Sustainable and advanced manufacturing processes of light structural materials of the transport sector

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Abstract: 30% of emissions in the European Union (EU) originate from transport, and there are commitments by all sectors involved, road transport, civil aviation and maritime for a progressive reduction. The mass of the vehicles has a significant influence on their consumption and emissions, so there is a need to replace traditional heavy materials with light structural materials or combinations of them, and to optimise their manufacturing processes. This work reviews the scientific literature published during the period 2015-19. Aiming to select the most relevant articles minimizing the bias, a search strategy is defined, applied in the Web of Science database, and the selection limited to publications in Open Access, English, Q1-Q2 journals or prestigious conference proceedings, from 01/01/2015 to 01/01/2020. The final objective of the work is to provide a global perspective of the latest trends in studies on light structural materials with application in the aeronautical and/or automotive fields, of studies oriented towards sustainability, and with a special interest in those that apply advanced manufacturing and/or machining processes.

Keywords: Hybrid components, Lightweight materials, Light alloys, Sustainability, Transport.

1. Introduction

The Intergovernmental Panel on Climate Change (IPCC) estimates in its 2018 report that human-induced climate warming reached 1 °C in 2017 from pre-industrial levels, and is increasing by 0.2 °C per decade. Emissions would need to be reduced by 45% from 2010 levels by 2030, and reach net zero by 2050 to stabilise warming at 1.5 °C [1]. In accordance with the conclusions of the IPCC, and the targets defined in the Paris Agreement [2], European regulations have begun to be established in order to accelerate the transition of the entire transport sector towards zero emissions. Transport is responsible for more than 30% of CO₂ emissions in the European Union (EU), and the EU has committed to reducing these emissions by 60% by 2050. In the case of the automobile industry, a total of 15.1 million new cars were registered in the EU in 2017, emitting an average of 118.5 g CO₂/km, an increase of 0.4 g CO₂/km compared to 2016 [3]. The mass per vehicle remained similar to previous years at an average of 1390 kg/per new vehicle, even though a 10% reduction in vehicle mass leads to a 5-7% reduction in fuel consumption [4]. On the other hand, the transition to zero-emission vehicles will be gradual, so that at least 80% of the new car fleet is expected to use an internal combustion engine by 2030 [5].

Regarding the aeronautics sector, the Advisory Council for Aeronautics Research in Europe (ACARE) has defined as targets for 2050 a 75% reduction in emissions per passenger and kilometre, and a 90% reduction in NOₓ, compared to capacities in the year 2000. Also, aircraft must not generate...
emissions when they taxi and must be designed and manufactured so that they can be recycled. To achieve these ambitious goals, it is necessary to optimise the current production processes and develop new processes and technologies. Lightweight structural materials need to be integrated into the design of airframes and cabin interiors. This involves new processes, lightweight materials, and multifunctional structures to reduce the weight and cost of manufacturing, and encourage the integration of reusable or recyclable materials [6]. Boeing’s first environmental objective is to reduce CO₂ emissions, and it has succeeded at reducing the consumption of each new generation of designed aircraft by 15 to 25% compared to the previous generation [7].

2. Methodology
The objective of the study is to carry out an unbiased selection and subsequent analysis of the recent scientific literature on light structural materials with application mainly in the aeronautical and/or automotive fields, in studies focused on sustainability, and where advanced manufacturing processes are examined, in particular machining, with a special interest in light alloys of aluminium, magnesium and titanium. The main goal is to acquire knowledge on the latest trends, both in lightweight sustainable materials and processes associated with them. Bibliographical research was defined in 2 stages, the first one is focused on published literature about lightweight structural materials, with application in the aeronautical or automotive sectors, and that includes advanced manufacturing and machining processes. The second one, on light alloys of aluminium, titanium and/or magnesium. For the final selection, each article is reviewed to ensure it meets the criteria, and the final selections is made up by the most cited articles of the period. In the case of studies on general lightweight materials, the literature is very extensive, so the 30 most cited articles were initially selected, and finally reduced to 28 after review of the inclusion criteria. In the case of the literature on light alloys of Al, Ti, and Mg, the literature is very limited, so all studies with at least 1 citation were included, 19 articles in total.

