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Ultrasonic testing of thin walled components made of aluminum based laminates

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ABSTRACT

The goal of this paper is to evaluate the feasibility of testing thin walled components made of aluminum based laminates using ultrasonic waves. Aluminum alloys are applied in aviation, maritime and railway industries. The advantages of aluminum alloys include high specific strength, good machinability, and formability. In recent years, the position of aluminum as preferred material in transportation has been challenged by composites. The share of composites in the structure of aircraft such as AirBus A350XWB and Boeing 787 Dreamliner exceeds 50%. The application of composites allow weight to be reduced by 10 ÷ 20%. In response to the proliferation of composite structures aluminum industry started developing the next generation of aluminum lithium alloys allowing a reduction in aircraft structure weight by 8 ÷ 15%. In Bombardier CSeries aircraft the fuselage was made of aluminum lithium alloy, while the wings were made of composites. In the near future, both aluminum and composites will be used in aviation. There is a need for the development of technology for testing of thin walled components made of aluminum based sheets. In this work, ultrasonic testing of the aluminum based laminate having section thickness of 1.5 mm is presented. The laminate comprised two aluminum sheets with and without the polyimide interlayer which were joined using friction stir welding technology. The suggested ultrasonic method allowed material discontinuities having a width greater than 0.4 mm to be detected.

1. Introduction

Aluminum is frequently used as a structural material in aerospace applications. The advantages of using aluminum include high strength, low density, good formability [1] and good machinability [2]. Application of aluminum in aviation is constrained by its low heat resistance. In supersonic aircraft, where temperatures of the skin exceed 240 °C, titanium is the preferred structural material [3]. The economic factors contributed to the development of the lightweight structures consuming less fuel. This led to the introduction of composite materials into the aviation industry. The share of composites in the structure of aircraft such as AirBus A350 XWB [4] and Boeing 787 Dreamliner [5] exceeds 50%. The application of composites allows a weight reduction of 10 ÷ 20% [6]. In response to the proliferation of composite structures, the aluminum industry started developing the next generation of aluminum lithium alloys allowing a reduction in aircraft structure weight by 8 ÷ 15% [7]. In Bombardier CSeries, a fuselage is made of aluminum-lithium alloy, while wings and tailplane are made of reinforced plastic [8]. In the near future, both aluminum and composites will be used in the aviation industry. There is a need for the development of technologies joining these materials and technologies for nondestructively testing such joints.

One of the most interesting solutions of recent years that enables the production of lightweight and high strength structures is the use of fiber metal laminates (FMLs). FMLs are hybrid laminates comprising alternate thin layers of metal sheets and fiber-reinforced composite material [9]. FML structures are characterized by higher strength, lower weight, higher corrosion and impact resistance compared to conventional aluminum structures. Lionetto [10] put a film made of Polyamide 6 between carbon reinforced epoxy resin and aluminum sheets. Subsequently, she applied a force normal to the material stack and ultrasonic vibrations to form a joint. Jung [11] applied continuous wave diode laser to join aluminum with carbon reinforced plastic. Technologies related to friction stir welding, FSW, can also be used for joining aluminum and composites. Nagatsuka [12] used a flat tool without a probe to join aluminum sheet and carbon fiber reinforced polyamide. Liu [13] used the same technique to join aluminum and MC Nylon-6. Goushegir [14,15] and André [16] used a spot variant of FSW technology called RFSSW (Refill Friction Stir Spot Welding) to join aluminum sheets with carbon-fiber reinforced poly(phenylene sulfide). In this work, conventional FSW technology will be used to join aluminum sheets in an overlap configuration with polyimide interlayer.

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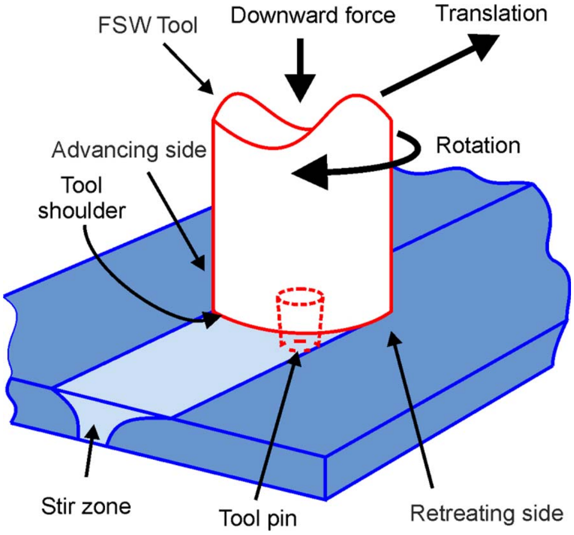

Fig. 1. Scheme of FSW process based on [25]. The sheets are in butt configuration.

