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Laser assisted joining of AA5053 aluminum alloy with polyvinyl chloride (PVC)

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ABSTRACT

Laser Assisted Joining (LAJ) of Aluminum AA5053 sheets with Polyvinyl chloride (PVC) is investigated. The process was performed by means of a diode laser with a maximum power of 200 W. The materials did not show good chemical affinity. Thus, laser sculpturing was performed on the aluminum substrate before joining. This enabled to produce teeth features on the aluminum surface. Thus, the main joining mechanism was based on the penetration of the teeth throughout in PVC surface. The influence of the scanning speed and laser beam power used during the LAJ process on the mechanical strength of the joints was investigated. Single lap shear tests were conducted. Morphological analysis was carried out by means of optical microscopy. Thermal analysis was also conducted to measure the thermal field and the thermal history of the specimen during LAJ process. The results indicated the presence of two opposite phenomena: poor penetration of the teeth (due to insufficient heating) and polymer degradation (due to excessive heating). Both these conditions affected severely the mechanical strength of the joints. Great variation of the temperature and the morphology was observed on the joints. Under optimal conditions (P = 200 W and Ss = 100 mm/min), the average joint strength reached 71% (15.3 MPa) of the base material shear strength.

1. Introduction

The growing development of new materials, including polymers, composite and layered ones along with the increasing employment of hybrid structures involving different materials are attracting great attention from transportation industries. This is due to the capability to reduce the weight and fuel consumption, CO_2 emissions and improve the performances. When dealing with hybrid structures, one of the main problems is represented by the choice of the joining process. Adhesive bonding and mechanical joining are commonly employed for this scope. However, such conventional processes are affected by a number of drawbacks. Adhesive bonding enables uniform distribution of stress during service life, good fatigue life, corrosion resistance, and high strength-to-weight ratio. Adhesive bonding requires specialized workers, substrate preparation and long curing time that increase the process cost, production time and produce high environmental impact [1]. In addition, adhesive bonds are affected by environmental sensitivity (like humidity and temperature) and great uncertainty regarding long-term structural integrity [2]. On the other hand, conventional mechanical joining processes, e.g. riveting or bolted connections, usually involve high stress concentration around the spot joints. The presence of relatively heavy external fasteners leads to an increased weight of the structure. Furthermore In the case of riveting and bolted connections, hole-drilling increases the overall joining time. To reduce the processing time, some solutions have been proposed including employment of punching rather than drilling for composite materials [3], or the employment of Self Pierce Riveting (SPR) [4], Mechanical Clinching (MC) [5–7], Friction Spot Welding [8] and Friction Spot Joining [9], ultrasonic joining [10–13] and Friction Assisted Joining [14–16]. However, the employment of spot joints still involves stress concentration.

Unlike the aforementioned processes, Friction Lap Joining (FLW) [17,18], Laser Transmission Welding (LTW) [19–24] Laser-Assisted Metal and Plastic bonding (LAMP) [25–42], and Lased Assisted Joining [43,44] can be adopted to produce continuum joints. These processes can be exploited to join even different materials including polymers, metals fiber reinforced plastics and fiber reinforced thermosetting. These processes are characterized by a reduced cycle time, absence of external fasteners, and no damage in case of the presence of fibers (in composite materials). The joining

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mechanism is due to the thermoforming of the polymer around the metal or fibers (in the case of composites). Different heating sources can be adopted including a laser beam or frictional heat produced by a rotating tool. Thus, the application of an external pressure enables the polymer or the composite thermoplastic matrix to melt and adhere to the counterpart substrate. Thus, the metal (or composite) and plastic can be bonded on atomic or molecular level [31,39] other than by mechanical anchoring effect. Different methods are available, to increase the adhesion between the substrates. These methods include: surface modification using either UV–ozone and plasma pre-treatment [45], pre-oxidation [41], anodization [46]. These processes improve the bonding of the substrates by increasing the wettability of the polymer and promoting the chemical affinity of the substrates. The researches involving micro-sculpturing of the metal substrate [47,48] indicated that even better results can be achieved. This pre-treatment produces a deep surface modification consisting in the formation of caves and protrusions (micro-teeth). This enables a superior mechanical interlock between the substrates given by a mutual penetration of the materials.

Optimization of the process conditions have been performed in a number of studies involving regression analysis [49–51], Artificial Neural Networks [52], and numerical analysis [53–57]. However, these studies were highly focused and treated specific aspects. On the other hand, a comprehensive process analysis would require the concurrent investigation of the joints quality, dimension, onset of defects and temperature distribution produced by varying the process conditions.

