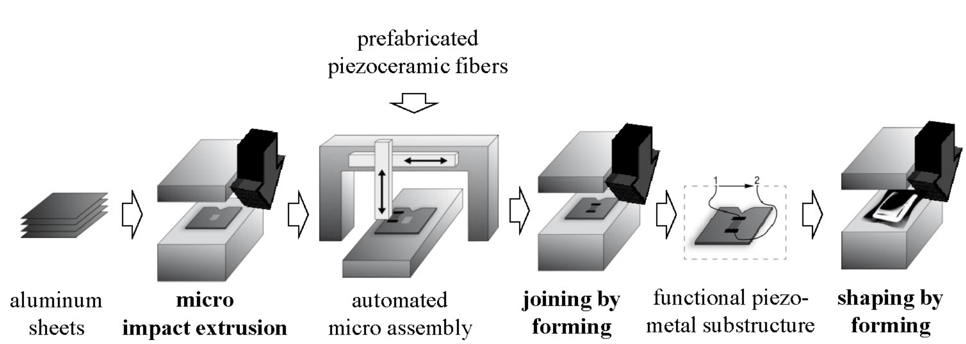

Fig. 1. Process steps for production of piezoceramic/metal composite substructures in sheet metal.