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REVIEW ARTICLE

Sustainable Applications for Disposal of Recycled Aluminum: A Systematic Literature Review Using the SciMAT Software

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Abstract

This review aims to carry out a scientific review of the current status of aluminum can recycling processes over the last 15 years, seeking to find sustainable applications for its destination. Thus, the research topics were defined by the identification of the structure of the scientific field of research and the relationship of aluminum recycling, casting processes, and formation of aluminum-based alloys, as well as their applications. Therefore, three topics were studied: the state of the art of aluminum recycling practices; processes being performed and aluminum casting techniques and methods; and the current state of formation of secondary aluminum-based alloys, the alloy elements being used, and their applications after the formation of alloys. Based on the above three topics, the research topics include (A) aluminum recycling, (B) casting processes, and (C) the formation of aluminum-based alloys and their applications. For bibliometric analysis, the software SciMAT was applied. Through the overlaid map and the evolution map, it was possible to detect the temporal evolution of the scientific field in the researched area. Cluster analysis allowed us to identify the motor words. Through the connections network, keywords connected to the motor themes were verified that indicated the connection areas of the research field and the main authors. The simulation models were factors of innovation in the area, as well as the software packages ANSYS and ProCAST. In the area of alloy formation, the liquid metal cleaning analyzer technique was highlighted in the production of high-quality alloys. The important connections to aluminum recycling feasibility are presented in this review.

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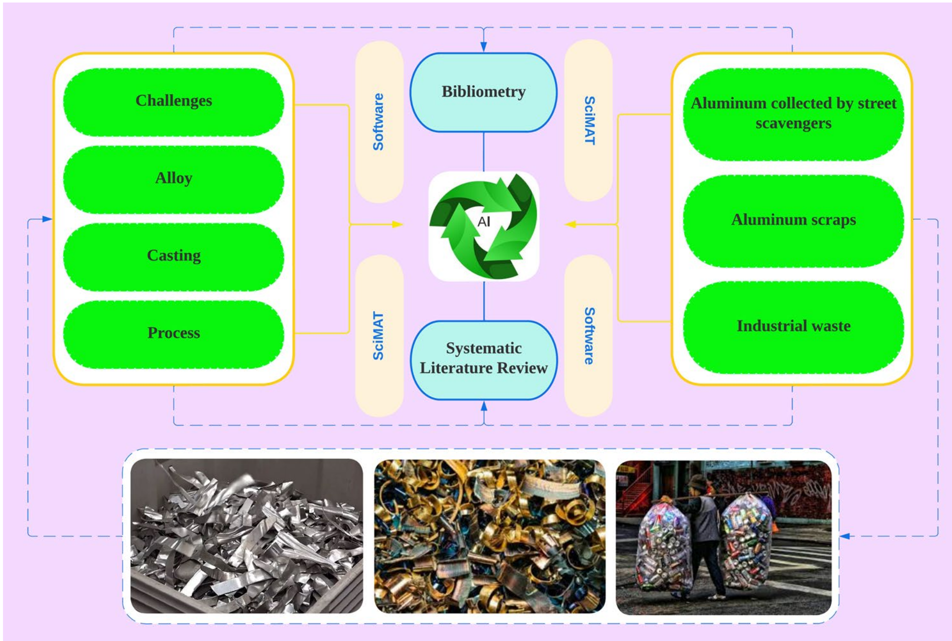
Graphical Abstract



Keywords Aluminum recycling · Sustainable applications · Aluminum casting · Aluminum alloys · SciMAT

Abbreviations

CA	Cellular automaton
CAP	Casting adjusted pressure
CDC	Casting and coupling stirring direct chill
CMP	Chemical polishing model
DC	Direct chill
ICME	Integrated computational materials engineering
LiCMA	Liquid cleaning metal analyzer
NDC	Normal direct chill
SLR	Systematic literature review
SciMAT	Science mapping analysis tool
VAC	Virtual aluminum casting

Introduction

Scientific studies focused on aluminum recycling have relevance to the industry and to the general population. The innovations in this area provide new solutions for materials applications in addition to opportunities for recycling in urban centers that provide the return of these materials to the production chain as a raw material of mode sustainable. In this process, there are positive impacts with decreased energy consumption, which reduces greenhouse gas emissions because it avoids further extraction of ore from the crust of the Earth and promotes the sustainability of the environmental.

In 2010, based on the analysis of secondary aluminum reserves in 19 countries, there were mainly 85 million tons in the USA, 65 million tons in China, 29 million tons in Japan, and 413 million tons worldwide. In the USA, the estimates were that their secondary reserves would be larger than their primary reserves and that considerable amounts of secondary aluminum materials were still accumulating in landfills [1].

During recycling, an aluminum slag is formed. This industrial waste is harmful to humans and the environment; direct and indirect recycling, strategies for the recovery of these residues and methods for the management and reuse of these materials are recognized as being relevant [2]. An aluminum salt slag is formed during aluminum residue smelting, which contains 15–30% aluminum oxide, 30–55% sodium chloride, 15–30% chloride potassium, 5–7% metallic aluminum, and impurities, such as carbides, nitrides, sulfides, and phosphides. Its disposal in landfills is prohibited in most European countries and must be managed in accordance with current legislation. Depending on the crude mixture, the amount of slag can vary from 200 to 500 kg per ton of secondary aluminum [3].

Conventional recycling by remelting aluminum and light alloy chips also requires study because it can be replaced by solid-state recycling techniques that convert chips directly into dense bulk materials and provide several advantages, such as energy reduction, decreased metal losses, and decreased harmful gas emissions. The mechanical properties of samples, which depend mainly on the chips quality and the microstructure of the bulk materials, are important for the improvement of solid-state recycling techniques and the future prospects for the recycling processes [4].