Table 1. Search strategy and characteristics of the selected bibliography.

| Criteria | Features |
|----------|----------|
| Type of studies | Scientific journals Q1 (30%) - Q2 (26%) & conference proceedings (44%) |
| Publication period | 5 years from 01/01/2015 to 01/01/2020 |
| Date of last search | 30/03/2020 |
| Search "lightweight materials" | Boolean equation (1) |
| Features of articles (search 1) | 28 articles most cited / 45.8 citation per article |
| Search 2 “Light alloys” | Boolean equations (2) |
| Features of articles (search 2) | 19 articles most cited / 2.3 citation per article |
| Bibliography sources | Only databases included in Web of Science (WoS) |
| Search Engine | Web of Science |
| Language | English |
| Type of publication | Only Open Access |

(1) TS=((aeronaute* OR aircraft OR aeroesp* OR air transport OR aviation OR automobile* OR vehicle* OR automotive*) AND (drilling OR turning OR cutting OR machinability OR machining) AND (hybrid compo* OR hybrid materia* OR hybrid structur* OR multi-materia* OR multimateria* OR lightweight* OR light-weight* OR light allo* OR light materia* OR structural materia*) NOT (nano*)) AND (magnesium OR aluminium OR titanium OR steel OR FRP OR GFRP OR CFRP OR Metal OR Polymer OR Ceramic OR Polymer OR textile))

(2) TS=((aeronaute* OR aircraft OR aeroesp* OR air transport OR aviation OR automobile* OR vehicle* OR automotive*) AND (hybrid compo* OR hybrid materia* OR hybrid structur* OR multi-materia* OR multimateria* OR lightweight* OR light-weight* OR light allo* OR light materia* OR structural materia*) AND (drilling OR turning OR cutting OR machinability OR machining) AND (magnesium OR aluminium OR titanium) AND (sustainabili* OR carbon dioxide OR carbon emission* OR energy efficiency OR fossil fuel OR fuel consumption OR fuel saving OR global warming OR sustainable OR green OR energy-efficiency OR environment*) NOT (nano*))

The search strategy and characteristics of the selected bibliography appear in table 1. The exclusion/inclusion criteria define Web of Science as the search engine, and only articles published in English, in Open Access, in Q1-Q2 scientific journals or recognised peer-reviewed conferences, during the period 2015-19. The used boolean equations are shown in (1) and (2) (see table1).
3. Literature review. Sustainable trends in transport lightweight materials

The study is divided into an initial analysis of current manufacturing processes with a sustainable approach, and a subsequent analysis of the lightweight materials most commonly used in these studies. Table 2 shows a summary relating main materials and topics covered.

| Materials | Additive manufacturing | Multi-materials | Drilling | Welding | Refrigeration |
|-----------|------------------------|-----------------|----------|---------|---------------|
| Al        | [8-10]                 | [4,8,18-27,9,28-32,11-17] | [20]     | [15-17] | [25-28]       |
| FRPs      | [9]                    | [24,33]         | [33-39]  | -       | -             |
| Ti        | [8,40-42]              | [25,33]         | [33]     | -       | [25,33,43-45] |
| Mg        | -                      | [25,26,46]      | -        | -       | [25,26,46]    |
| Steel     | [8,47]                 | [4,22,23,48]    | -        | [17]    | -             |

3.1. Latest trends in sustainable processes

Conventional machining processes provide great flexibility, but have a low material use ratio and are therefore only recommended in the case of low demands [49]. However, other technologies, such as additive manufacturing, reduce wasted materials, manufacturing times, and increase added value by obtaining parts with a shape close to the final shape [21]. By applying additive manufacturing technologies such as Wire Arc Additive Manufacturing (WAAM) [8,21] or Selective Laser Melting (SLM) [40,42,47] it is possible to upgrade from a Buy To Fly (BTF), ratio of the initial mass to the final mass of the final part, from values of 25 to values of 1.2, and with a saving in the final mass up to 50% through numerical optimisation and design flexibility [41]. Moreover, aerospace and automotive sectors require very high standards of quality and predictability to both static and dynamic loads; for this reason, common objectives associated with recent studies on additive manufacturing are the reduction of residual stress, the optimisation of mechanical properties, and the study of fatigue performance [41,50]. Tensile Residual Stress (TRS) has a negative impact on fatigue behaviour and several methods are being investigated to counteract it by generating Compressive Residual Stress (CRS) [47]. Table 3 summarises the most cited articles of the period.

