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RESEARCH PAPER

EXPERIMENTAL INVESTIGATION OF JOINING THE METAL/ POLYMER/METAL COMPOSITE SHEETS BY CLINCHING METHOD

Ľuboš Kaščák[1]*, Ján Slota*[1]*, Jana Bidulská*[2,3]*, Róbert Bidulský*[3,4]*, Andrzej Kubit*[5]

[1] Technical University of Košice, Faculty of Mechanical Engineering, 040 01 Košice, Slovakia
[2] Technical University of Košice, Faculty of Materials, Metallurgy and Recycling, 042 00 Košice, Slovakia
[3] Bodva Industry and Innovation Cluster, Budulov 174, 045 01 Moldava nad Bodvou, Slovakia
[4] Advanced Research and Innovation Hub, Budulov 174, 045 01 Moldava nad Bodvou, Slovakia
[5] Rzeszów University of Technology, Faculty of Mechanical Engineering and Aeronautics, 35-959 Rzeszów, Poland

*Corresponding author: lubos.kascak@tuke.sk, Tel.: 055/6023508, Department of Technology, Materials and Computer Supported Production, Faculty of Mechanical Engineering, Technical University of Košice, Mäsiarska 74, 040 01 Košice, Slovakia

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ABSTRACT

Advances in sandwich composites have given rise to materials that amalgamate the elevated flexural stiffness and buckling resistance found in metals with the lightweight characteristics of polymers. These materials exhibit significant potential for use in contemporary lightweight structures, not solely due to the aforementioned attributes, but also owing to their effective provision of sound, vibration, and thermal protection. In the structures using sandwich materials, joining methods based on fusion welding, adhesive bonding or mechanical fastening are employed. Clinching is a manufacturing technique that mechanically joins two or more materials without the need for heat or additional components. This method relies on achieving high plastic deformation to establish a secure bond. The research deals with the possibility of using the clinching method for joining metal/polymer/metal composite sheets in combination with high-strength steel and micro-alloyed hot-dip galvanised steel sheets. The clinching method with a rigid die proves unsuitable for joining the examined combinations of sandwich material with steel sheets.

Keywords: sandwich composites; clinching; tensile test; metallography

INTRODUCTION

Advancements in sandwich composites have resulted in the creation of materials that blend the elevated flexural stiffness and resistance to buckling found in metals with the lightweight characteristics of polymers. Composite materials combine materials with different properties to create a unique material with better features than its component materials [1-3]. The composite materials industry has achieved remarkable developments and has become the backbone of many industries, especially in aviation [4,5]. Composite materials are often used to create high stiffness and strength structures and maintain a low weight to keep pace with the increasing global demand for materials whose production requires less energy to face global warming and develop sustainable products.

Composites are materials with a heterogeneous structure composed of two or more materials with different properties. Most frequently, one of the components is the matrix, which provides the structure with adequate flexibility and cohesion [6]. These materials hold significant promise for use in contemporary lightweight structures, not only due to the aforementioned attributes but also due to their efficient capabilities in sound, vibration, and thermal insulation.

Steel and non-ferrous metal alloys are commonly used to produce multilayer structures consisting of adhesively bonded metallic layers. A metal-plastic composite sandwich material comprises three layers: upper and lower steel sheets with a plastic core. Reinforced composites are classified into four groups: particulate-filled polymer composites, diffusion composites, layered composites, and composites reinforced with a thermoplastic or thermosetting polymer matrix [7].

In addition to the commonly known sandwich composites based on aluminium alloy sheets, interest has increased in hybrid structures consisting of a combination of steel sheets and a polypropylene core. Steel-polymer laminates (steel/polymer/steel) show high fatigue strength and impact strength [8,9]. Examples are Bondal and Litecor sandwich materials. BONDAL laminate with a configuration of 0.5/0.5/0.5 mm is used for damping applications. LITECOR® laminate consists of two layers of HX220YD interstitial steel sheets (0.2–0.5 mm) with a polyamide (PA)/polyethylene (PE) intermediate layer (52 wt.% PA6, 36 wt.% PE and 12 wt.% other additives) [10]. The significant advantages of this class of materials are their improved acoustic and thermal damping properties.

ThyssenKrupp Steel Europe's LITECOR® composite material began to appear in several studies, including weldability by resistance spot welding [11], mechanical joining based on the mortise-tenon joint [12], and relying on three-stage joining to produce a more significant and stiffer mechanically locked joint [13]. Furthermore, studies expanded to investigate whether a commercial sandwich material can fill the role of automotive and industrial applications [14,15].