Holzschuh et al. [5] explored different compositions of recycled materials. Recycled aluminum with primary aluminum, rice husk ash, magnesium, and copper was melted through the gravity casting process and drained into a mold. Ashes from rice husk, magnesium, and copper were added to the ingot to produce a metallic matrix that was characterized by several techniques. The inclusion of rice husk ash into molten aluminum was analyzed using scanning electron microscopy, density analysis, and Brinell hardness and Charpy impact force testing. The metallic matrix formed by the methodology that involved varying the addition parameters and metal incorporation appeared feasible for several industrial applications.

In general, in aluminum recycling process from the use of refuse until the smelting process, there have been innovations and new trends as well as the evolution of scrap pretreatments, such as sorting, crushing, and dismemberment. The casting technologies, operating conditions, and the relationship between the cost and efficiency of casting and furnace operations are also relevant to ensure the development of improved aluminum recycling processes with low economic and environmental impacts [6].

In this context, a review about sustainable techniques of aluminum recycling is important and can assist with decisions about process improvements. The research can be systematized with the help of bibliometric tools by Zupic and Čater [7], Cobo et al. [8], and Kipper et al. [9], the meta-analysis by Hermansson et al. [10], and results from a systematic literature review with SLR [11]. We consider that carrying out the synthesis of previous research is one of the essential tasks for technological advancements and the implementation of innovations. The qualitative approach of the review and the quantitative analysis can be complemented with scientific mapping methods that make the review accurate [7].

In this way, we aimed to recognize the current state of the art of secondary aluminum recycling, in particular, the recycling of aluminum cans from waste collection in the main urban centers of the world, contributing in a sustainable way and innovations in the reuse/recycling of this material. In addition, we sought to analyze aluminum casting by investigating smelting techniques, in which alloys are formed and applications are recommended due to alloy elements in the final product.

Methodology

For this study, SLR and bibliometric methods were used according to Kitchenham and Charters [12], Neto et al. [13], and Cobo et al. [14] evidence-based methods, and a bias of the revision was avoided. The qualitative and quantitative approach used explicit criteria with a search strategy defined in comprehensive sources [7, 9, 11, 15–18].

To identify the structure of the scientific field of research, three relevant research topics were defined: (A) aluminum recycling (i.e., the state of the art of aluminum recycling practices and processes), (B) casting processes (i.e., the processes being performed and aluminum casting techniques), and (C) the formation of aluminum-based alloys and their applications (i.e., the current state of formation of secondary aluminum-based alloys and the alloy elements that are being used as well as their applications after the formation of alloys).

The search period was limited to 15 years, considering that more than 60% of the published documents on aluminum recycling in the Scopus database occurred in this period, as shown in Fig. 1. Since 2011, research in the area has advanced considerably, but it experienced a slight decline in 2015. In 2016, the research increased and peaked in 2019.

The inclusion criteria applied to search for primary studies included the title, abstract, and keywords of the documents, as presented in Table 1.

SciMAT software was used as a research tool for the extraction and quantification of information. This software is free and offers treatments, algorithms, and quality and performance measurements for all stages of scientific mapping, from preprocessing to visualization of the results [9, 14].

During the preprocessing stage, which corresponds to the extraction and analysis of the data, the verification of duplicate items, words, and documents occurred, and

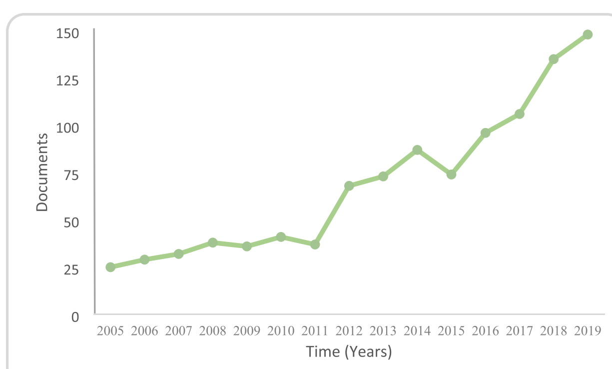


Fig. 1 Publications between 2005 and 2019 in the Scopus database using the keywords presented in Table 1

Table 1 Search strings used in the Scopus database and citation inventory to quantitative studies

Research topic	Search strings	Citation (primary documents)	Co-citation
A	"Aluminum recycl*" AND "Aluminum can*" OR "Aluminum reuse" OR "Aluminum reprocess*" OR "Process mapp*" OR "Recycl* process*" OR "Recycl* methods" OR "Recycl* techniques" OR "Identify process*"	67	763 documents cited 67 documents
B	"Aluminum Cast*" AND "Aluminum Can*" OR "Yield" OR "Process*" OR "Reprocess*" OR "Reuse" OR "Cast* Methods" OR "Aluminum Reprocess*"	857	3.962 documents cited 857 documents
C	"Aluminum Alloy" AND "Alloy formation" OR "Alloy production" OR "Alloy preparation" OR "Addition of metals" OR "Metal incorporation" OR "Metal inclusion" OR "Metal Melting" OR "Alloy Applications" OR "Alloy Purposes"	302	3.304 documents cited 302 documents

clusters as well as similar terms were formed. A total of 1182 documents remained in the data for processing. The analysis was performed based on the studies of Cobo et al. [14] and Kipper et al. [9]. In the first step, the documents were distributed into 5 subperiods (2005–2007; 2008–2010; 2011–2013; 2014–2016; 2017–2019). Then, in the second step, the unit analysis, considered the selected words and Autor's words. Subsequently, for the reduction of data methods, in the third step, the box was checked and a minimum frequency of two in each period was defined. In the step four, the selection of the matrix type to build the network was defined by co-occurrence.

