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Joining Aluminum with Titanium alloy sheets by mechanical clinching

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ABSTRACT

The feasibility of titanium aluminum hybrid joints is investigated. Titanium grade 2 was coupled with different aluminum alloys of 5xxx, 6xxx and 7xxx series. The joining process was performed by means of a clinching machine at room temperature using extensible dies. Different joining forces and tools configurations were adopted. The material flow was investigated by means of experimental observations of cross sections. A numerical model of the joining process was also developed to study how the material flow develops. Single lap shear tests were performed to determine the mechanical behavior of the joints. The results highlighted a narrow join-ability window. Only aluminum AA7075 was capable to be joined to titanium sheets. The other alloys were susceptible of different material flow issues e.g. fracture development or no interlock formation that yielded to unsuccessful joining conditions.

1. Introduction

Hybrid Structures (HS) involve components made by different materials. These structures exploit the philosophy of "the right material at the right place". HS are increasingly involved in different fields including transportation (automotive, aeronautical, shipbuilding), aerospace, as well as biomedical. HSs can involve very different materials including metals, polymers, composites and ceramics. The main problem when dealing with such materials is represented by the adoption of the proper joining process. Such a problem is still very challenging even when joining different metals such as titanium and aluminum. These materials are being increasingly coupled (especially in automotive and aerospace structures) due to their high performances. Actually, both these materials are characterized by extremely high strength-to-weight ratios. In addition, aluminum parts enable to reduce weight and cost, while titanium parts are characterized by high corrosion resistance as well as high strength at high temperature. As above-mentioned coupling such materials is still a challenging issue as they show very different thermal, physical and metallurgical properties. This generally leads to the formation of brittle compounds when brazing/welding processes (brazing [1,2], laser welding [3–7], diffusion bonding [8], friction stir lap [9] and friction stir welding [10,11]) are adopted for Ti/Al joints.

Fast mechanical joining processes such as Self-Pierce Riveting (SPR) and Mechanical Clinching (MC) could be also adopted for this purpose. Both these processes involve great advantages as compared to common mechanical processes including: low cycle time, no preparation requirements (e.g. drilling a pre-hole for the insertion of the fastener), easiness of automation, low cost, enhancement of the material behavior (as the processes involve strain hardening). Both self-pierce riveting [12,13] and clinching [14,15] have been extensively adopted for aluminum alloys and have been extended for joining titanium sheets. Compared to self-pierce riveting, mechanical clinching enables several advantages, e.g. MC does not require external fasteners, which involve structure weighting and increase in cost. In addition, MC requires lower joining force (almost 70% lower) than that involved in SPR. However, these joints are generally characterized by lower strength. MC joints are produced by imposing a plastic deformation of the sheets by means of a simple equipment that includes a punch, a die and eventually a sheet ejector/blank holder. As the sheets are subjected to high deformation (up to 150%), the main limitation of clinching process is represented by the ductility of the sheets (especially that placed against the punch). Nevertheless, despite this limitation, a number of materials have been joined by MC, including aluminum/steel joints [16], aluminum alloys [17–21], magnesium [22], titanium [14,15,23–25], copper [26]. Recent developments also included hybrid connections e.g. metal/plastics [27,28], metal/wood [29] and metal/composite [30–36] joints.

In some cases, to overcome the formability problem, heating of the sheets has been adopted. Different heating systems based on induction [22] convective [19], laser [37], flame heating [14] as well as friction assisted clinching [30,31] have been involved before or during clinch joining. Heating the sheets before joining enables two advantages: increasing the ductility of the material and reduce the joining force. However, the employment of such heating systems may involve some

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issues including efficiency of energy consumption (convective heating), difficulty to integrate the system directly on the clinching press (flame heating), production of thermal distortions (as expected by flame heating), relatively high cost of the heating system (laser and induction systems) and safety for the operator (laser source).

Thus, cold clinching is preferable as it involves lower energy consumption, lower processing time as well as material strain hardening, which results in higher strength of the joint.

For the aforementioned reasons, cold clinching of titanium and aluminum sheets is investigated. Different aluminum alloys including 5xxx, 6xxx and 7xxx series were involved in the study and were coupled with titanium grade 2 sheets. This enabled to establish how the flow stress and ductility of different materials influence the material flow during the clinching operation. Different types of tools were used. A finite element model of clinching process was developed in order to study the main features concerning the materials involved. After validation of the model, a clear understanding of the material flow is provided. Mechanical characterization tests were performed to determine the strength and failure mode of the sound joints. These tests were based on single lap shear tests.

2. Materials and methods

2.1. Experimental procedures and characterization

Sheets with 2 mm thickness of titanium alloy Grade 2 were joined to different types of aluminum alloys: AA5053, AA6082-T6 and AA7075 with 2 mm of thickness. Mechanical characterization of the base materials was performed by conducting tensile tests according to ASTM E08 M standards. The tensile tests were performed on a Universal Machine model 322.121 by MTS equipped with a load cell with 25 kN full scale under constant velocity of 2 mm/min. Three repetitions were performed for each material. The main mechanical properties of the materials is reported Table 1. The equation representing the flow stress reported in Table 1 were found by fitting the experimental curves reported in Fig. 1, where ε represents the true plastic stress and σ the flow stress.