| Materials | Technology | Ref. | Year | Country       | Cites / year |
|-----------|------------|------|------|---------------|--------------|
| Ti /Al /St| WAAM       | [8]  | 2016 | United Kingdom| 53.8         |
| NiTi alloys| SLM       | [50] | 2016 | USA          | 30.0         |
| Ti        | SLM        | [40] | 2015 | Germany       | 12.6         |

On the other hand, current requirements in high-performance applications make it difficult to design them using a single material; therefore, a new trend in the manufacture of advanced lightweight materials is the use of combinations of multi-materials or hybrid components with superior properties and, to this end, new manufacturing processes are being developed and existing ones optimised [26]. Another possibility is the development of new materials and alloys. In this direction, recent studies have worked on NiTi alloys that have memory and superelasticity effects and on gamma alloys, but it is a slow and sometimes unsuccessful process. For example, in the case of gamma alloys, 40 years passed between the first exploratory research and the first engine in flight with pieces of alloy 4822 [51]. The topics of greatest interest in manufacturing linked to multi-material composites are the joining of different materials and the optimisation of their machining processes. The main types of joints are mechanical, by drilling and bolting or riveting [33], and thermal, where different welding technologies are applied. The machining process in multi-materials needs to be optimised for each multi-material combination, as the optimal cutting conditions can be very different to those of the individual materials, and that implies the use of compromise solutions in the selection of the cutting and tooling conditions that limit the efficiency of the process, producing tool wear, low surface quality and geometric deviations [17,24,25,33]. Table 4 contains a summary of the most frequently cited articles of the period.
Table 4. Selection of 3 most cited articles on multi-materials.

| Materials                          | Technology               | Ref. | Year | Country     | Cites/year |
|-----------------------------------|--------------------------|------|------|-------------|------------|
| FRP - Ti                          | Drilling / State of Art  | [33] | 2016 | France      | 17.8       |
| Al-Ceramics (SiC, B4C)            | State of Art             | [12] | 2016 | South Africa| 6.8        |
| Multiple (Al, St, Mg, Cu, plastics, composites) | State of Art | [4]  | 2017 | United Kingdom | 8.3        |

Besides, drilling plays a vital role in the assembly of parts in the aircraft industry. It is estimated that 50% of all machining operations employ it, and it is present in 75% of the selected studies that include machining. The most frequent problems in the drilling process are related to tool wear [33], surface quality and diameter tolerance [37]. Also, in the case of multi-materials, scratches appear at the interface between materials and in the chip removal path, with the influence of the tool geometry and coating [33,38,46]. A problem associated with drilling in Fibre Reinforced Polymers (FRPs) is the risk of delamination. This is a function of the angle between the feed force and the fibre direction, and the tool geometry [35], and it is important for its prevention the knowledge of the critical thrust force value above which it starts [34,37,38]. The process is made difficult by the hardness and abrasion capacity of the fibres and their cutting during drilling. This generates heat that can increase the temperature of the resin above its temperature limit, resulting in thermal degradation. For epoxies, this critical temperature is within the range of 120°C to 270°C [39]. In the drilling of aluminium and polyethylene (PE) multi-material sandwich panels, frequently used in industries such as civil, naval, aerospace and transport, the most frequent defects are burrs at the entrance and exit of the drill, geometric deviations, and delamination [20]. Table 5 contains a summary of the 3 most cited articles on the drilling process of the period. On the other hand, the mechanical joining of parts by riveting is common in aerospace, military and commercial aircraft applications. A new type of riveting is Self-Piercing Riveting (SPR) in which a mechanical joint is made between 2 or more plates of material by introducing a rivet that penetrates the different plates and is mechanically fixed to the last one by deformation. This method is capable of efficiently joining multi-material components formed by aluminium, steel, magnesium, copper, plastics, wood or composites. It does not require pre-drilling or heat treatment and, for this reason, it is already used by automotive companies such as Audi, Jaguar, Land Rover, Volvo, BMW, Daimler, Tesla and Ford as an alternative to Resistance Spot Welding (RSW) technology. Its disadvantages are the need for access from both sides, the deformation generated on one side, the possibility of galvanic corrosion and the limitations of use on fragile materials [4]. Weltsch et al. [48] carried out an experimental test in 2018 on the joining of steels of different qualities, using different joining techniques: high resistance adhesion, brazing, arc welding and riveting. The study concludes that the strength of the bonding of multi-materials is determined by the strength of the weakest material, the rivet in the particular case of the test.