Thus, an experimental analysis was conducted on polyvinyl chloride (PVC) and Aluminum AA5053 sheets. These materials showed poor chemical affinity. Thus, the aluminum surface was modified by means of laser micro-sculpturing process to increase the joints strength. This enabled micro-joining of the substrates, which is mainly controlled by the thermal field experienced by the polymer during laser assisted joining process. The scanning speed and the laser beam power were analyzed as the main process parameters. Temperature distribution, morphology, development of defects, dimension of the joined area and mechanical behavior of the bond were analyzed.

2. Materials and methods

Aluminum alloy AA5053 sheets, 2 mm in thickness, were coupled to polyvinyl chloride (PVC), 3 mm in thickness. These materials are often found for production of windows frames for civil applications. The selection of such materials was also made to verify the suitability of LAJ to join material with poor chemical affinity. The main mechanical properties of the materials are summarized in Table 1.

A 200 W diode laser (DLR-200-AC, by IPG), with a fundamental wavelength of 975 nm, was used to perform Laser Assisted Joining experiments. The laser beam was characterized by a circular shape with 6 mm of diameter. The collimator was mounted on a 3+1 axis CNC system (Finecut Y 340M, by Rofin). No focusing lens were adopted.

During LAJ process, the laser beam irradiates the aluminum sheet. Thus, heat conduction throughout the aluminum sheet is exploited to heat the underlying PVC material. The sheets were clamped with a pressure of almost 1.0 MPa. A schematic representation of the laser assisted joining setup and specimen is reported in Fig. 1a. As the laser power ramp up, the laser was switched on outside the sheets (with a distance of almost 10 mm from the sheets edge). This enabled to avoid variation of the laser power and scanning speed before the entry region and after the exit region.

The main process parameters, i.e. the laser power (P) and scanning speed (S_S), were varied according to a full 2 × 6 factorial experimental plan, whose levels are reported in Table 2.

The base materials showed a poor chemical affinity, as reported by the authors in [15,16] and confirmed by preliminary experiments on “as-received” specimens. Thus, laser ablation was performed on aluminum sheets to improve micro-mechanical interlock between the substrates. The micro-sculpturing was performed by a 30 W fiber laser (YLP-RA30-1-50-20-20 by IPG). The laser beam was moved by means of two galvo-mirrors placed in a scanning head and focused by a flat field lens onto the workpiece. The sculpturing was carried out by following a net pattern, with the following process parameters: average power of 30 W; pulse frequency of 30 kHz; speed of 1000 mm/s; hatch distance (i.e. the

Table 1
Main mechanical and thermal properties of the materials.

Material	Young modulus [GPa]	Yield strength $\sigma_{y0.2}$ [MPa]	Tensile strength σ_{max} [MPa]	Elongation at rupture [%]	Thermal diffusivity [m^2/s]	Melting temperature [°C]
AA5053	67	100	250	15	9.7×10^{-5}	607–649
PVC	2.8		37	2	8×10^{-8}	>210

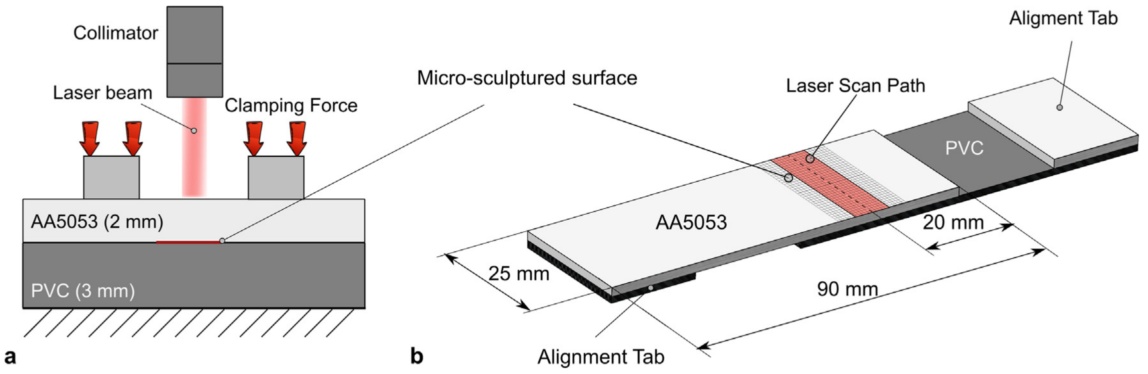

Fig. 1. (a) Schematic representation of the laser assisted joining setup and (b) main dimensions of the specimens used for single lap shear tests.