Regarding components crafted from steel-polymer sandwich composites, Hoffmann [16] demonstrated that they achieve nearly identical weight reductions compared to those composed entirely of aluminum (with only a 10% increase in weight), yet at a considerably reduced cost (at least 30% more economical). Steel/polymer/steel composites can be deep drawn, bent [17,18] and joined [19]. Plastic working of composite materials requires knowledge of the changing mechanical and tribological properties [20] of plates during these processes. Various approaches have been suggested for joining metal/polymer/metal laminates to address their inherent limitations. A very important area of research within sandwich materials is their joining. Various approaches have been suggested for connecting metal/polymer/metal sandwich materials to address their inherent limitations. In the assembly of diverse materials for constructing structures, traditional joining techniques like fusion welding, and adhesives encounter or mechanical fastening challenges. For instance, in the fusion welding of metal/polymer/metal combinations, the significant difference in melting temperatures poses limitations. The fusion welding method is constrained because, when the metal reaches its melting point, the polymer undergoes deterioration [21]. The process of mechanical fastening results in property deterioration owing to stress concentration near the junction area. Stresses develop around the fastener holes, leading to a reduction in strength and ultimately giving rise to corrosion-related issues. Additionally, non-uniformly distributed loads can generate substantial local stresses. Other drawbacks include heightened component weight and specific mechanical pre-operations, such as hole predrilling and thread creation. Adhesive bonding, on the other hand, demands an extended manufacturing duration and is unsuitable for certain corrosive environments or instances where the structure is exposed to chemical compositions [22,23].

Gower et al. [24] outlined laser spot-welding as well as continuous high-speed, precise, and discrete one-pulse welding methods for the bonding of metal-polymer laminates. Due to the enhanced heat resistance of polymers under high heating rates, employing a brief thermal cycle can help minimize damage to the polymer layer. Murzin [25] employed the laser welding technique to perform butt welding on the upper and lower metal layers of a metal-polymer-metal composite. The primary goal during the laser welding of these materials is to minimize substantial degradation of the polymer core layer. Consequently, the parameters for laser welding were selected to ensure that the polymer structure remained nearly unchanged. Friction stir welding [26] is another of the techniques investigated when joining sandwich materials. Huang et al. [27] investigated friction stir welding to unite a short carbon fiber-reinforced polymer sheet and an aluminum sheet, concurrently managing both shape and performance. While the technique holds promise for connecting thermoplastics and metals, additional research is required to investigate surface pretreatments like surface patterning and micro-arc oxidation. Buffa et al. [28] evaluate the viability of using Friction Stir Welding to join thin sandwich components comprising two outer steel layers and an internal polymeric layer. The welding process involves the use of both a pin and a pinless tool to weld the upper and lower surfaces of the joint simultaneously, achieving solid-state bonding of the metal and fusion welding of the polymer.

The quasi-static tensile behavior and failure characteristics of composite single-lap single-bolt sandwich joints, considering various geometric parameters through both experimental and numerical analyses were investigated by Li et al. [29]. The strong agreement demonstrated the efficacy of the numerical approach.

A novel joining-by-forming process designed for assembling two metal-polymer sandwich composite panels longitudinally and perpendicular to each other was presented by Contreiras et al [30]. The technique combines sheet-bulk forming with mortise-and-tenon joints, resulting in mechanically interlocked joints featuring large and rigid flat-shaped heads. He found the process cost-effective and efficient for assembling lightweight sandwich composites using portable equipment. Baptista et al. [31] introduce an innovative joining process designed to create lap joints in metal-polymer sandwich composite sheets. The procedure entails drilling a blind hole in each sheet to remove the upper metal skin and the polymer core layer. The sheets are then secured together by compressing a metal insert placed in between, resulting in a form-fit mechanical nugget. The joint's cross-section mirrors that of resistance spot welding, with the cold-formed insert (referred to as the 'nugget') concealed within the sheets. Khan [32] investigated an effective and economical approach for spot welding PP composite to aluminum alloy, eliminating the need for surface or material pre-treatment. The resulting joint exhibits a sufficiently high loading capacity, consistently inducing failures in PP substrates during lap shear tensile tests away from the bonded area. The joining of sandwich composites based on copper and low-carbon steel was investigated by Gladkovsky et al. [33]. This paper presented the results of research on explosive welding of this type of sandwich material.