Network reduction filters were applied in sequence due to the large number of identified words. For that, five step, only keywords with at least 3 associated documents were selected. The similarity between the keywords was assessed using the equivalence index by Callon et al. [19], six step, which calculates the bond strength between clusters [20]. For the criteria of cluster formation, seven step, a simple center algorithm was applied that demonstrated the strength of the link between the clusters; for the construction of the network, the configuration of the maximum and minimum size of the cluster was applied in 25 and 4 words, respectively [21]. To perform the document mapping, eight step, the following configurations were used: a core mapper and secondary mapper. For the nine step, as a quality measurement, the *h* index and sum citations indicator were applied. For longitudinal measurements of the maps, ten step, Jaccard's index was used to evaluate the map evolution, and to evaluate overlapping maps, the inclusion index was used.

Regarding the author selection, a new analysis wheel was carried out. The same 5 periods were selected in step one. In step two, the words button was selected, Author's words check box, in the data reduction method, a minimum frequency of 2 authors per cluster was considered. In step four, the type of aggregate coupling hue based on authors was selected. For the network reduction method (step five), a minimum value of 8 was used. In step six, as a normalization measure, an equivalence index was used.

For the formation of the cluster algorithm, we used the simple center algorithm with a minimum value of 10 and a maximum of 15 (step seven). In step eight, as a document mapping, a core mapper was used, step eight, and for the quality measure, the *h* index and the sum of citations in step nine were used. To conclude the analysis and define the measurement of the longitude map, the Jaccard's index and an overlay map for the inclusion index were used in step ten.

The issues detected were visualized using two different visualization instruments: a strategic diagram by He [22] and a thematic network [21]. For the discovery of thematic areas, the review was deepened, their temporal evolution was analyzed, and the mapping and identification of the research topics were completed. For the construction of thematic maps, the inclusion index was used. Finally, the contributions related to the research topics was assessed in a quantitative and qualitative way using the *h* index, which measures the number of published documents and the number of citations received in each document.

Results

Bibliometrics Data

After a general analysis, countries like the USA, Germany, and China and, to a lesser extent, Brazil, the Russian Federation, and Norway, appeared in the first three positions for aluminum recycling. The publication areas for aluminum recycling are highlighted in Materials and Mechanical Engineering, Materials Science, and Physics, followed by Environmental Engineering and Environmental Science.

For the periods, considering the statistical data provided by the SciMAT software, it was observed that the production was maintained over the two-year periods, indicating that the area was still in scientific development (Fig. 2).

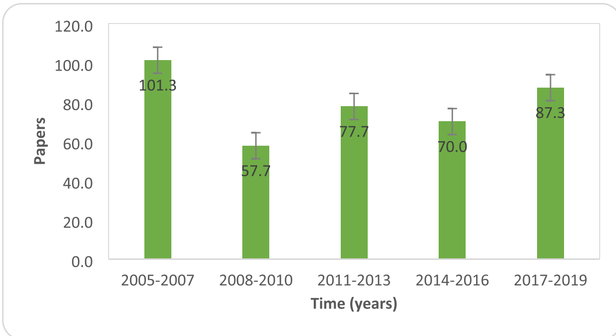


Fig. 2 Average and standard deviation of scientific production related to the three questions investigated, in a study related in periods according to the SciMAT software

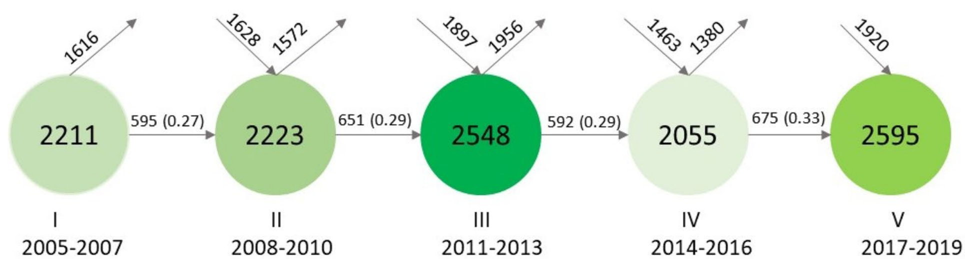
Figure 3 corroborates these values and considers the overlapping map with the evolution of keywords, in which the circles represent the number of keywords in the subperiod, the horizontal arrows represent the number of keywords shared between the subperiods and index of stability (%). The arrows converted to the circle or not correspond to the variation that occurred in the period, where the upper entry arrow represents the number of new keywords entering the period and the upper exit arrow represents the words displayed in that subperiod that are not mentioned in the next subperiod because they were discarded due to an innovation in the area [8, 9, 14].

Regarding the most relevant topics, the main line of research over the 15 years took place across the top line in Fig. 4 that highlights the main theme in the area according to subperiod. In the first subperiod, the research was focused on searching for aluminum alloys; in the second period, the word "aluminum" stood out as the focus.

In the third period, interest turned to aluminum smelting, and in the fourth and fifth periods, the concentration returned to research on aluminum alloys. It was noticed that from the third period onward, the word "Recycling" appeared with a continuous line, showing interest in its exploration. This interest remained in the fourth period and assumed a more important role in the fifth period, confirming that the interest of researchers in this area was linked to the formation of alloys, which was highlighted as the main theme.

For the longitudinal analysis of the thematic areas, an overlay map of the keywords was produced over the researched period. Figure 4 shows the evolution of keywords in the scientific field, represented by means of an overlaid map, with each subperiod highlighting the keywords that