Table 5. Selection of 5 most cited articles on drilling process.

| Material      | Theme                | Ref.   | Year | Country | Cites / year |
|---------------|----------------------|--------|------|---------|--------------|
| FRP - Ti      | State of Art         | [33]   | 2016 | France  | 17.8         |
| FRP           | RUM*                 | [34]   | 2016 | USA     | 15.3         |
| FRP           | Process optimization | [35]   | 2015 | France  | 8.6          |

*Rotary Ultrasonic Machining (RUM)

Regarding thermal joints, traditional welding techniques are based on the fusion of the base material and the filler material along the welded joint. The cooling of the weld is the most critical part in this type of welding, and where many of the defects occur such as segregation, dendritic recrystallisation, porosity and formation of intermetallic compounds, which is why it must be done in a protected atmosphere. For this reason, many recent studies are researching or developing new welding techniques by applying them to specific multi-material combinations. Laser welding is a promising technique in the aerospace industry, and has important advantages compared to conventional arc welding such as lower...
temperature, higher productivity and less deformation; although specific problems of each material to be welded must be solved. For example, laser welding in aluminium is difficult due to its reflectivity, high thermal conductivity, excessive fluidity and its tendency to form pores, modifying the final properties depending on the vaporisation and loss of alloying elements [15,22]. The Friction Stir Welding (FSW) process has a high potential, as the peak working temperature is 0.6-0.95 the melting temperature, and is already used in the automotive sector, although its use is limited in large parts due to the high forces required. Moreover, small variations in the process parameters such as thickness, temperature, wear or difference in the positioning of the tool or even deformation of the clamping tools can modify the quality of the joint [16,17,29,30,35]. Moreover, in 2019, Gullino et al. [23] carried out an interesting analysis of the state of the art of welding technologies available for joining multi-materials, based both on the fusion of base materials and on solid joint technologies, and focusing their analysis on technologies applicable to the joining of steels and wrought aluminium alloys. The technologies studied include RSW, Laser Beam Welding (LBW), Arc Welding, Explosion Welding and Transition Joints (EWTS), Magnetic Pulse Welding (MPW), Roll Bonding (RB), FSW, Friction Bit Joining (FBJ), and Ultrasonic Spot Welding. Table 6 contains a summary of the 3 most cited welding articles.

| Material | Theme | Ref. | Year | Country | Cites / year |
|----------|-------|------|------|---------|-------------|
| Al/St    | FSW   | [17] | 2018 | USA     | 6.5         |
| Al       | Laser | [15] | 2015 | Italy   | 2.6         |
| Al       | FSW   | [16] | 2015 | Germany | 2.6         |

Finally, and from an environmental perspective of the machining processes, the development of sustainable technologies that reduce the use of cutting fluids and thus the environmental and health damage caused by them is of great interest. In this sense, the most popular working lines are the quasi-dry machining options such as Minimum Quantity Lubrication (MQL) [33,43] and dry machining [25–28,46]. Additionally, innovative solutions such as cryogenic cooling are also proposed, to increase tool life in titanium alloys; however, the working conditions at very low temperatures (up to -150°C) lead to a hardening of the workpiece and an increase in the cutting forces. Therefore, modifications of the process are being studied with good results in which cryogenic cooling is integrated into an internal tool circuit [45] or where the cryogenic process and MQL are combined, obtaining in both study lines significant reductions in machining forces with important increases in tool life [44]. Table 7 contains a summary of the 3 most cited refrigeration articles.

| Materials | Theme | Ref. | Year | Country | Cites / year |
|-----------|-------|------|------|---------|-------------|
| FRP/Ti    | Several | [16] | 2016 | France | 17.8       |
| Ti        | Cryogenic machining | [43] | 2015 | USA     | 6.6        |
| Al/Ti/Mg  | Dry machining | [25] | 2018 | Spain   | 1.5        |

