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Mechanical properties and forming behaviour of laminated steel/polymer sandwich systems with local inlays – Part 2: Stretching and deep drawing

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ABSTRACT

In part 1, a fundamental study on mechanical properties and deep drawing of a steel/polymer/steel sandwich (SMs) combination was accomplished investigating one type of reinforced SMs (R-SMs). In this part, the effect of reinforcements (REs) with different geometries, sizes, materials and locations on stretching and deep drawability is introduced. Additionally, the influence of reinforcing SMs with different mechanical properties and skin/core thicknesses is considered. Therefore, a deep drawable steel grade with thicknesses 0.49 mm and 0.24 mm was utilized. For the core polyolefin (PP-PE) foils with thicknesses of 0.3 mm and 0.6 mm were used.

Substantial reduction of the deep drawability was found if the RE is located in the forming region (close to the punch), however, only locally if located in the flange area. Inserting the RE in the flange has no remarkable effect on the drawing force but on the forming potential represented by the cup height at failure.

The stretching results show that increasing the RE size reduces the forming potential. The RE creates a sharp interface with the neighbour core layer accelerating failure. A negligible effect of the RE geometry was found, however solid REs show reduced forming limits compared to the mesh-like ones.

1. Introduction

The literature survey describing the need for developing lightweight materials especially the sandwich materials, their structure and production technologies was described in part 1 [1].

Forming of these multi-layered sheets face some obstacles due to the inhomogeneous cross-section structure, where their forming limit depends on the mechanical and geometrical properties of the skin and core layers and additionally the shear strength between them. The shear strength between the used components, as discussed before in [2], is enough to guarantee delamination-free forming in all cases examined.

Joining the steel/polymer/steel sandwich (SMs) is one of the major challenges facing their processing due to the existed polymeric core layer; the core layer is electrically insulating (hinders the welding process), soft (leads to dimension distortion under mechanical joining) and not thermally durable/stable (degrades under elevated temperature processes like welding and some coating processes). An overview of the possibility, advantages and disadvantages of various SMs joining methods is given in [3–5].

Various approaches were developed to overcome these drawbacks. Joining of sandwich laminates can be performed by traditional methods like resistive welding; either after pressing the core like Litecor® [6] or after substituting the polymeric core with metallic inserts in the joint [7,8] in order to reinforce the joining location and provide electrical conductivity. The behaviour of the local metal hybridization for Carbon fibre reinforced polymer/Titanium joints was investigated for bolted lap joints under tensile loading and temperature conditions [9–12], where different configurations of the transition region between the reinforced region and the adjacent core are investigated. These reinforcements enable a considerable increase in the coupling efficiency of highly loaded composite structures. The indentation resistance of reinforced sandwich laminates under bolting with different moments could be improved [13].

Main drawbacks of the locally reinforced laminates can be listed as following:

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Nomenclature

Symbol	Terminology, Unit		
f_c	core volume fraction, [−]	R-SMs	reinforced (R−) sandwich (SMs)
h	dome or cup height for stretching and deep drawing, [mm]	SMs	sandwich materials
n	strain hardening exponent, [−]	t	thickness, [mm]
r	normal anisotropy ratio, [−]	UTS	ultimate tensile strength, [MPa]
RD	rolling direction	YS	yield strength, [MPa]
RE	reinforcement	ε	strain (here the logarithmic major strain), [−]
		ε_f	tensile strain at failure, [%]
		ε_u	uniform strain, [%]

1) The development of an automated production scheme for inserting the inlays during the laminate production in-line, preferably by rolling. In this regard, a concept for a continuous production by rolling of weldable band-like metal/polymer/metal/sandwich laminates, containing a locally treated polymer core with conducting elements to insure the electrical conductivity, is patented by [7].
2) The location of the reinforced regions should be monitored/recognized during/after shaping the formable reinforced laminates. This point has been studied by the authors in this paper and previously [13,14]; predicting the location of the inserts and their influence on the forming limits of various sandwich structures is the main focus.
3) The interface at the RE edge – between the RE and the neighbour core layer - has a significant effect on creating stress concentration regions that can accelerate failure during processing and application. This point was handled in [10,15] by creating different overlapping regions between the inserts and the neighbour core.

