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Solid State Joining of Thin Hybrid Sandwiches Made of Steel and Polymer: a Feasibility Study

Gianluca Buffa[a]*, Davide Campanella[a], Archimede Forcellese[b], Livan Fratini[a], Michela Simoncini[c]

[a]*University of Palermo, Dept. of Chemical, Management, Computer Science and Mechanical Engineering, Viale delle Scienze, 90128 Palermo, Italy*
[b]*Università Politecnica delle Marche, DIISM, Via Brecce Bianche, 60121 Ancona, Italy*
[c]*Università degli Studi eCampus, via Isimbardi 10, 22060 Novedrate (CO), Italy*

* Corresponding author. Tel.: +39-091-23861869; fax: +39-091-238-61869. *E-mail address:* Gianluca.buffa@unipa.it

Abstract

The growing demand for more environmentally friendly vehicles has led to an increased use of light materials in the transportation industry with the aim to reduce structural weight, fuel consumption, and gas emissions, thereby boosting cost-effectiveness and recyclable properties. Complex multi-material steel-based components would allow to improve mechanical properties and minimize weight even further. In particular, new sandwich materials made by steel outer skins and a polymeric internal layer seems very promising for obtaining mechanical performance and lightness at the same time. Unfortunately, traditional welding techniques, like arc welding, laser welding, and resistance spot welding, usually used to join steels and aluminum alloys, cannot be applied for these materials due to their peculiar nature. In this paper, the feasibility of Friction Stir Welding to join thin sandwich components made of two steel outer layers and an internal polymeric layer was assessed. Both a pin and a pinless tool were used to weld the upper and the lower surface of the joint in order to obtain solid state bonding of the metal and fusion welding of the polymer at the same time.

Keywords: Metal-polymer-metal sandwich composite; Mechanical properties; Friction stir welding

1. Introduction

In last years, most sectors of the transportation industry, such as the automotive, aerospace, aeronautical and trucking ones, are pushing towards an increasingly research focused on the development of new lightweight components and materials, in response to the growing demand for lighter, safer, energy-efficient and more environmentally friendly vehicles [1]. In order to satisfy such increasingly stringent requirements, hybrid sandwich materials, normally obtained by combining two thin facing steel sheets and a polymeric inner core, represent a very good solution for many engineering applications [2]. As a matter of fact, multi-layers sandwich composites, by combining the advantages offered by different materials, lead to significant performance improvements as compared to monolithic steel sheets, both in terms of lightness and high mechanical strength [3], improved specific stiffness [4], damping capacity [5], thermal insulation [6] and impact-energy absorption [7].

However, the main drawback in the use of metal-polymer-metal sandwich composites is their assembly. Generally, mechanical fasteners and adhesive bonding are utilized for hybrid sandwich materials, even if such processes show several disadvantages [8]. In the mechanical fastening, pre-drilled holes create stress concentration around the hole, and fasteners lead to an additional increase in the structure weight. On the other hand, adhesive bonding requires extensive surface preparation and curing time that make it time consuming and costly operation. To this purpose, the main challenge for the wide industrial application of hybrid sandwich materials is

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related to the welding technologies to obtain complex structures, so as not to significantly modify their characteristics [9]. Welding of hybrid sandwich composites is a very sensitive operation to the properties of the polymeric core material. Despite the increasing interest in these materials, few studies on joining attitude of multi-layers sandwich composites are available in literature. Salonitis et al. investigated the CO2 laser butt welding of sandwich composites in viscoelastic polymer core between steel cover sheets and observed that excessive evaporation of core layer results in worsening of damping characteristics of the sandwich laminates [10]. Gower et al. attempted pulsed laser welding to realize spot joining of metal-polymer sandwich materials in order to minimize the degradation of the polymer core during fusion welding process of the metal layers, but they observed cracks in the joint due to the high cooling rate provided to prevent degradation of the polymeric layer [11]. Unfortunately, polymers, characterized by a non-crystalline nature, exhibit an extremely low solubility in metal so direct welding is always very difficult due to the structural dissimilarities of these materials [9]. Therefore, an alternative technique has to be used for joining hybrid sandwich materials. One of the possible techniques is Friction Stir Welding (FSW). The friction stir welding process takes advantage from the generation of frictional heat between a rotating tool and the top surface of the sheets to be welded [12]. A conventional FSW tool consists of a shoulder with a probe or pin at its end which penetrates into the parent material and traverses along the weld line. The material is softened due to frictional heat and the rotating pin can stirs it under the shoulder's axial force [13-15]. FSW, among modern joining techniques, is now being more and more extensively used owing to its eco-friendly nature and low production costs [16-17].

