Lightweight Structural Materials

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1. Introduction

This reduction in CO_2 and pollutant emissions by transport-related industries can be addressed through different lines of work, such as developing more efficient combustion engines or engines based on new technologies [1] and reducing the mass of cars and aircraft, either by replacing conventional materials with lightweight materials such as advanced polymers, light alloys, and multi-materials [2], or by designing structures with optimized mass-to-mechanical strength ratios [3].

Another critical aspect of sustainability is the recycling of materials. Over the next 20 years, more than 12,000 aircraft are expected to complete their life cycle, so the use of materials that enable recycling or reuse at the end of an aircraft's life is critical. Since 2007, Airbus has recycled 117 jets, with 92% reuse of remaining parts and 100 engines fully recycled [4].

On the other hand, high-performance components can no longer be designed using a single material or material type. Today, to optimize the specific properties of each material, it is common to use multiple materials in the manufacture of a component, especially in lightweight material design. These combinations of materials are called hybrid compounds or multi-materials, and they require the optimization of manufacturing processes. For example, in the machining of a multi-material frequently used in the aeronautics industry, the CFRP/Ti composite, the simultaneous machining of two dissimilar materials requires a choice of compromised manufacturing conditions, leading to worse results than machining them individually [5].

On the other hand, it is necessary to point out that the research aims at sustainable mechanical forming processes involving lightweight materials and multi-material materials, and the field is already vast. For this reason, although adhesive bonding is a topic of great relevance and interest in structural lightweight multi-materials, it has not been included in the search equations in order to focus the study on the main objective of the research. However, the literature associated with the adhesives is extensive, and researchers interested in this type of technology can find extensive reviews of the state of the art [6][7][8], research on process optimisation [9][10], on the repair and detection of damage in adhesively bonded composites [11], or on the debonding of adhesively bonded multi-materials [12], among others.

2. Methodology: Trend Analysis in Structural Lightweight Materials

The field of lightweight structural materials is a very vast domain. It includes all plastic materials and light alloys, either individually or as part of multi-material composites. **Figure 1**a shows a graph of the studies found in the Scopus database, using a general search of papers that include the topic "lightweight materials" and apply to the aeronautical and automotive sectors. As the graph shows, the number of studies increased by a factor of more than five over the last 20 years [13].

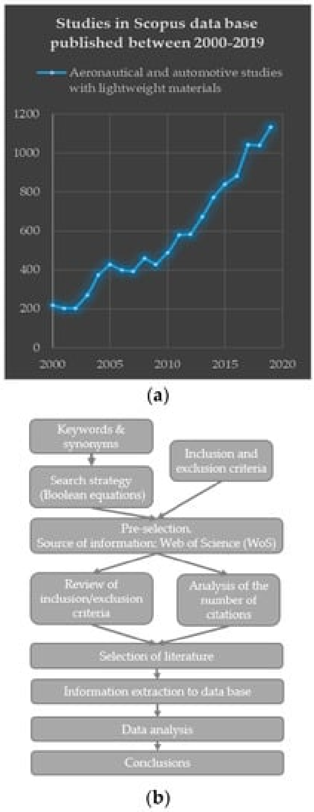

Figure 1. (**a**) Trend according to the number of studies on lightweight materials applied to the aeronautical and automotive sectors; (**b**) Defined strategy for literature search.

The flow chart in **Figure 1**b graphically depicts the methodology applied for selecting and analyzing the literature. The goal is to obtain a selection of relevant, comparable articles chosen based on pre-established criteria and, thus, to minimize the risk of bias by standardizing all the decisions involved in the process.

3. Trend Analysis in Structural Lightweight Materials

Moreover, aluminum matrix composites (AMCs) are composite materials with excellent properties: good mass-to-strength ratio, good ductility, high strength and modulus of elasticity, low coefficient of expansion, excellent wear and corrosion resistance, high creep temperature, and good fatigue behavior. For these reasons, they are widely used in the automotive and aerospace industries in applications such as robots, high-speed machinery, high-speed rotating shafts, automobile engines, and brake parts. The reinforcement microstructure of the matrix must be homogeneous, i.e., the ceramic particles must be homogeneously distributed in the metal matrix. The degree of reinforcement of the final multi-material depends on the amount, distribution, size, and shape of particles. The most commonly used particles in aeronautical structural applications are SiC and B4C [2]. In addition, the use of conductivity-enhancing particles within the aluminum matrix, such as TiB2, provides an increase in conductivity sufficient to be machined by non-conventional manufacturing processes such as electric discharge machining (EDM) [14][15]. This type of reinforced composite has been used, in recent years, in structural components with stringent requirements in the aerospace, defense, automotive, and sports sectors. **Table 4** shows the studies included on aluminum alloys in the present study, listed by average number of citations and showing the main characteristics.