Fig. 3 Overlapping map of keywords in each subperiod



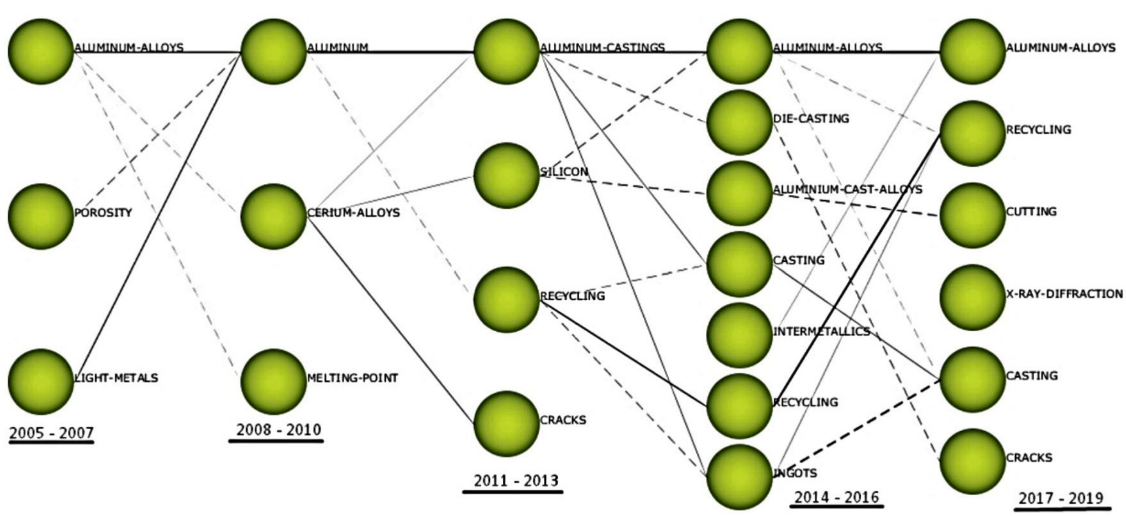


Fig. 4 Longitudinal evolution of the research field on the overlaid map of the studied periods, obtained in the SciMAT software

obtained the most citations. The lines connecting the keyword clusters represent the connecting force between the words, and the thicker the line, the stronger the relationship between the connected words.

For a detailed analysis in each research subperiod, the data were synthesized in the form of strategic diagrams for the research field (Fig. 5), which classified the clusters according to their centrality and density. Centrality measures the intensity of the links between a given cluster and other clusters. The more numerous and stronger these links are, the greater their importance for the research field. According to Callon et al. [19] and Cobo et al. [14], clusters are a necessary and essential crossing point for anyone interested in investing efforts in the associated clusters, directly or indirectly. The density provides a good

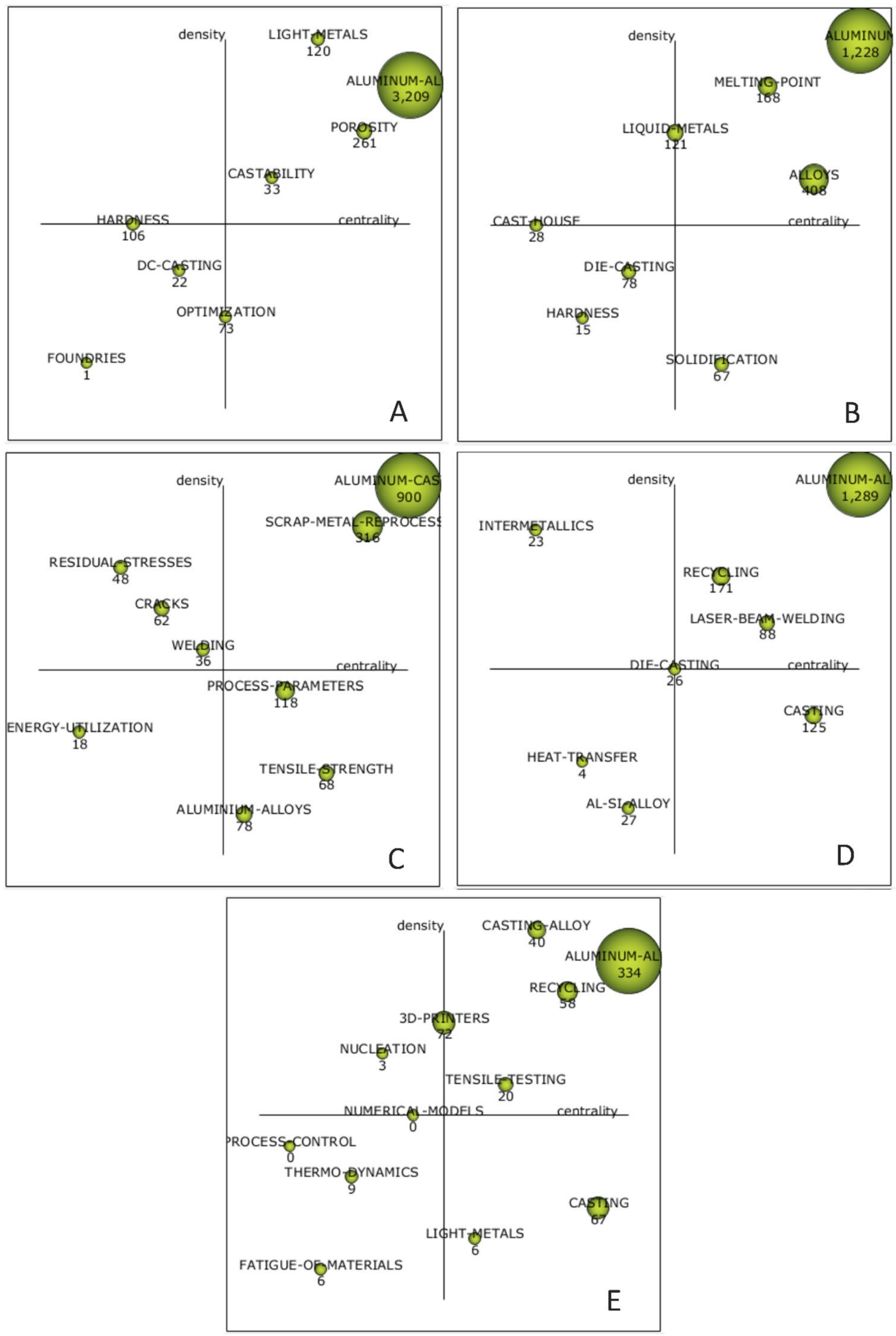


Fig. 5 Strategic diagram highlighting the engine theme in each of the 5 subperiods assessed, where **A** 2005–2007; **B** 2008–2010; **C** 2011–2013; **D** 2014–2016; and **E** 2017–2019

representation of the ability of authors to maintain and, over time, develop in the field of research.