Based on the above considerations, also due to the increment in interest for lightweight structures, different industrial sectors have been adopting this new strategy, e.g. aeronautics and aerospace for plane structures and space transport fuel tanks, transportation for train and car structural parts and as well as computer hardware for the production of computer casings [18].

FSW has been demonstrated effective for several different metals, as well as for a number of polymeric materials. However, FSW of polymers is a critical process, due to different physical and rheological differences present in each polymer. The determination of optimum process parameters becomes more challenging when it comes to welding polymers which have a low melt viscosity such as nylon-6 [19]. Rotational speed and feed rate can be considered as the main process parameters in FSW process for the determination of the heat input, which varies for each material depending on their physical properties [20].

Higher rotational speed can lead to the degradation of the polymer, whereas lower rotation may result in poor mixing and voids in stir zone. Therefore, the need to investigate the optimum parameters for each polymer is crucial. On the other hand, squeeze-out of plasticized or semi-molten material is a significant additional drawback to avoid in order to maximize weld quality as it can result in excess of flash formation and poor surface [21].

In this paper, the feasibility of Friction Stir Welding to join thin sandwich components made of outer skin of steel and inner polymeric layer was evaluated. A pin and a pin-less tool were used to weld both the upper and the lower surface of the joint in order to obtain solid state bonding of the metal and fusion welding of the polymer at the same time. Finally, a process parameter map was established highlighting the effect of tool rotation and feed rate.

2. Materials and methods

2.1. Material

The material investigated in the present work was a metal-polymer-metal sandwich composite, obtained by assembling a polyolefin 0.4 mm-thick core foil made of a mixture of polypropylene–polyethylene (PP-PE) polymer between two 0.2 mm thick steel sheets, with high yield strength for cold forming. (Fig. 1). Effectively, the polymer's low density equal to 1.03 g/cm^3 provides no-added weight to the sandwich composite. A two-stage roll bonding process was used to produce the hybrid sandwich. A 10 μm thick adhesive layer was initially applied on the steel sheet and activated by curing at about 260°C. Subsequently, the polymer film was heated at 120°C and roll bonded to the steel sheet. Finally, the steel/polymer half sandwich was roll bonded with the second pre-treated steel sheet.

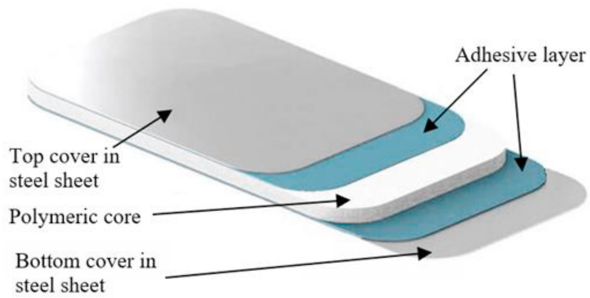

Fig. 1. Scheme of the metal-polymer-metal sandwich composite.

2.2. Uniaxial tensile tests

The mechanical properties of the hybrid sandwich were investigated by means of uniaxial tensile tests carried out according to ASTM E8/E8M and BS EN 895. Standard tensile samples were water jet cut at different angular orientations with respect to the rolling direction (RD), namely 0°, 45° and 90°. Tests were carried out at room temperature with a crosshead speed equal to 0.1 mm/s. The following strength and ductility properties of sandwiches were obtained: yield strength (YS), ultimate tensile strength (UTS), total uniform elongation (e_u) and elongation to failure (e_f).

At least three repetitions of each test condition were performed to ensure the repeatability of the result.

2.3. Experimental setup

The experiments were carried out on an ESAB LEGIO 3ST machine (Fig. 2). This machine was developed for FSW processes allowing the control of the vertical force on the tool. This feature was of particular relevance, since the extrusion force is one of the most important technological parameters to be regulated during the FSW of polymers.

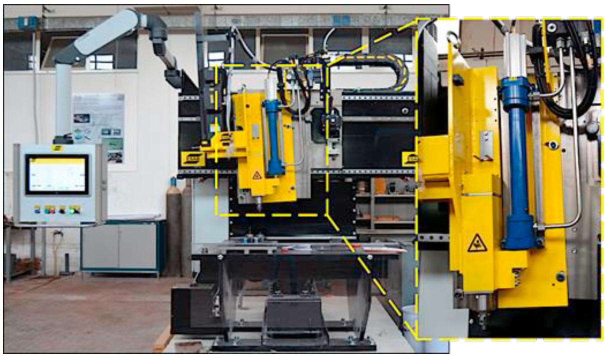

Fig. 2. ESAB LEGIO 3ST FSW machine for the experimental campaign used

For the experiments, the sheets were firmly clamped, in the butt joint configuration, on the back plate in order to avoid distortions during the process due to their small thicknesses. A specially designed tool was mounted on the machine spindle with the geometrical parameters presented in the latter sections.