Titanium alloys offer good corrosion and fatigue properties and excellent mechanical characteristics, thanks to their metallographic structure. In addition, the increasing use of FRPs is pushing aircraft manufacturers to replace aluminum alloys with titanium alloys, because of the incompatibility between aluminum alloys and carbon [16]. However, titanium alloys are considered a challenging material to machine due to their low thermal conductivity, low modulus of elasticity, and high chemical affinity with tool materials [17]. According to the average number of article citations per years published, the most popular article is focused on titanium alloys, with 75.8 citations/years published, and its topic is additive manufacturing using welding. Williams et al. [16] conducted a study in 2016 in additive manufacturing using WAAM technology; a scheme is shown in **Figure 2**.

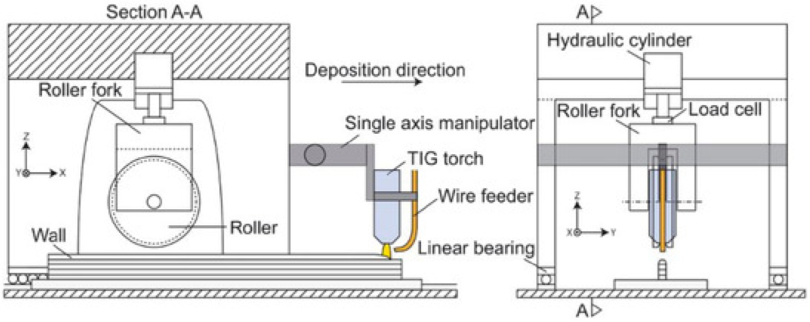

Figure 2. Schematic diagram of rolling and welding equipment [16].

Otherwise, regarding the turning process of titanium alloys, some literature has also been published on optimizing process parameters and conditions and integrating sustainable cooling in the machining process. Ti-5553 alloy has high strength and excellent properties at both ambient and high working temperatures. It has better corrosion and fatigue resistance than UNS R56400 alloy, which makes it an ideal substitute. This alloy has already been used in the aircraft industry in components for landing gear, fuselages, wings, corrosion-prone or difficult to inspect areas, and in the military sector. However, this alloy has high reactivity leading to rapid tool wear, low thermal conductivity leading to high temperature, and heat band formation leading to high dynamic loads and vibration during machining. In the article [18], Sun et al. report a study on machining forces, finishing surfaces, and tool wear for Ti-5553 alloy, using cryogenic cooling, and comparing the results with those of flood cooling and minimum quantity lubrication (MQL). In the experimental trial, the machining forces are decreased when using cryogenic cooling up to 30% compared to MQL. However, MQL cooling achieves a better finish, as it is more ductile at higher temperatures. On the other hand, cryogenic cooling shows less wear of the insert nose. The study also presents a finite element model that simulates the cutting forces in cryogenic machining, with a good correlation between experimental and predicted results. In the comparison carried out in the study, abrasive wear is found for all three types of cooling. The forces are lower when using cryogenic cooling, with lower adhesion and lower temperature in the cutting zone resulting in less adhesion of material on the insert. The reduction in machining force is lower when using a lower feed rate, as the temperature increases less and the plastic deformations are smaller. On the other hand, surface roughness increases with increasing feed rate for the three types of cooling systems compared, cryogenic, MQL, and flooding. **Table 1** shows the studies included on titanium alloys in the current study, listed by the average number of citations, and shows their main characteristics.

Table 1. Summary of studies including titanium alloys, listed by the average number of citations, taking into account the number of years the article has been published.

Ref.	Citations Averaged	Publication Type	Year	Material(s)	Key Topics Addressed	Origin
[16]	**75.80**	**Q1**	**2016**	**Ti/Al/steel**	**[1] AM**	**United Kingdom**
[19]	**50.67**	**Q2**	**2015**	**Ti**	**[5] M**	**China**
[17]	**21.00**	**Q1**	**2016**	**Ti/FRP**	**[5] M**	**France**
[20]	**16.00**	*** PP**	**2015**	**Ti**	**[1] AM/[3] SoA**	**Germany**
[21]	**16.00**	**Q2**	**2018**	**Ti**	**[1] AM/[3] SoA**	**Australia**
[22]	**8.67**	*** PP**	**2018**	**Ti/steel**	**[1] AM/[4] * WT**	**Spain**
[18]	**8.33**	*** PP**	**2015**	**Ti**	**[5] M**	**USA**
[23]	**5.5**	**Q1**	**2017**	**Ti/FRP**	**[2] HC/[5] M**	**China**
[24]	**5.5**	**Q1**	**2017**	**Ti/Al/steel**	**[1] AM/[3] SoA**	**USA**
[5]	**4.23**	*** PP**	**2013**	**Ti/FRP**	**[5] M**	**India**
[25]	**1.88**	**Q1**	**2008**	**Ti/Ni**	**[5] M/[3] SoA**	**China**

* Proceedings Paper; [1] Additive manufacturing; [2] Hybrid Component; [3] State of Art; [4] Welding Technology; [5] Machining.