The first research subperiod shown in Fig. 5A presented the word "aluminum alloy" as the motor theme with 3209 accumulated citations, an *h* index of 29, and citations in 225 documents. The words "Porosity" also appeared in the quadrant of motor themes along with "Light-Metals" and "Castability" with 261, 120, and 33 citations, respectively. This demonstrates that, although the main motor theme was "aluminum alloys," the researchers made combinations with these words in conjunction with the main word. For the second subperiod represented by Fig. 5B, "Aluminum" was highlighted as a motor theme (1228 citations) that was strongly linked to the themes "Alloys," "Melting Point," and "Liquid Metals," that presented 408, 168, and 121 accumulated citations, respectively, indicating that investigations regarding the formation of aluminum alloys occurred during this subperiod.

"Aluminum casting" with 900 citations in 152 documents stood out as the motor theme during the third subperiod, as shown in Fig. 5C, showing a strong connection with "scrap-metal-reprocessing" that was present in 316 citations in 42 documents and had an *h* index of 10. Thus, there was an increased level of aluminum waste and scrap. In Fig. 5D, "aluminum alloys" received 1289 citations in 152 documents with an *h* index of 16 and showed a strong connection with "recycling," "laser-beam-welding," and "die-casting." This connection demonstrates the interest in forming alloys using recycled materials, as well as in laser welding and pressure casting processes.

The alloys were again highlighted in the last subperiod, as shown in Fig. 5E, where they received 334 citations in 172 documents with an *h* index of 8. In the quadrant with the motor themes, the words "recycling," "casting alloy," "3D-printers," and "tensile-testing" had a strong connection with the motor theme, indicating research interest related to the formation of aluminum alloys, recycled materials, alloy casting, three-dimensional (3D) printing, and stress tests. In the lower right quadrant, the word "casting" stands out with 67 citations in 30 documents and an *h* index of 5, indicating the word as basic or transversal, where this word lost the connection with the motor themes of this subperiod.

Figure 6 shows an analysis of the main authors. These authors represent the theoretical reference base for the research that was carried out. According to the strategic diagram analysis, the three main authors in each three-year

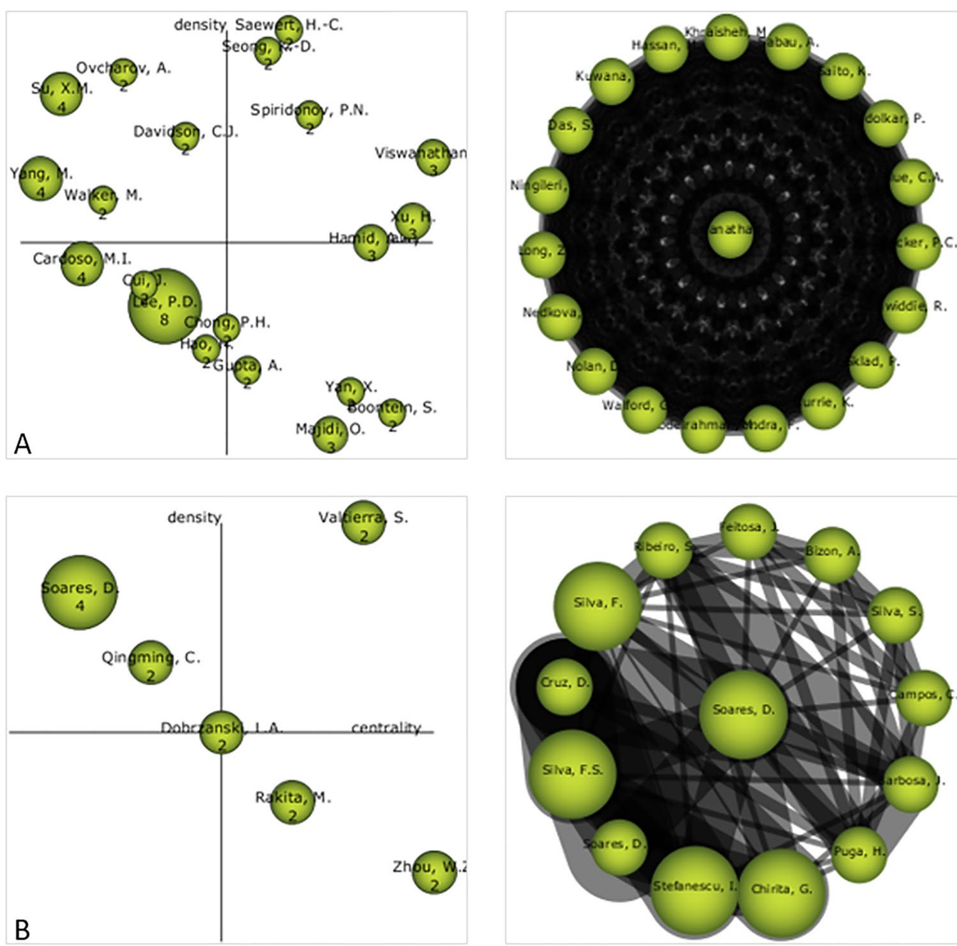
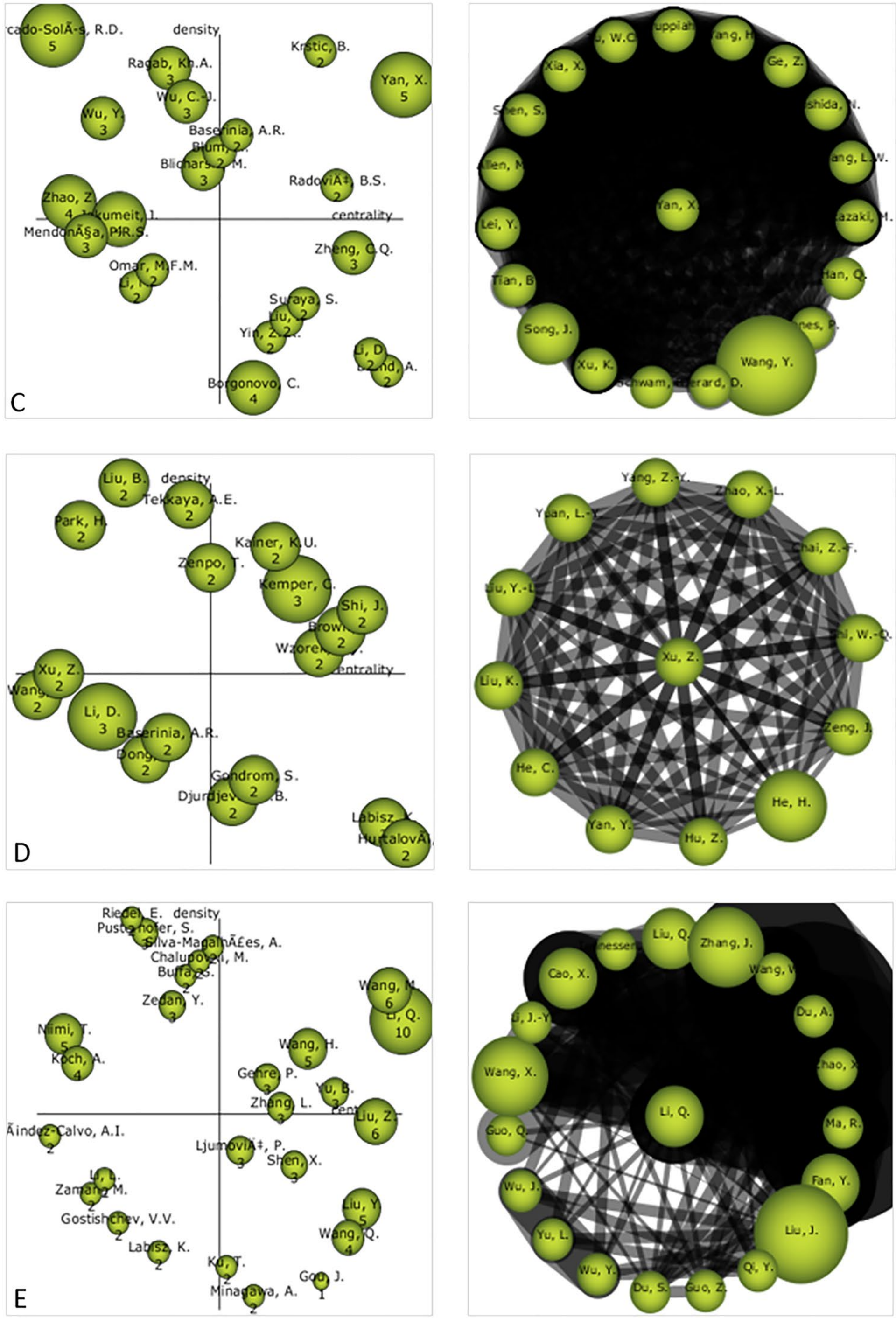