The aim of this paper is to study the effect of the RE size, geometry, material (mesh- and solid-like RE), and location in respect to the forming tool (at the punch edge and in the flange) on the forming behaviour of SMs under deep drawing and stretching conditions. The formability of the reinforced sandwiches (R-SMs) was determined by means of the forming force, cup/dome height at failure in addition to the local and global strain distribution compared to non-reinforced SMs. The location of the RE was monitored through successive forming steps. Additionally, varying the SMs properties and thickness on the forming behaviour of R-SMs was considered.

2. Experimental work

2.1. Materials

The sandwich laminates used consist of: a) two steel grades as skin sheets, 0.5 mm thick stainless steel 316L and a sn-coated deep drawing steel TS245 (EU 1.0372 grade delivered by thyssenkrupp Rasselstein GmbH, [16,17]) in two thicknesses, 0.49 mm and 0.24 mm, and b) PP-PE core layer with 0.3 mm and 0.6 mm thicknesses. The production scheme of the SMs and R-SMs was illustrated in [1]. It is noteworthy that the RE thickness is approximately the same as the replaced core minus (0.05 – 0.1) mm tolerance. Four SMs combinations were investigated; their notation and structure and additionally their mechanical properties are given in Table 1 and Fig. 1. It can be observed that SMs1 (based on the 316L grade) possesses the highest strength and strengthening index (n-value) which means that a higher forming force is required in respect to the other SMs' (SMs2–SMs4), however a different drawability potential based on the normal anisotropy (r-value) is expected. Although SMs2 and SMs4 have different skin/core thicknesses but a constant core volume fraction ($f_c = t_{core}/t_{SMs}$), their mechanical properties, according to the rule of mixture, are the same. SMs3 contains a higher $f_c = 0.76$, therefore, its strength is deceased.

The formability of the reinforced and non-reinforced SMs is characterized by deep and stretch forming as descried in the next sections.

2.2. Stretching behaviour

The stretching experiments were carried out using a 75 mm^Ø semi-spherical punch with a 180 mm^Ø SMs blank. The applied blank holding force was 100 kN, sufficient to avoid blank sliding. The punch displacement rate was 0.5 mm/s. These experiments were carried out primarily on SMs1 to determine the principal correlations of the different RE specifications like size, geometry and materials on the formability of the R-SMs. An overview of the studied R-SMs' and their notations is given in Table 2. In this table, various RE parameters were considered like a) the size effect (Cs36 vs. Cs50), b) the geometry effect (Cs36 vs. Ss36) and c) the material effect (solid vs. mesh). The stretching test was performed stepwise: at a dome height of 20 mm and until failure. At each drawing step, the drawing force and strain distribution were evaluated. The RE's were placed in the centre of the SMs blank i.e. directly in the forming region where the tensile stresses are acting, as shown schematically in Fig. 2. Positioning the RE's in the flange is not meaningful for stretching conditions as the blank is clamped and no material flow is allowed.

2.3. Deep drawing

Deep drawing tests were carried out using a 75 mm^Ø flat punch with a 180 mm^Ø blank. The punch displacement rate was kept 0.5 mm/s. Deep drawing was performed stepwise in three steps – each 10 mm and until failure – as shown for SMs1 in Fig. 3a, and photogrammetrically analysed after every step using the GOM-ARGUS® system (Fig. 3b). In the photogrammetric analysis, point pattern (1 mm^Ø with 2 mm distance) was printed electrochemically on the SMs surfaces and monitored for the successive forming steps. The dimensions of the drawing tools are listed in Table 3. This table is given to consider the geometrical aspects of the forming tools for interpreting the results. For instance, the (gap size/t_{SMs}) ratio has a significant influence on the cup height (h) at failure; for a larger gap, higher h values can be reached.

The RE was placed in different locations in the blank; in the cup flange and at the punch edge i.e. at 60 mm and 37.5 mm distance from the blank centre as shown in Fig. 4. The performed deep drawing experiments with varied RE sizes, geometries and materials inserted in the four SMs are described in Table 4.

Studying the flow behaviour of the RE is essential in order to estimate the extent of the flow blocking due to inserting the RE. This flow behaviour was determined through monitoring the