One of the methods falling into the category of mechanical joining was dealt with by Huang [34]. The author explores the forming characteristics of self-piercing riveting and the joint strengths of aluminium plates made of foam iron-nickel/copper sandwich composite in conjunction with aluminum alloys. The findings indicate that foam metal sandwich composite aluminum plates can enhance the interlock width, thereby improving the self-locking performance of joints. The bottom thicknesses experience significant increases when foam metal sandwich composite aluminum plates are used as the bottom plates in the riveting process.

Clinching is a deformation-assisted joining technique designed to secure thin sheets without requiring additional consumables or pre-drilled holes. This process utilizes dedicated punches and dies to plastically deform the sheets, creating a form-fit mechanical interlock [35,36]. Typically conducted at room temperature, clinching can join sheets composed of dissimilar materials, as well as pre-coated and pre-painted sheets, without causing damage to their surfaces. The primary constraint of clinching lies in sheet formability, as it needs to be of good quality to prevent failure through cracking [37,38]. Clinching is widely employed in the high-speed production of automotive, white goods, and electronic components, often replacing traditional methods like riveting and spot welding [39].

A review of the literature shows that there is a lack of comprehensive results of joining by clinching, especially in steel/polymer/steel laminates. In light of these findings, the research aims to introduce a clinching-based joining process designed for creating mechanical connections between overlapping metal-polymer composite sheets and hot-dip galvanized steel sheets.

MATERIAL AND METHODS

A mechanical clinching with a rigid die [23] was used for the preparation of the round joints. The mechanically clinched joints were produced by combining three types of hot-dip galvanized steel sheets (dual-phase high-strength steel HCT600X, micro-alloyed grade steels HX420LAD and HX340LAD) and steel/polymer/steel sandwich material - Litecor. LITECOR comprises a polymer core with a thickness of 0.7 mm and outer layers made of HX220YD + Z75 steel sheets, with a thickness of 0.3 mm. The manufacturing process involved hot adhesive bonding, and a zinc coating (ZE75) was applied to safeguard the external steel layers against corrosion. The basic mechanical properties of joined materials, along with their thickness are shown in **Table 1**. Properties shown in the table were determined by the standardized tensile test, according to the corresponding standards. Properties of the sheet materials were tested in the rolling direction. The samples for the clinching were prepared according to the standard ISO 12996:2013 - Mechanical joining — Destructive testing of joints — Specimen dimensions and test procedure for tensile shear testing of single joints.

Table 1 Thickness and basic mechanical properties of joined materials

Material	a_0 [mm]	$Rp_{0.2}$ [MPa]	R_m [MPa]	A_{80} [%]
HCT600X+Z	0.7 1.5	369	633	22.5
HX420LAD+Z	0.7 1.5	503	565	17
HX340LAD+Z	0.7 1.5	408	487	19
HX220YD (from Litecor)	0.3	240	390	32

($R_{p0.2}$ – yield strength; R_m – tensile strength; A_{80} - elongation)

The clinched joints can be prepared in two manners when the arrangement of both sheets is considered (punch-sided material, die-sided material), because the load-bearing capacity of the clinched joint is affected. This is important, especially in the case of “difficult to join” materials. For this experiment, various material combinations were chosen. Table 2 describes the material combinations which were chosen for the experiment, concerning the punch and die side. Since two different thicknesses (0.7 mm and 1.5 mm) were used for all steel sheets, two sets of punches (ø3.6 and ø5 mm) and dies (ø5 and ø8 mm) were used for clinching.

Table 2 Combinations of joined materials and their location concerning the punch and die (* clinched was created but with a crack in the interlock area)