Fig. 6 Strategic diagram highlighting the authors in each of the 5 subperiods assessed, where **A** 2005–2007; **B** 2008–2010; **C** 2011–2013; **D** 2014–2016; and **E** 2017–2019

Fig. 6 (continued)



period were identified based on their position in the strategic diagram, the number of documents published in the subperiod, and their network of connections. Thus, the reference for the state of the art of the research was defined by the authors highlighted in each subperiod. In 6A, it is Viswanathan, S., Su, X.M., and Yang, M.; in 6B, it is Soares, D., Qingming, C., and Valtierra, S.; in 6C, it is Yan, X., Mercado-Solís, R.D., and Wang, Y.; in 6D, it is Yan, X., Mercado-Solís, R.D., and Wang, Y.; and in 6E, it is Li, Q., Wang, Y., Gehre, P., and Wang, H.

When analyzing the documents listed through a synthesis of the main authors, a strong relationship was observed among them; the authors that were cited in almost all analyzed subperiods were noticed, which indicated their importance and relevance in their research areas. In this sense, the following authors can be highlighted: Valtierra, S. Liu, B., Wang, Y., Wang, T., and Wang, H. as well Soares, D., Yan, X., Xu, Z., and Li, Q. These authors also share common areas of research, according to Table 2.

The author frequency can be observed in the timeline shown in Fig. 7.

Therefore, the basis of the SLR was shown, and then, we presented the state of the art about the initial issues considering the highlights in the periods, keywords, and authors.

State of the Art

Aluminum Casting

The casting process was studied by different techniques. Chirita et al. [48] presented the centrifugal effect on castings with functional reinforcement based on silicon particles. A solidification characterization was carried out at various points of the mold during casting. An analysis of the dynamics of the fluids inside the mold and the solidification behavior were verified in different parts of the component, as well as the phase distribution, shape of the silicon eutectic, and pore density. They compared the castings fabricated by the centrifugal casting technique and by the gravity casting technique and concluded that the centrifugal process did not influence the chemical composition throughout the casting; however, it interfered with the morphology and distribution of the phases. These effects were related to the solidification process during the nucleation stage. In addition, variables, such as the fluid dynamics and vibrations, can explain the difference in the metallurgical characteristics of the molten material.

Chirita et al. [49] again mentioned that the main variable that affects mechanical and metallurgical properties during the process is the fluid dynamics.