Mechanical clinching was performed by means of a clinching machine model Python by Jurado srl (Rivotorto–Perugia, Italy). The machine was equipped with two types of punches: a truncated cone punch and a cylindrical punch (both with a filler radius of 0.2 mm). These tools were selected as the cylindrical punch generally produce larger interlocks while the truncated cone reduce the concentration of the stress during the drawing phase. Extensible dies were used as they generally reduce compressive hydrostatic stress as compared to those developing with grooved dies. This leads to a reduction of the forming forces and also an increased interlock dimension [40]. Two dies were adopted with die anvil depth of h = 0.8 mm and h = 1.1 mm. The materials used for the punch and the three sectors composing the split die was a steel alloy K340. The main geometries and dimensions of the tools are reported in Fig. 2.

The material flow was assessed by cross section observations and morphological analysis. To this end, the specimens were cut near the diametric plane. The specimens were molded and polished according to standard metallographic procedures. Cross section observations were performed by using a metallographic microscope model DMI5000 by LEICA. Morphological observations were performed by using a stereomicroscope model Stemi DV4 by ZEISS equipped with a DSLR camera model D5200 by Nikon.

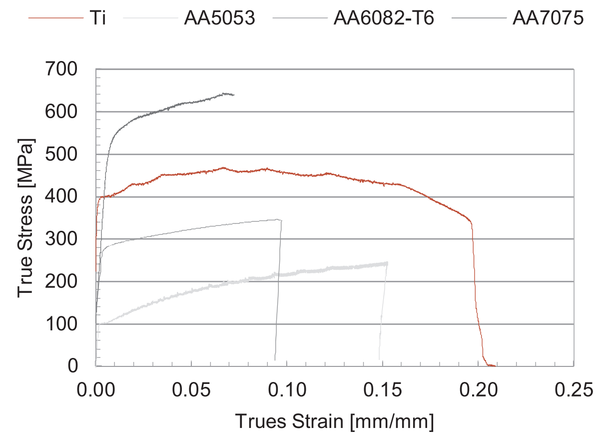

Fig. 1. True stress-true strain curves of the materials analyzed.

Single lap shear tests were performed to determine the mechanical behavior of the joints. To this end, the above-mentioned machine was used to conduct the tests at 2 mm/min. Five repetitions of the characterization tests were performed for each joining condition. The fractured surfaces were then analyzed by means of the above-mentioned equipment

2.2. Numerical model

A numerical model of the clinching process was developed in order to understand how the materials flow. To this end, an explicit time integration model was adopted within the framework provided by Abaqus 6.17. As the nearly-axisymmetric nature of the process, an axisymmetric model was developed to save computational time. An elastic-plastic behavior was assumed for the sheets with isotropic hardening (with flow stress defined by fitting the stress strain curve from tensile tests, as reported in Table 1). Linear 4-node elements were adopted for discretization. The element size varied from 0.025 mm up to 0.5 mm. The adoption of very small elements within a confined region (as shown in Fig. 3a) was driven by the need of accurately capturing the crack propagation during the process.

The tools were simulated as analytical rigid surfaces. The die was assumed to be fixed, while the punch followed a prescribed law of motion. The blank holder and the sliding die sector were connected to (fixed) reference points by means of spring elements. A schematic of the developed model is reported in Fig. 3a.

Lagrangian-Eulerian (ALE) adaptive mesh domain was adopted to avoid excessive mesh distortion during the simulation.

Surface to surface contact algorithm was adopted to model the interactions among the components. A modified Coulomb friction model was adopted with a limit on the maximum shear stress equal to the $\tau_{max} = \sigma_y/\sqrt{3}$, where σ_y is the yield stress of the material with the lower mechanical strength. Different values of the Coulomb coefficients were adopted to simulate the shear stress at the interface between the parts. Such values, which are summarized in Table 2, were chosen in

Table 1
Main mechanical properties of the materials.

Material	Young Modulus [GPa]	Yield Strength $\sigma_{y0.2}$ [MPa]	Tensile Strength, σ_{max} [MPa]	Elongation at rupture [%]	Flow Stress [MPa]
Titanium Grade 2	120	394	450	20	$\sigma = 555 \cdot \varepsilon^{0.0663}$
AA5053 [38]	67	100	250	15	$\sigma = 414 \cdot \varepsilon^{0.278}$
AA6082-T6 [39]	67	280	350	9.5	$\sigma = 467.5 \cdot \varepsilon^{0.098}$
AA7075	67	468	650	8.4	$\sigma = 806 \cdot \varepsilon^{0.0865}$