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Controlling the sensor properties of smart structures produced by metal forming

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ABSTRACT

A rotary swaging process is presented which allows the manufacturing of smart structures by forming hollow shafts and joining sensor elements simultaneously. A reasonable form- and force-fit of the sensor element is required to ensure the desired sensory properties of the structure, such as linearity, long-term stability and repeatability. However, the conjoint forming process is subjected to uncertainty which leads to fluctuations of the remaining pre-tension forces. In order to increase the adjustability and accuracy of the process, the utilization of the sensor signals for a control approach is investigated. A prediction model is established on the base of a correlation analysis. It was found that the sensor forces occurring during the integration process can be used as a measure to predict the resulting pre-tension with sufficient accuracy. In order to manipulate the process in a beneficial way a control variable has to be identified. Therefore, several test series are conducted to investigate the suitability of infeed speed and mandrel force as possible control variables. A prerequisite is that the joining process can be manipulated, while the resulting geometry of the part remains unchanged. A possible time slot for an intervention is determined and a first control approach is implemented. Two different target values of the pre-tension force are tested. Compared to open loop controlled processes the accuracy of the targeted pre-tension condition could be improved significantly.

1. Introduction

Digitalization has changed industry and our daily lives in a radical manner. Today 15 billion connected digital devices are already in operation while its number is still increasing significantly and expected to account 28 billion by 2021 (Ericsson Mobility Report, 2015). Sensors and connectivity are conquering machines and cars, manufacturing tools and health care products. In this context also load-bearing structures are increasingly equipped with sensors and connectivity. So called smart structures are known as load-bearing components with additional functionality to identify their state and loads, to determine failures or to react to changing environmental conditions (Elspass and Flemming, 1998). For instance, future health care products can assist the patient's rehabilitation process by measuring various physiological parameters (Gubbi et al., 2013); sporting devices with tracking functionality help athletes to track their performance or to combine the exercise with gamification elements (Swan, 2012).

The state of the art in manufacturing smart structures is characterized by often complex and costly production chains. Sensors and electronics parts are assembled or bonded to the load-bearing components after their manufacture. Often the sensors are arranged on the surface of the component and therefore exposed to the danger of being damaged. Current research focuses on the integration of sensors inside the structural parts. This allows for an increase in robustness and manufacturing efficiency for smart structures (Hufenbach et al., 2011). Additionally, the freedom of design and the aesthetics of integrated smart structures are improved. The number of process steps required to manufacture smart structures can be reduced by simultaneously forming the structure and joining the functional elements (Groche and Türk, 2011). For this, the term "Conjoint Forming" is introduced by Groche et al. (Groche et al., 2016)

According to Dumstorff et al. (2014), sensor-integrated structures can be classified according to their degree of integration. For bulk integration mechanical and thermal stability as well as compliance are of utmost importance. One of the most important prerequisites for sensor-integrated structures is that the structure does not get weakened by the sensor integration. This accounts especially for those metallic structures, which are load-bearing components. There is therefore a need for novel manufacturing methods to produce metallic structures with integrated sensors in a minimal invasive manner.

Schwankl et al. (2015) use a high-pressure die casting process to integrate a piezoelectric module in a structural component. A direct

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integration of piezoelectric sensors in sheet metals by a combined micro structuring and deep drawing is presented by Drossel et al. (2014). Thin metal sheets are joined with a thermoplastic polymer enriched with piezo ceramic powder (Kräusel et al., 2015). Joining by plastic deformation is also known as a promising manufacturing technology for smart structures (Groche et al., 2014). For example, sensory fasteners are efficiently manufactured by a recess rotary swaging process (Groche and Brenneis, 2014). An infeed rotary swaging approach allows for the manufacturing of structures with even outer contours. The design of the process and its numerical simulation is presented in (Groche and Krech, 2017).

The fluctuation of sensor properties of the produced parts has been a phenomenon already observed before (Groche and Brenneis, 2014). With one set of parameters the batch of produced smart structures are highly fluctuating due to uncertainty in the process. A usual measure to increase process stability in other manufacturing processes is to implement a closed-loop control. According to Allwood et al. (2016), one difficulty in implementing such a control results from the fact that the properties of the produced parts evolve after forming due to thermal and elastic recovery. To encounter this problem, inline measurement techniques and prediction models are required. Ghiotti et al. (2017) present a novel in-line measuring technique for reducing the running in period of bended tube geometries. Sah et al. (2016) integrate sensors into stamping tools to gain continuous insights directly from the contact zone of the forming process. Kirchen et al. (2017) propose a prediction model to determine the quality of tailored blanks produced in an incremental manufacturing process. For this, the forces and positions of the rolling tools are measured and fed to an incremental regression model.