As to the factors that influence the process of filling in permanent molds with slit openings, Qingming et al. [53] developed a real-time X-ray image monitoring system to

Table 2 Common areas shared by the main authors of the period

Aluminum in the automotive sector	[23–28]
Process simulation, using computer systems and mathematical models	[29–39]
Specific applications in the formation of aluminum-based alloys with the inclusion of other elements, offering new alloy proposals	[40–47]
Casting processes, material development—analysis of microstructures and formation of grains and crystals of metallic structures demonstrated by optical microscopy, electron micrography, X-rays and chemical analysis, as well as physical and mechanical tests	[48–58]
Aluminum recycling	[59, 60]

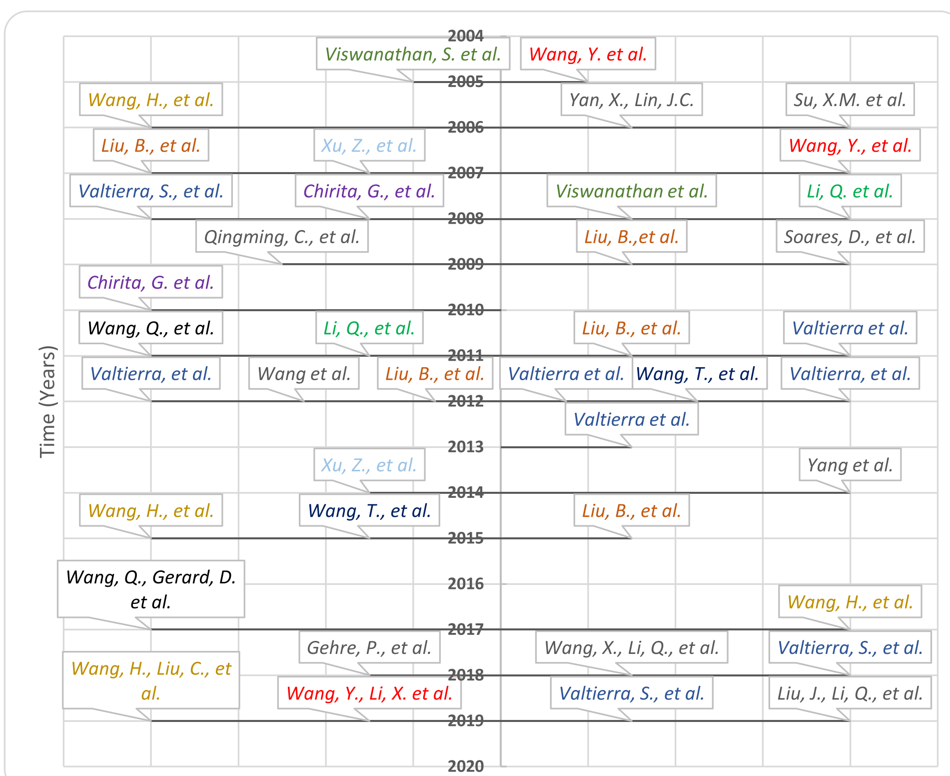


Fig. 7 Timeline of relevant authors in the research period

assess melt flow. Certain variables were identified, such as the dimensions, groove thickness, roughness of the mold coating layer, and the temperature at the top of the mold cavity during the flow of molten material. The control of the temperature gradient is considered to be fundamental during the casting and solidification processes as well as during the formation of the grains of the formed metal.

Casting of thin and complex aluminum walls can be carried out with ceramic molds and castings against gravity. A pressure adjustment is necessary to create a nonturbulent flow and clear contours in the melt during solidification and facilitate the shrinkage compensation during solidification [57].

In previous research, these authors Xu et al. [56] had already investigated pressure casting to determine the changes in the hydrogen content of molten aluminum in a casting under adjusted pressure (CAP). The proposal was to perform a new low-pressure casting process with degassing by using a pressure adjustment. They also studied the influence of the humidity in the air on the hydrogen content during cyclic pressurization under vacuum, which positively impacted the molten aluminum-refining process. Under the condition of dry compressed air, the hydrogen content can be maintained at a low level to facilitate the fabrication of castings with a low porosity.

Wang et al. [55] investigated aluminum thin walls using plaster molds combined with vacuum casting and solidification under pressure. They performed a multipoint control and optimized the casting time, casting position, mold temperature, and casting temperature. The resulting thin walls were considered according to the specification required for this material.

Li et al. [50] developed a double-roll aluminum electromagnetic casting system with an independently controlled three-phase AC/AC converter. Through harmonic analysis and real-time measurement, they verified that the electromagnetic system had complex and rich harmonic waves that could improve the quality of the samples. The spectrum analysis showed that the basic frequency of the current of each phase was half the frequency that provided central control. Metallographic analysis of the cast aluminum at a frequency of 1070 by an AC/AC converter indicated that the application of a converted electromagnetic AC/AC casting system can also achieve the same grain refining effect as an Al–Ti–B modifier, and the impurity elements were evenly distributed.

Li et al. [51] researched the effect of a solution treatment on the mechanical proprieties and microstructure of an AA7085 alloy compared to that on an AA7050 alloy. The results indicated that the high Zn content along with low Mg, Cu, Fe, and Si contents made the AA7085 matrix a single phase with an elevated melting temperature and multiphase eutectics. Using a pretreatment with a low temperature, the initial melting temperature of the alloy can be increased, and thus, the complete dissolution of the remaining constituents was achieved without overheating. With the elevation of the last temperature of the solution treatment, the matrix supersaturation degree and the cavity density were increased, which resulted in an increased fracture toughness and in the optimization of the microstructure after aging.

