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Technical Paper

Laser beam welded structures for a regional aircraft: weight, cost and carbon footprint savings

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ABSTRACT

Laser beam welded structures offer great opportunities for the lightweight design of fuselage structures in order to reduce structural weight for increased fuel efficiency. Our main objective is to validate and demonstrate that laser beam welding (LBW) technology provides the best opportunities in terms of weight reduction, production time and energy consumption for manufacturing aircraft components. To this end, a comparison in terms of energy, process time, cost and carbon footprint is assessed against the 'conventional' manufacturing process of riveting, to prove that LBW is actually an environmental friendly process. Manufacturing of a four-stringer stiffened flat subscale component was the case of the present work that was called in the Clean Sky Eco-Design Airframe (EDA) project as the B1 demonstrator (742 mm × 384 mm). The LBW process has been broken down into several sub-processes and activities according to the Activity Based Costing (ABC) methodology and the weight reduction, production time and energy consumption results were compared against the respective of the riveting process. It was proved that for the specific subscale LBW component, it consumes half the energy and can be processed in less than half the time needed (in serial processing of the component) with riveting. Manufacturing of the component with the LBW process (door to door approach) is more environmentally friendly, since it produces 53% less CO_{2e} emissions than the respective riveted process. This is a clear advantage to this manufacturing process in order to assure a sustainable life cycle of the final product.

1. Introduction

The continuous challenges in aerospace engineering impose new directives that are dealing mainly with the reduction of greenhouse gas (GHG) emissions coupled with reduced manufacturing and operational cost along with improved structural safety [1]. In order to support the global environmental sustainability, the aviation industry was forced to reduce its gas emission during the production as well as the operational phases. Aviation industry is responsible for the 2% of annual global emissions, and in order to cope with that fuel consumption optimization strategies are applied mainly via the reduction of aircraft weights [2]. New structural design concepts and innovative materials can contribute to the weight reduction of aircraft structures. Moreover, such concepts should increase the aircraft payload as well as damage tolerance resulting thus to the reduction of fuel consumption and GHG emissions and to the improvement of safety and reliability.

Aluminum alloys have been the primary material of choice for structural aircraft components since 1930 because of their high stiffness-to-weight and strength-to-weight ratios [3]. However, the development of polymer matrix composites the last decades and their application in modern commercial aircraft (e.g. Boeing 777) [3] has driven aluminum alloy producers to develop lighter and weldable alloys with higher damage tolerance capabilities. To this end, current research focuses on lithium containing aluminum alloys. Aluminum–Copper–Lithium (Al–Cu–Li) alloys are attractive for potential aerospace applications due to their lower density, higher specific strength and rigidity, better corrosion and fatigue crack growth resistance properties, when compared to conventional aluminum alloys [4]. Lithium (Li) is the lightest metallic element, so the Li addition results to the reduction of the weight of the alloy; it was calculated that when 1 wt% Li added to Al, its density is reduced by 3% and the modulus of elasticity is increased by almost 6% [5]. The use of high strength Al–Cu–Li alloys instead

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of conventional Al–Cu alloys, e.g. 2024, can reduce the structure's weight by 10–15% and increase the rigidity by 20% [6]. For further reduction of structural weight and manufacturing costs, the introduction of advanced welding methods as an alternative joining processes to riveting in the manufacture of primary aircraft structure is necessary [6,7].

Riveting has been the state of the art joining technology for aircraft fuselage since the 1920s [3,8]. Nevertheless, this joining technology demands a large amount of material which restricts the weight saving requirements currently applied. For most aircrafts, a low overall weight is important to allow the use of smaller and less powerful engines to reduce fuel consumption [9]. Also, the riveting process accounts for a large proportion of manufacturing time and cost while, at the same time, it is an already mature technology in which it is difficult to make any further improvements [10]. Having so many limitations, aircraft manufacturers have turned their attention to other joining processes, e.g. laser beam welding of integral structures.

In the European continent, Airbus has already applied LBW to the fabrication of fuselage and pressure bulkhead skin-stiffener panels, implementing welding for the A318, A340 and A380, respectively [9]. LBW is a promising welding process for assembling the thin-walled components found in aircraft panels. Furthermore, the speed of the joining process is higher, as compared to riveting. In addition, LBW process results in reduced final weight of the fabricated panel because of the removal of fasteners and sealant [8].

