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Efficient production of sensory machine elements by a two-stage rotary swaging process—Relevant phenomena and numerical modelling

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ABSTRACT

A process sequence enabling an efficient production of hollow sensory machine elements with adapted wall-thickness and a smooth outer contour is presented. The applied conjoint forming approach aims to simultaneously form a tubular part to its final shape whilst integrating a functional element into it. Additionally, the forming process is adjusted in order to set up a pre-tension in the assembly. Thus, a lift-off of the sensor element in case of tensile forces during application is prohibited and a high sensor linearity is ensured. In order to predict the achievable pre-tension and to determine the maximum process force, a three-dimensional numerical model is introduced. The underlying mechanisms of the pre-tensioning process are discussed on the basis of a forming process with and without a mandrel. A direct comparison of the two basic swaging strategies – recess and infeed swaging – reveals advantages of the infeed swaging strategy to achieve a high pre-tension of the assembly. The cold work hardening of the preform, the thermal heating and the machine stiffness are relevant phenomena of the process which influence the forces significantly. A detailed validation proves the necessity to include the mentioned effects in the numerical model. Furthermore, a trial of a sensory rod is presented. The high linearity of the sensory structure underlines the high potential of the proposed process to integrate sensor elements into massive metallic structures.

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1. Introduction

A persistent problem in the development and usage of load-bearing systems is the identification and control of structural health and load paths of components. A high amount of effort is put into ongoing product recalls, preventive maintenance, damage recovery, or system adjustments (Smith, 2011). An approved remedy to encounter this uncertainty is the intentional oversizing of load-bearing components. However, this approach is often non-economical and does not comply with current lightweight design criteria. Therefore, there is a need for controlling the uncertainty inside load-bearing components in a more reasonable way. Ongoing research deals with “intelligent”, “smart” or “adaptive” parts which are able to detect loads (Deckers and Becker, 2004) as well as their structural health condition (Park and Inman, 2003). Furthermore, they can estimate their remaining life time (Denkena et al., 2014) or allow an interaction with the structure, e.g. a damping of harmful vibrations (Preumont et al., 2008). The electric energy required to power the sensor nodes can be generated by energy harvesting methods (Xu et al., 2013).

Functional materials such as piezo ceramics are used for these functionalities and are coupled to the load-bearing components. According to the current state of the art, these structures are usually processed separately and then assembled (Elspass and Flemming, 1998). However, this approach requires additional manufacturing steps and prolongs the process chain. Moreover, the subsequent assembling steps can have different cycle times, for example a manual bonding of strain gauges or piezo patches. The required efforts hinder a wide utilization of function-integrated machine elements in mass production.

Technologies for the integration of structural and functional materials during their manufacturing process promise a more efficient way for manufacturing these structures. Forming technologies offer a big advantage with regard to processing time and material utilization. In case of simultaneous forming and joining of composite structures, the term “*conjoint forming*” is introduced by Groche et al. (2016). This describes the “*joining of two or more*

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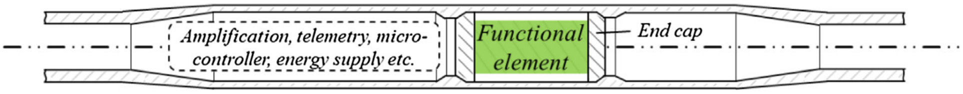

Fig. 1. Example of a function-integrated machine element with additional electronics.

workpieces by a plastic deformation which is necessary to reach the desired shape of at least one workpiece outside of the joining zone".

Approaches for the direct integration of functional elements exist for planar structures. Piezo ceramic fibers are integrated into cavities in sheets processed by microstructuring (Drossel et al., 2014b) or by joining and forming piezo ceramic metal composites during the liquid phase of the bonding layer (Drossel et al., 2014a).

For bulk metal structures, only few comparable studies for simultaneous joining of functional elements exist. A promising approach is the incremental cold forming process "rotary swaging" to produce tubular function-integrated structures (Groche and Türk 2011). In a more recent investigation, a manufacturing method for producing sensory bolts by recess rotary swaging is derived (Groche and Brenneis, 2014). In both approaches, restrictions exist regarding the shape of either the final product or the semi-finished part.