3.2. Latest trends in lightweight materials

From the analysis of the topic of the works selected for this study on lightweight structural materials, it can be concluded that the three most common types of materials in the recent scientific literature are Al, FRPs and Ti. The literature linked to aluminium alloys deals with many different subjects: effects related to fatigue behaviour and residual tensile stress control [11,27], Aluminium Matrix Composites (AMCs) [12,13,52], their application in the development of new technologies such as drones [9] or Micro Air Vehicles (MAV) [14], the development of new welding methods [23] such as FSW for multi-materials [16,29], laser welding [18] or Electromagnetic Pulse Technology (EMPT) [31], Optimisation of processes such as drilling with robots in hybrid Al-Carbon Fibre Reinforced Polymer (CFRP) compounds [24], optimisation of repair and maintenance operations by re-drilling hybrid Mg-Al
compounds in the aeronautics sector [24] or predictive models of automotive matrices to control crack formation [32]. On the other hand, FRPs have acquired great importance in commercial aircraft, and examples of their use can be found in fuselage cladding, or wings [19]. The main families are CFRPs, Glass Fibre Reinforced Plastics (GFRPs) and Fibre Metal Laminates (FMLs). Fibres provide lightweight, stiffness and strength, while the polymer matrix provides load-bearing capacity and structural integrity. The maximum resistance is obtained in the direction of the fibres and the minimum resistance in a perpendicular direction. CFRPs have attractive properties such as low density, high stiffness-to-weight ratio, excellent fatigue behaviour and wear resistance, high dimensional stability, low coefficient of friction, expansion and electrical conductivity [34]. When used in hybrid compounds with metals, e.g. Ti-CFRP, a poorly evacuated metal chip can cause erosion and abrasion, and heat is difficult to evacuate at the FRP-metal interface, causing degradation of the FRP polymer matrix [33]. The heterogeneous and anisotropic structures of FRPs make their machining difficult, producing frequent defects such as delamination, pull-out and temperature damage. Its main machining techniques are sawing, milling, drilling and grinding, and although they are manufactured in close to net forms, they often require finishing by machining for subsequent assembly [33,36].

Titanium has good corrosion and fatigue resistance, and very good mechanical properties due to its metallographic structure. Therefore, titanium alloys can be found in landing gear parts, wing reinforcements, wind tunnel parts [8], fuselages, corrosion-prone or difficult-to-inspect areas, and the military industry [43]. However, titanium alloys are considered extremely difficult to machine due to their low thermal conductivity, low elasticity modulus and high chemical affinity with the tool materials [33,40,45]. For that reason, it appears in many studies both for the optimisation of machining by milling [53] and drilling [25,33] and for cryogenic cooling aimed at increasing tool life and machining quality [43,45]. Regarding magnesium, its density is 66% of the density of aluminium and 25% of the density of steel, and therefore an ideal candidate to replace them. It is currently used by automotive manufacturers such as Volkswagen, General Motor, Ford, Toyota and BMW in the production of some of their components[10]. However, its use is limited by its low forming capability due to its hexagonal crystalline structure. For this reason, an interesting study proposes improving its formability by reducing the grain size by extrusion at 80 °C and achieving, in this way, a reduction in the thickness of the sheets from 10 mm to 1.5 mm without producing cracks [54]. Table 8 contains a summary of the most cited articles on each material.

| Materials | Theme | Ref. | Year | Country | Cites / year |
|-----------|-------|------|------|---------|--------------|
| Ti        | Process optimization | [53] | 2015 | China   | 57.4         |
| Al        | Additive Manufacturing | [8]  | 2015 | China   | 53.8         |
| FRPs     | Drilling / State of Art | [33] | 2016 | France  | 17.8         |

4. Conclusions
This study is based on a systematic selection of the most relevant works with a sustainable orientation applied to the aeronautics and automotive sectors published during the period 2015-19 on lightweight structural materials. About the sustainable processes identified, additive manufacturing is a relevant topic, and the development of new technologies, fatigue behaviour and the improvement of the effect produced by TRS, are the most interesting topics related. Another important topic is the multi-material combinations, especially new processes to join dissimilar materials by mechanical or thermal joints. Drilling is the most analysed machining processes, found in 75% of the studies related to machining, and, regarding thermal joints, there is great interest in FWS and laser technologies, as they use lower temperatures than conventional welding, thus avoiding their problems. Concerning the refrigeration processes applied in machining processes, a new trend of cryogenic cooling to increase the life of the tool is studied, employed alone or in combination with other existing refrigeration processes such as MQL. In terms of the materials, the materials most present in the selected studies are Al, FRPs and Ti. The article presents summary tables with the main information of the most relevant articles selected on
additive manufacturing, multi-material compounds, drilling and welding processes, refrigeration technologies and individual materials, and a summary table relating materials and topics.

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