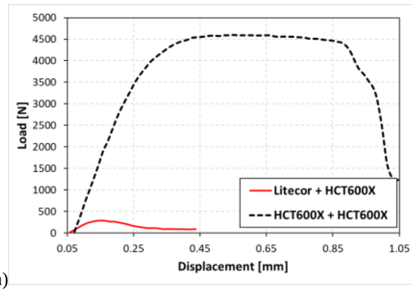
Clinching combinations				
Punch side	**Die side**	**Puch [mm]**	**Die [mm]**	**Joint creation**
L (a_0 = 1.3mm)	600 (a_0 = 0.7mm)	ø3.6	ø5	*NO*
600 (a_0 = 0.7mm)	L (a_0 = 1.3mm)	ø3.6	ø5	*NO*
L (a_0 = 1.3mm)	420 (a_0 = 0.7mm)	ø3.6	ø5	*NO*
420 (a_0 = 0.7mm)	L (a_0 = 1.3mm)	ø3.6	ø5	*NO*
L (a_0 = 1.3mm)	340 (a_0 = 0.7mm)	ø3.6	ø5	*NO*
340 (a_0 = 0.7mm)	L (a_0 = 1.3mm)	ø3.6	ø5	*NO*
L (a_0 = 1.3mm)	600 (a_0 = 1.5mm)	ø5	ø8	**YES***
600 (a_0 = 1.5mm)	L (a_0 = 1.3mm)	ø5	ø8	*NO*
L (a_0 = 1.3mm)	420 (a_0 = 1.5mm)	ø5	ø8	*NO*
420 (a_0 = 1.5mm)	L (a_0 = 1.3mm)	ø5	ø8	**YES**
L (a_0 = 1.3mm)	340 (a_0 = 1.5mm)	ø5	ø8	*NO*
340 (a_0 = 1.5mm)	L (a_0 = 1.3mm)	ø5	ø8	**YES**

(L – Litecor; 600 – HCT600X+Z; 340 – HX340LAD+Z; 420 – HX420LAD+Z)

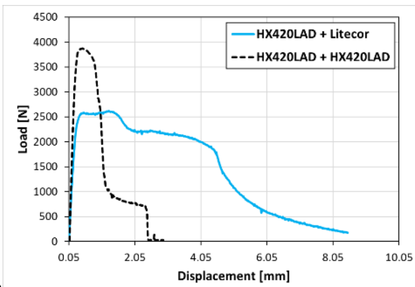
Table 2 shows that the clinched joints for the combinations of the sandwich material Litecor with all investigated steel sheets HCT600X+Z, HX420LAD+Z and HX340LAD+Z with a thickness of 0.7 mm and in both orientations were not successfully created. In combinations of sandwich material Litecor with 1.5 mm thick steel sheets, the formation of clinched joints was observed in three combinations and orientations of materials: HX340LAD+Z with Litecor, HX420LAD+Z with Litecor and Litecor with HCT600X+Z. However, in the latter combination with the HCT600X+Z steel sheet, although the clinched joints were formed, a crack was observed in the interlocking area.

RESULTS AND DISCUSSION

The results of the tensile-shear test of the clinched joints provided observations such as the maximum force Fmax needed to failure of the joint (**Table 3**), the load–displacement curves, and the failure mode of the joint-neck fracture mode or pull-out mode. The load–displacement curves for material combinations Litecor + HCT600X, HX420LAD + Litecor and HX340LAD + Litecor are shown in Fig. 1. For comparison, the graphs show the load–displacement curves of the joints created only on the steel sheets. The lowest load-bearing values were measured for the Litecor and HCT600X samples, which was caused by the formation of a crack in the joint interlocking area during the joining process.



a)



b)

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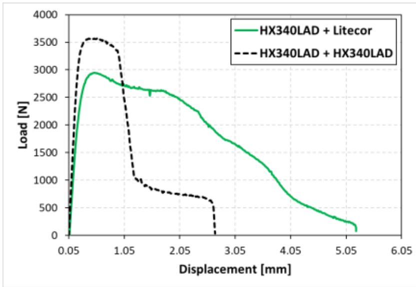
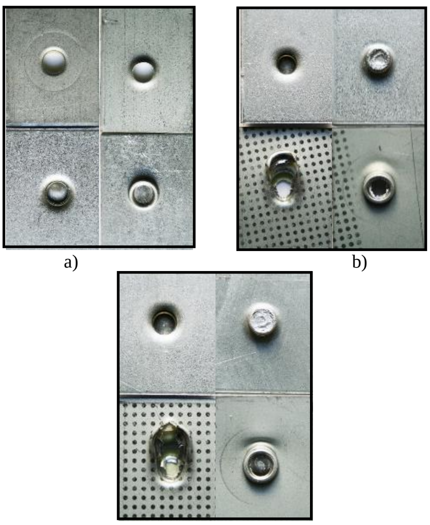


c)

Fig. 1 The comparison of load–displacement curves: a) Litecor and HCT600X+Z, b) HX420LAD+Z and Litecor, c) HX340LAD+Z and Litecor