A novel approach therefore aims for decoupling the geometry of the function-integrated part from the joining zone, thus allowing to produce machine elements with a smooth outer contour with standardized semi-finished parts without a special pretreatment. As an exemplary process, a two-stage rotary swaging sequence is presented by Groche and Krech (2015) to manufacture thin-walled tubes with a flexible, smooth outer contour.

In comparison to previous contributions, a thermo-coupled numerical model is introduced to investigate the two-stage forming process. The effects of thermal shrinking and expansion of the inhomogeneous tempered joining partners are investigated in detail. Furthermore, a direct comparison between the two fundamental process strategies – recess and infeed rotary swaging – is presented and the influence of a mandrel is investigated. A sensitivity analysis of important parameters such as the machine flexibility or cold work hardening reveals the necessary modelling depth needed to obtain reliable numerical results.

2. Targeted product architecture

2.1. Design of function-integrated machine elements

A possible design for a targeted integrated sensory structure is shown in Fig. 1. The hollow shaft is able to detect torsional loads, bending moments and axial forces, depending on the used sensor element. Additional electronic components are required for an autonomous operation of the sensory elements and can be placed inside the unused space. The wall-thickness of different zones of the part is adapted to meet the local requirements of load capacity and stiffness.

In this contribution, the integration of strain-gauge elements is presented, as they offer practical advantages compared to piezoelectric sensors, such as simplified handling, temperature compensation, and the possibility to measure bending moments. In order to allow a unique identification of compression and bending in all spatial directions, three independent linear strain gauges are bonded on orthogonal surfaces as depicted in Fig. 2.

2.2. Process principles of rotary swaging

The integration of the functional elements is performed by a two-step rotary swaging process. This forming method is an incremental forming process which implies that the final shape of the part is achieved by various "[.] loading and unloading cycle[s] due to the action of one set of tools within one production stage" (Groche et al., 2007).

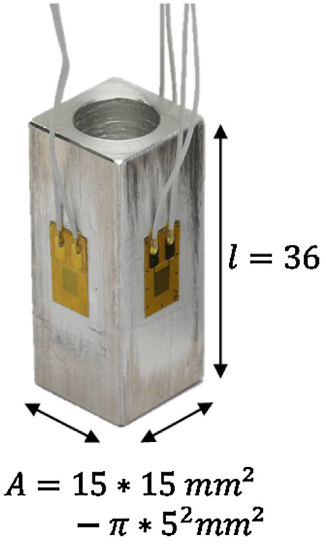

Fig. 2. Strain-gauge based sensor element.

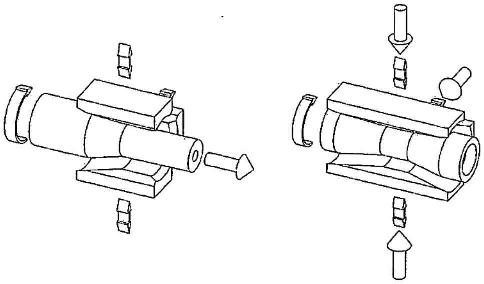

Fig. 3. Rotary swaging variants: Infeed (left) and recess (right) swaging (Gärtner, 1999).

The swaging dies are oscillating in radial direction, while the rotational movement of the workpiece ensures the accurate roundness of the produced part. Two different processing strategies are distinguished, namely recess and infeed rotary swaging (Fig. 3). In recess swaging, the reduction is achieved by a radial axis movement of the dies, whereas in infeed swaging, an axial infeed motion of the workpiece in combination with an inlet zone of the dies is used to achieve the desired reduction of diameter. In both variants, mandrels can be used to limit the radial material flow and to achieve an axial elongation of the swaged zone.

2.3. Process sequences

The proposed process sequence consists of the generation of a preform and a subsequent joining of the preform with the functional element with the help of another forming step. Aluminum and steel tubes are processed to preforms in a 1st stage using rotary swaging with one or two mandrels. Two variants for manufacturing the preforms can be distinguished (Fig. 4). On the one hand, two mandrels from both, the infeed and counterholder side, can be

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