FSW is a solid state joining technology. Unlike in conventional fusion welding processes, the temperature of a material doesn't exceed the melting point. The key element of the process is an FSW tool comprising a shoulder and a pin (Fig. 1). The tool rotates and moves along an interface between joined components. The tool shoulder has the contact with the external surface of the joined material, while the tool pin works in the material. The purpose of the tool action is threefold, to heat the material through friction and plastic strains, to stir the material and to prevent its movement outside the joint [17]. The process is self-stabilizing i.e. the increase of temperature causes the decrease of the heat production rate which in turn decreases the temperature [18,19]. The combined effect of high temperatures and high strain rates contributes to the material recrystallization inside the weld. Refill friction stir spot welding, RFSSW, is a variant of conventional FSW technology producing spot welds without an exit hole [20–22]. The exit hole occurs as a result of the tool exit. In order to achieve spot welds without the exit hole, RFSSW utilizes the tool comprising three separate parts. FSW is used primarily for joining aluminum. There are ongoing efforts to apply FSW for joining steel and titanium. The main challenge is in building the tools from materials that can retain high strength at high temperatures [23,24].

The typical defects occurring as a result of FSW process include tunnels and kissing bonds. Tunnels are volumetric defects occurring along the welding trajectory usually in the bottom part of a weld. The probable cause of tunnels is insufficient temperature decreasing the degree of the material stir [26]. A kissing bond is an interface between two volumes having diminished strength. It can be observed in metallographic specimens as a thin line [27]. The preferable method of detecting the defects should be non-destructive [28]. Eddy currents method is suited for detecting vertically oriented near surface defects especially lack of penetration defects occurring in FSW butt joints [29]. X-ray radiography enables detecting volumetric defects [30], though it has difficulty in recognizing narrow horizontally oriented gaps. The ultrasonic method allows interfaces between two materials having different speeds of acoustic waves propagation to be detected. In the context of FSW joints, it enables volumetric defects and narrow gaps oriented perpendicularly to the direction of acoustic waves to be detected. Recent developments in ultrasonic inspection of FSW joints include the application of pulse inversion consisting in sending the first impulse followed by the second phase-inverted pulse. Sewell [31] used this technique to detect defects in 6.35 mm thick FSW joints, Delrue [32] used pulse inversion to identify kissing bonds in 10 mm thick FSW joints.

Table 1
FSW joints.

Joint ID	Top sheet	Interlayer	Bottom sheet	Tool shoulder diameter, mm	Welding speed, mm/s
A	Al 7075, 1.0 mm	None	Al 7075, 1.0 mm	10	3.3
B	Al 7075, 1.0 mm	None	Al 7075, 0.8 mm	7	3.3
C	Al 2024, 1.0 mm	None	Al 7075, 1.0 mm	7	3.3
D	Al 2024, 1.0 mm	Polyimide, 0.08 mm	Al 2024, 0.5 mm	10	0.5

2. Materials and experimental procedure

The goal of this work is to assess the feasibility of ultrasonic testing of thin walled components made of aluminum based laminates. The composite structure consists of two aluminum sheets and polymer interlayer between the two sheets. The aluminum sheets and the polymer interlayer were joined using FSW technology. The joints described in this work are presented in Table 1. The ultrasonic testing procedure was developed based on the joints B and C. These joints comprised two aluminum sheets without an interlayer. The tool shoulder diameter in joints B and C was smaller than the tool shoulder in joint A and D, which resulted in narrower welds. The narrow welds are more difficult to inspect using ultrasonic method. The testing procedure developed based on joints B and C was then applied to joint D comprising the two aluminum sheets and the polyimide interlayer. Joint A was welded with the same tool as joint D but it didn't contain the polyimide interlayer. It was presented to show the thermal cycle and temperature distribution during the welding process.

Aluminum 2024 and 7075 are high strength aluminum alloys typically used in the aviation industry. The main alloying elements of aluminum 2024 are copper (3.8–4.9%) and magnesium (1.2–1.8%). The main alloying elements of aluminum 7075 are zinc (5.1–6.1%), magnesium (2.1–2.9%) and copper (1.2–2%) [40]. The increase in yield stress is achieved through solution heat treatment, quenching and subsequent age hardening [33]. Both alloys are susceptible to corrosion. The Alclad layer consisting of pure aluminum is applied to the external sheet surfaces to increase their corrosion resistance. Aluminum 2024 and 7075 are poorly weldable. Conventional fusion welding technologies lead to solidification and liquation cracking [34,35]. In industrial applications, these alloys are joined using riveting [36]. FSW is also applied since it doesn't melt the material during welding.

A polyimide film, having commercial name Kapton HN, was joined with the aluminum sheets. The foil is dedicated for high-temperature applications. The glass transition occurs in the temperature range between 360 °C and 410 °C, [37]. According to Meng [38], single major decomposition of polyimide starts at temperatures above 500 °C. Weight losses of 5% and 10% correspond to temperatures of 572 °C and 589 °C. Sazanov [39] researched the impact of the constant heating rate on the thermal degradation of a polyimide film. The increase in the heating rate was correlated with the increase in the temperatures at which weight loss was equal to 0% and 5%. For the highest analyzed heating rate equal to 20 degrees per minute, the weight loss in the range between 0% and 5% was corresponding to the temperature range between 490 °C and 540 °C.

The comparison of the selected properties of aluminum 2024 and polyimide film Kapton HN is presented in Table 2. The main difference between the two materials is the significantly lower thermal conductivity of the polyimide film.

A thermocouple was used to measure thermal cycle during welding of joint A made of aluminum 7075. Since the thermal properties of aluminum 7075 are close to the thermal properties of aluminum 2024