The main traditional manufacturing techniques are casting, which works at high temperatures, degrading functional properties, with a need for finish machining and excessive tool wear, and powder metallurgy (PM), which allows for the production of close to net shapes but has the disadvantage of a high level of impurities, with a process limitation on the control of form and porosity in complex parts. The study aims to advance towards an additive manufacturing method to produce intricate shapes of potential use in the aeronautics and biomedical industries. There are three key points when designing a manufacturing process for this alloy: the first is preparing the Ni–Ti powder, where the ratio of the elements is crucial for the final properties obtained. The second is the choice of process parameters that will affect density and impurities and, thus, the final properties. Finally, the third is the use of an inert atmosphere to minimize oxidation and impurities and improve the surface quality and density. The reduction of impurities is essential in biomedical industry applications. The most frequent problems in additive manufacturing are structural defects, pores, cracks, and residual stress. After a good choice of process parameters, the functional behavior is similar to conventional manufacturing. However, a heat treatment is needed to create the precipitates that provide the superelasticity, and then the oxidation caused needs to be removed by polishing or machining. For this reason, and because of the current limitations in machining and polishing complex parts, it is not possible to obtain the superelasticity feature in intricate geometries. Finally, there are also bibliographical references to nickel-, aluminum-, and cobalt-based superalloys. Two-thirds of these alloys are used in aeronautics to manufacture jet engines, and the remaining one third is used in the chemical, medical, and structural industries. These superalloys have unique properties of high-temperature resistance, hardness, and resistance to wear and corrosion. This fact is functionally very positive, but makes them very difficult to machine, as they have a low thermal conductivity that causes the heat to concentrate in the tool/workpiece and tool/chip contact zone, producing very high cutting temperatures and accelerating tool wear. In 2004, Ezugwu [26] carried out a state of the art of technologies developed during the preceding decade and applied to the machining of superalloys: self-propelled rotary tooling technology (SPRT), in which both the tool and the part to be machined are equipped with rotational movement, thereby reducing the tool–part contact time and increasing its useful life; high pressure coolant supply (HPCS), which introduces high-pressure coolant into the cutting zone to reduce its temperature in materials such as Inconel 718, and through which tool life was increased seven times; or more well-known cooling/lubrication strategies such as MQL, which is based on the use of a minimum amount of water-soluble oil, supplied to the cutting edge by compressed air, or cryogenic cooling (CC), that cools far below the softening temperature of the tool.

4. Conclusions

The aim of the study is not only to carry out a state of the art through a narrative analysis of the scientific literature associated with the subject, but also to analyze and understand, through a systematic review, the trends and needs of researchers in the area of lightweight structural materials associated with studies in the aeronautical and automotive sectors.

Sometimes, in investigations based on existing studies or existing literature, not all publications, studies, or articles offer the same guarantees of veracity, methodological quality, and interest. For this reason, this study applies a methodology adapted from the PRISMA statement to engineering for limiting possible biases in the selection and analysis of the literature. The final objective is to have the most relevant and representative articles of proven quality, applying clear and homogeneous inclusion and exclusion criteria, and carrying out an unbiased analysis of the information obtained to conclude the current trends in materials and manufacturing processes used. The key points of the methodology are: prior definition of quality and inclusion criteria to select the literature, search using Boolean equations based on the previously established criteria, the definition of the search engine, an initial preselection, subsequent review to obtain the final selection, and, finally, unbiased analysis based on closed and univocal questions on the final selection of scientific literature.

Based on the data extracted and analyzed, it can be concluded that, regarding structural lightweight materials, the materials that have attracted the most attention during the last six years are aluminum alloys, titanium alloys, and steels, which appear in 30% of the studies each, followed by FRPs in 23.3% of studies (a study may contain several materials). In an overall analysis of the last 20 years, the relevance of these materials is maintained, highlighting the importance of titanium alloys (29%), aluminum alloys and FRPs (27%), followed by steels (24%), magnesium alloys (11%), and nickel alloys (8%). Regarding the topics identified as the most trending and relevant topics, 30% of the studies published over the last six years include a hybrid or multi-material compound. In contrast, only 14% included a hybrid component or multi-material compound in the period of 2000–2014. Among these multi-material studies, the combination of metal + metal is the most studied recent combination, with 44.5% during the period of 2015–2020. In the analysis of the percentages, it is necessary to consider that a study may include several materials and topics in its research.

Regarding the origin of the studies published in the period from 2015 to 2020, the USA leads the number of selected studies with 20%, followed by the UK and China (17%), Australia (10%), Germany, Italy, France (7%), and India, South Africa, Japan, Switzerland, and Spain (3%). In addition, all the information obtained is summarized in tables to facilitate the search and interpretation, by interested researchers, of the articles with the highest average number of citations per year published during the periods analyzed, and their main characteristics are shown as follows: aluminum alloys, titanium alloys, FRPs, special alloys, hybrid or multi-material components, additive manufacturing, and the drilling process.

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