Table 3 Load-bearing capacity of tested combinations of materials

Material combination	Fmax [N]
Litecor (a_0=1.3 mm) and HCT600X+Z (a_0=1.5 mm)	286
Litecor (a_0=1.3 mm) and HCT600X+Z (a_0=1.5 mm)	275
Litecor (a_0=1.3 mm) and HCT600X+Z (a_0=1.5 mm)	275
HX420LAD+Z (a_0=1.5 mm) and Litecor (a_0=1.3 mm)	2620
HX420LAD+Z (a_0=1.5 mm) and Litecor (a_0=1.3 mm)	2810
HX420LAD+Z (a_0=1.5 mm) and Litecor (a_0=1.3 mm)	2548
HX340LAD+Z (a_0=1.5 mm) and Litecor (a_0=1.3 mm)	2949
HX340LAD+Z (a_0=1.5 mm) and Litecor (a_0=1.3 mm)	2334
HX340LAD+Z (a_0=1.5 mm) and Litecor (a_0=1.3 mm)	2846



a) b) c)

Fig. 2 The failure modes of the clinched joints: a) Litecor + HCT600X, b) HX420LAD + Litecor and c) HX340LAD + Litecor

Figure 2 documents the failure mode of the examined joint samples. The "neck fracture" mode was observed on the sample of Litecor + HCT600X combination (**Fig. 2a**), which was significantly affected by the formation of a crack in the interlocking area of the joint. The "pull-out" failure mode was observed on the samples of the combination HX420LAD + Litecor (Fig. 2b) and HX340LAD + Litecor (**Fig. 2c**).

Metallographic observation confirmed the formation of a crack in the interlocking area of the joint in sample Litecor and HCT600X+Z (**Fig. 3a**), which was the reason for the low values of the bearing capacity of these joints. In the samples with a combination of HX420LAD + Litecor (**Fig. 3b**) as well as HX340LAD + Litecor (**Fig. 3c**), cracks did not appear in the interlocking area of the joint. However, cracks in the lower sheet Litecor were observed at the bottom of the joints, which may lead to the separation of part of the bottom of the joint, which is unacceptable.

c)
b)
c)

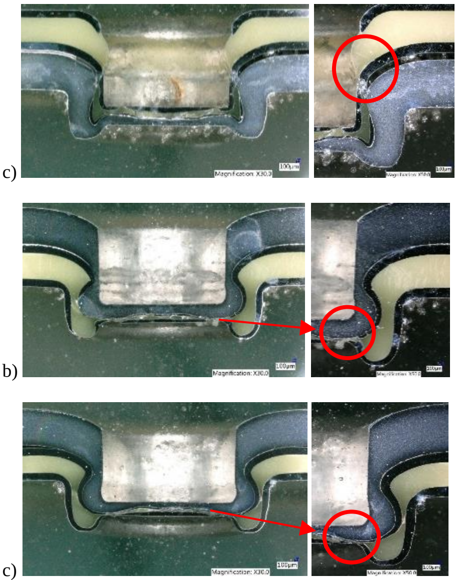


Fig. 3 Clinched joints: a) Litecor and HCT600X+Z, b) HX420LAD+Z and Litecor, c) HX340LAD+Z and Litecor

The size of the bulge within the die groove depends on the materials being joined. Clinching undergoes three primary phases - offsetting, upsetting, and flow pressing, as described by Israel et al. [40]. During the offsetting phase, there is a reduction in the material wall thickness around the punch, resulting in an increased material flow during the upsetting phase and ultimately in flow pressing. The mechanical properties of the Litecor together with small thickness of HX220YD (0.3 mm) significantly impact their ability to stretch without fracturing.

CONCLUSIONS

Mechanical joining by the clinching method with rigid die was presented in this research for joining a combination of sandwich material with selected steel sheets of different quality and thickness. This clinching method is not a suitable for joining the studied combinations of steel/polymer/steel sandwich material Litecor with the dual-phase high strength steel sheet HCT600X+Z and micro-alloyed grade steel sheets HX420LAD+Z and HX340LAD+Z. Although some combinations of materials, sheet thicknesses and sheet orientation concerning the punch and the die produced clinched joints, they cannot be considered as

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quality and acceptable joints. The limiting factor of the clinching joint was the thickness of the outer layer of the sandwich material, which significantly influenced the formation of the clinching joint.

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