The contribution at hand makes use of the possibilities given by the sensor being integrated to encounter these tasks. The aim of this paper is to control the sensory properties of smart structures during a conjoint forming process. For this, an inline-measurement and prediction strategy is implemented to encounter uncertainties occurring during forming. The paper is structured as followed: Chapter 2 emphasizes the importance of the pre-tension of the integrated sensor element, as fluctuations occurring in the manufacturing process directly affect the usage behavior of the produced parts. However, in order to realize a control approach various challenges have to be mastered: The pre-tension evolves throughout the process and cannot be influenced directly. Therefore, a correlation analysis is conducted in chapter 3 to investigate the correlation of process conditions and the final pre-tension level. Secondly, the interaction between adjustable parameters of the machine and the effect on the resulting pre-tension is analyzed in chapter 4. Thirdly, a closed-loop control approach is presented in chapter 5. It makes use of the signals from the sensor being integrated. The proposed approach is tested regarding its ability to adjust different pre-tension levels exactly.

2. Scope of the study

The investigated process is based on a cold rotary swaging process. This cold forming process is frequently used to produce axisymmetric parts, but is also suitable to create form and force fit joints between different components. For example, a bimetallic part with a radial joint is presented by Zhang et al. (2014). The shaping of the part is realized by numerous small strokes which gradually form the final shape of the part. Four oscillating tools are reducing a tubular part in different process steps. The proposed process sequence consists of 3 steps, which are depicted in Fig. 1.

In step I, a preform with a specific inner and outer shoulder is produced with the help of a mandrel. Seamless cold drawn steel tubes 30 × 3 made of E235C are used for this investigation (view Ia & Ib).

In step II, a sensory element including adjacent end caps are placed at the inside (view IIa). In this investigation a strain-gauge based sensor element is used, which is able to measure axial forces. The steel end

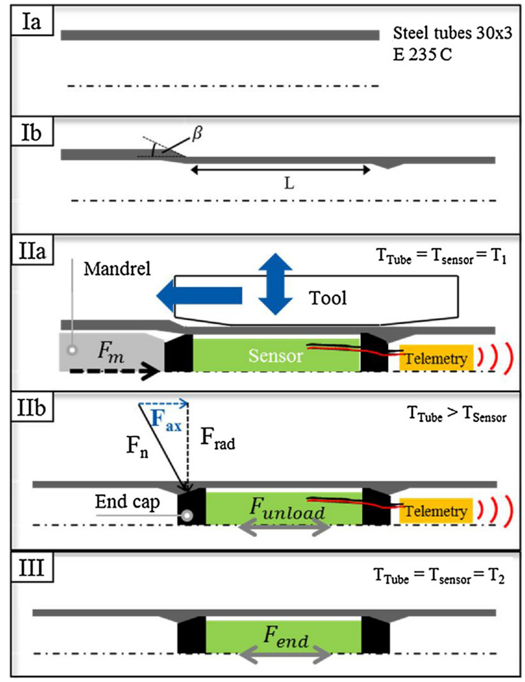

Fig. 1. Two-stage rotary swaging process to join and pre-tension sensor elements in hollow tubular parts.

caps are needed to protect the sensitive element and to allow the displaced material to generate a mechanical pre-tension inside the functional element during forming. An infeed tool placed above the sensor element reduces the left-hand side of the tubular part. Once again, a mandrel is placed inside to hinder the axial material flow. Furthermore, the mandrel also has the task to pre-tension the sensor element with the axial compressive force F_m. As the forming takes place, the sensor element experiences axial forming forces F_{ax}, which are caused by the tube material flowing on the chamfered end cap (view IIb). These forces are measured by the sensor. After unloading the workpiece, a pre-tension force F_{unload} remains. However, this is not the final state of the produced part, as the subsequent post-process follows up. After the forming step, the part is partially heated up due to the forming energy being converted to heat (step IIb). As shown in Groche and Krech (2017), the temperature increase for steel can account 20 °C – 30 °C in the deformation zone.

In step III, a temperature adjustment takes place. The sensor gets warmed up from its colder temperature T_1 and the tube cools down until they are equalized and reach the temperature T_2. The remaining pre-tension F_{end} results from both, the clamping mechanism due to the forming stroke and the temperature equalization process (step III). This value represents the total remaining residual stresses in axial direction within the relevant sensor zone of the tube and is suitable for comparing different process strategies. A further discussion of the strain and stress evolution during the forming process can be found in Groche and Krech (2017).

After a successful integration with a sufficient pre-tension the sensory component can be further processed. In a wireless bend weight bar, the bending moment is measured and transferred wirelessly by an integrated electronic unit, Fig. 2. This demonstrator illustrates the possibilities of sensory structures for applications in the Internet of Things (IoT).

The pre-tension generated during the joining process is of special interest for the later usage, Fig. 3. In case of a marginal pre-tension, the sensor element might change its contact condition under load, which leads to non-linearity. This happens when the external force reaches a level at which the sensor starts to lift off. Fig. 3 shows an example. A sensory tube with the ability to measure tensile and compression forces