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Forming limit curves of electrically conductive layers printed on sheet metal surfaces

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Abstract

Forming limit diagrams are a useful tool to anticipate the formability of sheets for various sheet metal forming processes. The objective of this paper is to propose a method for calculating forming limit diagrams for conductive and nonconductive printed layers on sheet metal surfaces. These printed layers can be used to manufacture printed electronics like strain gages or temperature sensors. In this paper the forming limits of these printed layers are determined in notched tensile tests by evaluating the crack pattern on the surface of the printed specimens. The crack pattern is digitized with a reflected light microscope. Additionally, the major and minor strains of the printed specimens are measured with an optical deformation analysis system. The forming limit diagrams for the investigated printed layers are subsequently calculated by synchronizing the crack pattern with the measured major and minor strains on the specimens' surfaces. The results achieved by this method are tested for reproducibility.

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Keywords: Printed electronics; Forming limits; Strain gages; Screen printing; Notched tensile tests

1. Introduction

The integration of electronics in formed parts is a promising approach to extend the range of technical product properties. Thus, the production of formed parts with electrical functions is economically feasible [1]. Various

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authors have investigated the use of sheet metal forming processes for the integration of electronics (e.g. electrical conductors, piezo-fibre modules) into formed parts by deep drawing or hydroforming [2, 3, 4]. Further, bulk metal forming processes like bar extrusion [5, 6] or rotary swaging [1, 7] were used to integrate electronics into metallic parts during the forming process. This paper proposes a method which determines the formability of conductive layers printed on sheet metal surfaces prior to the forming process. These printed electronics are used to integrate electrical functions, like the ability to measure temperatures or strains, into metallic parts.

Current and future applications of printed electronics are manifold. Recent examples for printed electronics are strain sensors [8, 9], humidity sensors [10], actuators [11, 12], RFID tags [12, 13] and flexible displays [14]. According to the Department for Business, Innovation & Skills of the United Kingdom Government, printed electronics have the following advantages compared to conventional electronics [15]: First, low-cost printing processes like inkjet, screen and gravure printing can be used to produce printed electronics economically in large quantities. Second, lower process temperatures reduce the environmental impact. Third, additive manufacturing processes like printing minimize the waste of material compared to subtractive manufacturing processes like etching. An additional significant advantage of printed electronics is their ability to maintain their functionality while changing shape. This favors their application on both flexible and formable substrates.

Bessonov et al. investigated the performance of graphite strain gages, which were screen printed on flexible polyethylene naphthalate foils with a thickness of 125 µm. These printed plastic foils were bent elastically up to a maximum strain of approximately 0.007 in 100,000 bending cycles without performance degradation [16]. Accordingly, it is possible to use these strain gages for the strain measurement in technical systems. The bonding of sensors on parts of the respective technical system requires a large amount of time and affects positional accuracy. This is even more critical if the surfaces of the parts, on which the sensors have to be bonded, are curved or hard to access.

Groche et al. proposed a process chain to manufacture formed parts with screen printed strain gages[17]. This setup spares a subsequent bonding process and guarantees positional accuracy on curved surfaces. In the first step a nonconductive layer with a homogenous thickness is printed on a flat aluminum sheet. In the second step the strain gages, which consist of conductive silver or carbon ink, are printed. The last step is the forming process, in which the printed aluminum sheet is formed into the desired geometry. The authors verified the functionality of the printed strain gages after forming. An example for a formed aluminum part with printed strain gages, which was manufactured using the described process chain, is shown in Fig. 1.

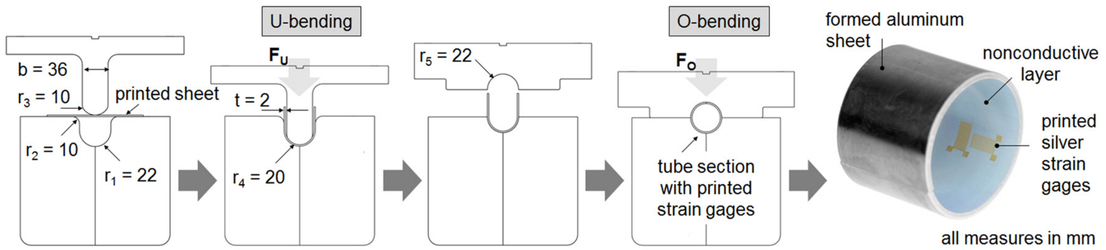

Fig. 1. Forming process for the manufacturing of printed tube sections with strain gages on the inner or outer surface [17, modified].

The formability of printed electronics, especially printed strain gages, and their nonconductive layers is limited. The knowledge about these forming limits is important and necessary in order to design forming processes. Different methods exist to determine the formability of organic layers on sheet metal surfaces. One of these methods is proposed by Vayeda and Wang [18]. The authors quantified the adhesion and the durability of coatings to sheet metal surfaces under plastic deformation by combining the notch-coating adhesion test and the cross-hatch tape test (ASTM D3359). The cross-hatched specimens were deformed plastically in tensile tests and rectangular stretch bend tests in order to examine the influence of plastic deformation on adhesion. Prior to the forming tests the specimens were conditioned for different durations in a humidity cabinet. Subsequently, the adhesion was inspected by a tape test in order to evaluate the coating performance. The tape test was repeated after forming. The