A few welding parameters must be considered when setting up an FSW process, i.e. geometrical (tool shoulder diameter, geometry of pin, if present, etc.) and technological (tool rotation, feed rate, tilt angle, etc.) ones. For the material of the tool, a W25Re alloy was chosen. This material has already been proven effective for FSW of high resistance alloys due to its mechanical properties at high temperature. The design of the tool (Fig. 3a) is a critical factor, as a good tool can both improve the quality of the weld and maximize the possible welding speed. A few different tools were considered, namely pin and pinless tool with different shoulder geometries (Fig. 3).

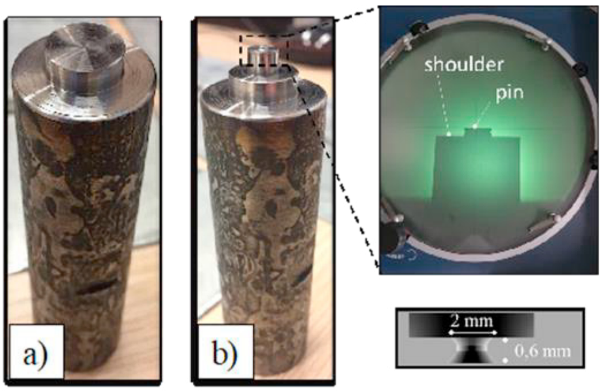

Fig. 3. Utilized a) pinless and b) pin tools

In particular, the pin tool was characterized by shoulder diameter and pin height of 14 mm and 0.6 mm, respectively. The pin was characterized by a "hourglass" shape, with major diameter of 0.6 mm and minor diameter of 0.4. As the pinless tool is considered, the shoulder of the tool was characterized by a diameter varying in the range between 6 mm and 14 mm. The experiments were conducted with rotational speeds (R) varying between 600 and 2000 rpm, and the feed rates between 50 and 900 mm/min.

3. Results and discussion

3.1. Mechanical characterization

Fig. 4 shows a typical nominal stress vs. nominal strain curve of the metal-polymer-metal composite structure. It can be observed that in the plastic region the nominal stress monotonically increases with nominal strain, in a wide range of homogeneous pre-necking deformation. After necking, the flow stress exhibits a very slight decrease with a further increase in strain until failure.

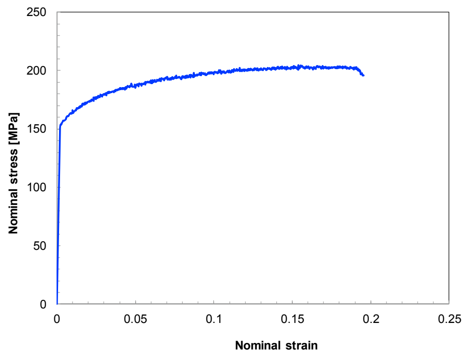

Fig. 4. Typical nominal stress vs. nominal strain curve of metal-polymer-metal sandwich composite (orientation: 0° to rolling direction).

Table 1 reports the mean values of yield strength, ultimate tensile strength, total uniform elongation and elongation to failure obtained on samples at different angular orientations with respect to RD. It can be observed that the angular orientation with respect rolling direction affects the strength and ductility properties of the sandwich composite. In particular, samples at 90° to RD are characterized by the highest yield strength and ultimate tensile strength values. Such UTS value is obtained at the lowest total uniform elongation as compared with the e_u values at the other orientations. On the contrary, the 45° angular orientation exhibits the lowest UTS value, that is reached at a highest e_u in percentage.

Table 1. Mean values of yield strength, ultimate tensile strength, total uniform elongation and elongation to failure of the metal-polymer-metal sandwich composite at different angular orientations with respect to the rolling direction.

Angular orientation	0°	45°	90°
YS [MPa]	150.6±5.9	151.6±7.1	168.8±6.8
UTS [MPa]	200.6±2.8	198.6±4.6	208.2±3.7
e_u [%]	17.1±1.6	19.5±1.9	15.7±1.1
e_f [%]	19.2±1.5	27.3±2	19.3±1.4

As far as the 45° angular orientation is considered, the tensile samples generally show a remarkable post-necking deformation whilst samples at 0° and 90° to RD are characterized by lower post-necking deformation values, indicating that the normal anisotropy at 45° is higher than those in the longitudinal and transversal orientations.