The main goal of this article is to compare directly the LBW with the riveting process in terms of weight, manufacturing cost, lead processing time and CO_2 emissions for the case of manufacturing a four-stringer aeronautical subscale component. The authors of the present article haven't found any similar article(s) on the literature regarding the quantitative advantages of the LBW process to manufacture aeronautical components. To this end, the materials as well as the different manufacturing processes for both laser beam welded and riveted structures, will be briefly described. Subsequently, cost models with the derived equations for the cost and carbon footprint evaluation of both innovative and conventional joining processes will be developed. Finally, a direct comparison based on the manufacturing cost and the environmental carbon footprint of a LBW against a traditional riveted subscale component is described in order to assess the "greenness" of the two technologies that assure a sustainable life cycle of the final product.

2. Background

2.1. Cost estimation

Lately, Activity Based Costing (ABC) has become a popular cost estimation method due to the poor results of the traditional costing systems. The ABC model is composed of both the cost assignment view and the process view with activities as the intersection of these two views [11]. ABC analysis provides an understanding of how costs are driven by the demands for activities within a process, and allows the identification of value and non-value added manufacturing operations as well as how resources are consumed [12].

More specifically, ABC method was introduced by Kaplan and Cooper [13] of Harvard Business School as an alternative to traditional accounting techniques. This method was also reported by [14] against the traditional cost allocation structures. ABC method is being used for product costing in both manufacturing (including the manufacturing system for joint products) and business applications [11,15–17]. ABC method is designed and implemented on the premise that cost objects (e.g. products, product lines, processes, customers, channels, markets, etc.), consume activities, activities consume resources and resources consume costs, as it can been seen in Fig. 1 [11,18]. For the convenience of the reader, it must be clarified that the manufacturing process of a component consists of many sub-processes and each sub-process has several activities. The resources used in manufacturing companies may include "people," "machines," "facilities," and "utilities," while the corresponding resource costs could be assigned to activities in the first sub-process of cost assignment view by using the resource drivers: "time," "machine hours," "square footage," and "kilowatt hours," respectively. The costs of different levels of activities can be traced to products by using different kinds of activity/cost drivers. For example, "number of machine hours" is used for the activity "machining," "setup hours" for "machine setup" [11] and so forth. To identify cost drivers, the analyst must investigate the process of production to determine what activities must be performed to produce a product [18]. For this cause, each manufacturing process was divided in multiple sub-processes to better monitor them, while cost drivers were built up and associated with each sub-process.

ABC method examines all activities that are actually relevant to the production of a product and attempts to determine exactly what portion of each resource is consumed. To this end, the cost estimation approach for the economical evaluation of LBW and riveting processes is based on the Activity Based Costing (ABC) method that lies on the following steps:

a) Identification of resources (i.e. which resource is used to provide work),
b) Identification of resource drivers (i.e. assigning the cost of the resources to activities based on effort expended),
c) Identification of activities (i.e. work),
d) Identification of activity/cost drivers (assigning the cost of the activities to products based on unique consumption patterns), and finally
e) Identification of the objects of work (to what or for whom work is done).

2.2. Carbon footprint calculation

Aviation is the fastest growing source of greenhouse gas emissions in the transport sector and the most climate-intensive form of transport. According to Lee et al. [19] aviation emissions have more than doubled in the last twenty years and the sector accounts for 4.9% of total worldwide emissions contributing to climate change. Apart from fuel technology, materials and structuring techniques are also important for the minimization of the environmental impact of the aviation sector. It is thus crucial to identify new production methods that will support the use of new materials and technologies, which will contribute toward the minimization of the carbon footprint and the recyclability of waste [20]. However, the "greenness" of the production methods themselves should be assessed in order to assure a sustainable life cycle of the final product [21].

To this end, we have calculated and assessed the environmental (carbon) footprint and the energy consumption of two different joining (fastening) techniques, namely the LBW and riveting for the manufacturing of the same four-stringer aeronautical subscale component. For the calculation of the environmental footprint, we adopted the PAS2050 standard methodology [22], that takes a process life cycle assessment (LCA) approach to evaluate the GHG emissions associated with goods or services, enabling companies to identify ways to minimize emissions across the entire product system. However, for our case the PAS2050 standard was applied only for internal processes "door to door" approach that is,