3.2. Welding defects identification

Several different welds have been produced with varying technological and geometrical parameters with the aim to assess process feasibility. In Fig. 5 the details of the seams with the defects are shown.

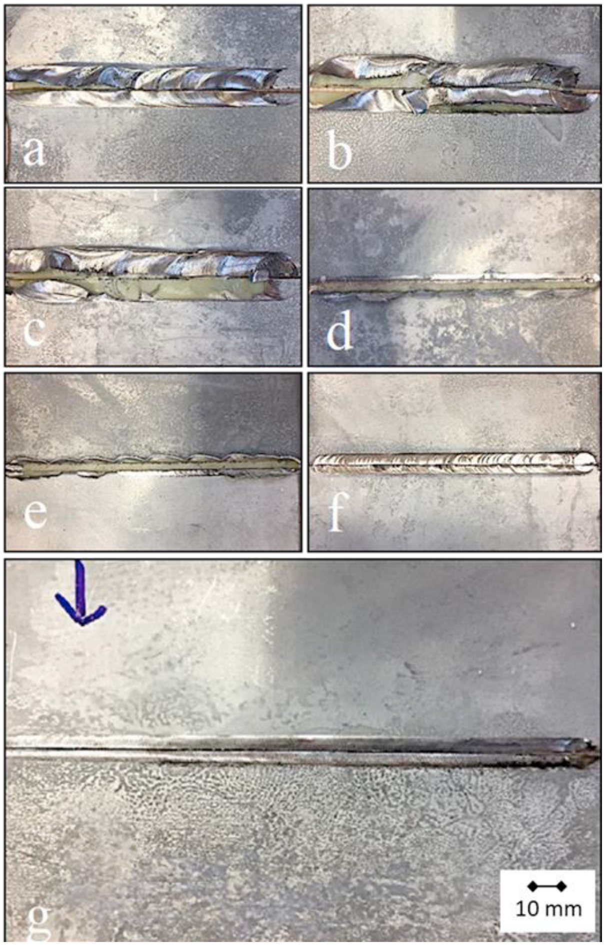

Fig. 5. Weld defects for different technological and geometrical parameters: (a) 300 rpm, 50 mm/min and φ of 12 mm (b) 300 rpm, 100 mm/min, (c) 700 rpm, 50 mm/min and φ of 14 mm (d) 700 rpm, 50 mm/min and φ of 8 mm (e) and φ of 8 mm (f) 700 rpm, 100 mm/min and φ of 8 mm (g) 500 rpm, 900 mm/min and φ of 6 mm

First, tests were carried out using a pinless tool having a 14 mm shoulder diameter. Considering a very slow rotational speed of about 300 rpm and 50 mm/min (Fig 5a) it was noted the detachment of the layer steel-polymer at the interlayer, due to excess of heat, resulting in a lift up of the steel layer. It was noted that also the increase of the feed rate or tool rotation does not affect the results significantly (Fig 5b, 5c). Further tests were carried out with a reduced shoulder diameter of 6 mm. For the tests carried out with the same rotational speeds and feed rate, the "litf up" effect was smaller, however the final result was similar to first cases (Fig.s 5d and 5e). The main difference was that, while with the large shoulder tool the layer separation took place during the welding, with the small shoulder tool the separation occurred after the tool passage, due to residual stresses. In the test shown in Fig. 5f, carried out at 700 rpm and 100 mm/min, a good junction was obtained in terms of thermal distortion. However, being the force applied very low proper bonding conditions could not be reached making the junction ineffective. In the case shown in Fig. 5g, the feed rate and rotational speed were increased up to 900 mm/min and 1500 rpm respectively. Using these parameters, it was possible apply a higher force since the heat generated could not propagate into the polymer during the tool passage. Even if the weld seams did not demonstrate any "lift up" defects, the solid bonding was limited.

In order to increase the material area involved in the bonding process, a tool having a specially designed pin (see again Fig. 5b) was also considered. However, it was observed that a part of the polymer mixed with steel burned on the surface due to the complex 3-dimensional plastic flow generated by the tool with a pin (Fig. 6).

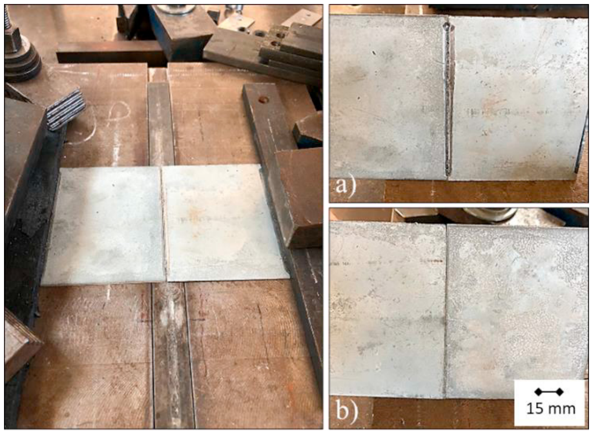

Fig.6. Defects shown using tool with a pin a) front and b) back views

The best solution was obtained by avoiding the inclusion of the polymer in the junction and carrying out a weld using a pinless tool, on front and the back side of the sheet.

Sound joints could be obtained using the pinless tool with 6 mm shoulder diameter and 2000 rpm, 900 mm/min and 2.5 kN as rotational speed, feed rate and force respectively. In Fig. 7 the sound joint is shown. Observing the top joint side of Fig. 7a, it can be seen that material continuity was reached in the steel layer. Additionally, preliminary joint testing showed that the heat conferred to the weld allowed melting and welding of the mid polymer layer. As expected, the bottom layer was not involved by the process. Hence, it can be stated that a two-pass process has to be considered in order to completely weld the whole sheet. In fact, as mentioned above, good welding conditions occur when the bonding process is carried out between layers without excess of vertical material flow resulting in detrimental mixing between polymer and metal.

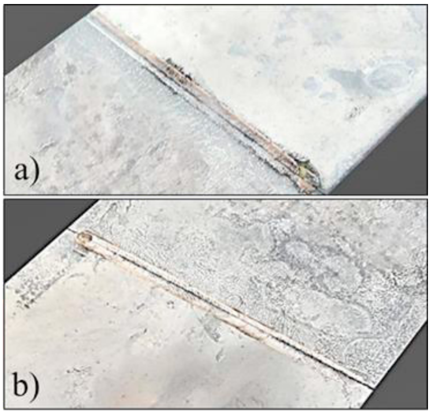

Fig. 7. a) top and b) bottom views of the sound joint.

Finally, based on the experimental results, a process parameter map was established, allowing the identification of the main defects occurring during the process as a function of the main process parameters, i.e. tool rotation and feed rate (Fig. 8).Note that different colored areas have been added to qualitatively identify the different process conditions.

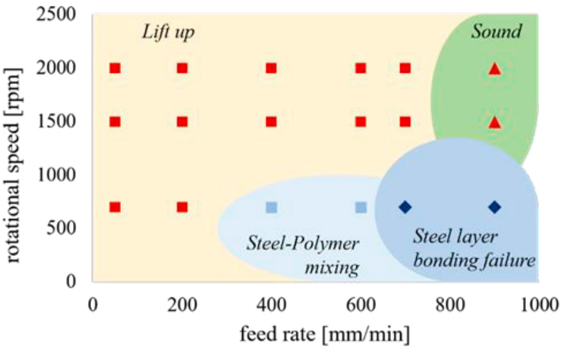

Fig. 8. Process parameter map and occurring weld defects.

4. Conclusions

In this paper, a feasibility study was presented on the solid-state welding of thin sandwich sheet made of two steel outer layer and a polymeric inner layer. The material was characterized form a mechanical point of view and several tests have been carried out with varying technological and geometrical parameters. Form the obtained results the main following conclusions can be drawn:

- the nominal stress monotonically increases with nominal strain, in a wide range of homogeneous pre-necking deformation, irrespective of the sample orientation with respect to the rolling direction;
- the 45° angular orientation to rolling direction is characterized by the highest total elongation to failure with a post-necking deformation equal to 28.5% of the total elongation to failure. The post-necking deformation exhibited by the 0° and 90°orientations to RD are about 11.0 and 18.7%, respectively, of the total deformation to failure;
- the 90° angular orientation to rolling direction is characterized by the highest yield strength and ultimate tensile strength values whilst the 45° one by the lowest ultimate tensile strength;
- due to the extremely reduced thickness of the outer steel layers, the heat conferred to the weld must be limited to avoid distortions and layer separation. Hence small shoulder tool and relatively high feed rate should be considered;
- although a specially designed pin tool can successfully contribute to increase the material area where deformation takes place, the additional vertical flow has a detrimental effect on the joint effectiveness by creating unwanted mixing between the polymer and the steel layer;
- a two-pass process must be considered in order to weld the whole sandwich structure as the bottom steel layer cannot be reached by the needed heat and deformation using the pinless tool which gave the best results on the top surface.

Future work includes the set up of a comprehensive experimental campaign aimed to identify a process parameters window as well as the evaluation of the main mechanical and metallurgical properties of the welded joints.

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