The application of a new coupling stirring DC casting process for large aluminum ingots was studied by Wang et al. [54]. Ingots comprising the 7075 alloy were produced by a normal casting process with direct cooling (NDC) and casting with direct cooling with coupling stirring (CDC). The effect of the method on the microstructure, composition segregation, and mechanical properties of the ingots indicated that the temperature variation during the CDC casting process was more uniform than that during the NDC casting process. The grains in the CDC ingots were finer and more spherical than the grains in the NDC ingots. The grain size at the edge, at 1/2 radius, and at the central position in the CDC ingot decreased by 28%, 22%, and 24%, respectively, compared to the grain size of the corresponding NDC ingot positions. Billets with an improved performance and decreased macro-segregation were obtained with the CDC process. The flow stresses and the difference in the positions of the DC ingots, measured in the thermomechanical simulator, decreased when an agitation technology was used.

Zhou et al. [58] evaluated the melt treatment by mixing a high-temperature melt with a low-temperature melt to refine a primary Al_3Fe compound. The experimental results proved that a fusion treatment could improve the morphology and refine the Al_3Fe. The alloy without fusion treatment was composed mainly of thick and long Al_3Fe needle-like structures that were poorly distributed and nonuniform. Furthermore, the uniformity and density of the microstructure were greatly improved. The results also suggested that an improved combination of high- and low-temperature melts existed. Temperatures that were too high led to coarse microstructures. The results of X-ray diffraction showed that the iron-rich compounds in the alloy with or without treatment were not changed and were still α-Al and Al_3Fe compounds. The main reasons for refining the microstructure included raising the nucleation rate and inhibiting the growth along the preferred orientation.

The effect of the initial microstructure of the A356 alloys through the mechanical behavior in the semisolid state was evaluated by Ning et al. [52]. A wide range of initial microstructures from a very thick dendritic structure to a fine globular structure was considered. These microstructures were produced in an A356 alloy using the method of controlled nucleation where the temperature of the flow was monitored during solidification. Materials produced with low overheating exhibited a fine globular structure; they presented a very low compression stress in the semisolid state compared to materials cast at high temperatures, which had a thick and dendritic structure.

Aluminum Alloy Formation

Alloy formation was widely explored by several authors in the last 15 years. Aluminum-based alloys offer several possibilities and variations, enabling applications in many areas. Al–Si alloys were one of the most studied alloys. Wang et al. [44] analyzed Al–Si alloy fabrication using the carbothermal smelting process of aluminum ore. The formation of impurities, such as iron, manganese, magnesium, and chromium oxides, were observed, but these impurities were removed through the filtration temperature control.

To improve the properties of the aluminum alloy based on Al–Si, Mohamed et al. [41] analyzed the influence of the addition of tin on the microstructure and mechanical properties in Al–Si–Cu and Al–Si–Mg alloys. Tin caused variations in the ductility and toughness of the alloys; however, it did not affect the resistance to flow and mainly impacted the stress–strain state in the matrix.

Canales et al. [40] also tested the mechanical properties of an Al–Si–Cu alloy that was fused and heat treated. The Si content was 5–11%, Fe was 0.3–0.8%, Cu was 3.1–3.5%, Mn was 0.4–0.45%, and Mg was 0.27–0.32%. The mechanical properties were affected to a larger extent by the microstructural refinement than by the amount of silicon added. Heat treatment increased the yield and tensile strengths but reduced the ductility of the material.

The liquid metal cleaning analyzer (LiMCA) technique was used by Samuel et al. [42] to produce high-quality cast aluminum, where cleaning by melting implies a relationship between the performance and quality of the product in addition to the inclusions in the molten metal. Therefore, the LiMCA technique was employed to investigate the ability to measure inclusions, such as Al_2O_3, Al_4C_3, MgO, CaO, TiB_2 and $TiAl_3$, that are normally found in aluminum alloys. The technique captures clusters of TiB_2 in the probe tube, which measures these clusters without clogging the filters. This is unlike other techniques, where clogging occurs and the measurements are interrupted. Thus, the LiMCA technique is recommended since Al–Ti–B alloys are used regularly for the refining of aluminum-based casting alloys.

Xu et al. [45] evaluated the use of Ti and Co as a wetting layer to fill the aluminum gap and evaluate the impacts of resistivity on the alloy. A chemical mechanical polishing (CMP) model was used in the aluminum. The model provided clear guidance for the selection criteria for the wetting layers, optimization of the deposition process, and consumption design.

A radio-frequency (RF) plasma synthesis system was designed as a high-temperature source to produce Al_2O_3 with 99.95% of the purity of the powder. The production was from aluminum cast slag and the results indicated the potential for commercialization [46].

Wang et al. [43] investigated the effect of adding Si on the stability of the Al–10Ti–5Cu–*x*Si interface. The SiC and Al–10Ti–5Cu–*x*Si alloys were compacted to obtain a stable interface with a 10% Si load. An analysis of the processing conditions and microstructures indicated that an excellent Ti_3SiC_2 phase was formed and the Al_4C_3 phase, which is a harmful substance, was successfully eliminated by adding a 10% Si load to the Al–10Ti–5Cu alloy. The formation of Ti_3SiC_2 initially increased and then decreased, while the formation of Al_4C_3 was gradually inhibited by the Si content. The Ti_3SiC_2 had good chemical stability and flexibility; however, Al_4C_3 deteriorated in a few days in composites exposed to environmental conditions. The presence of Ti_3SiC_2 at the interface and the elimination of Al_4C_3 improved the bonding of the Al–10Ti–5Cu–*x*Si alloy to SiC, thus improving the interfacial stability of the Al–10Ti–5Cu–*x*Si/SiC.

In a similar structure, the microstructure and properties of Al–Ga alloys with different Mg/Sn ratios were studied by Zhang et al. [47]. The degradability of Al–Ga alloys has a potential application in oil and gas fields, where their use is restricted by a low strength and expensive cost. The rate of controlled degradation, an adequate compressive strength and a low cost are the crucial issues to be overcome for the application of Al–Ga alloys to components in oil and gas fields. Multielement Al–Mg–Sn–Ga alloys with different Mg/Sn ratios were prepared in an electric melting furnace. The results indicated that the Al–Mg–Sn–Ga alloys consisted mainly of an Al matrix phase and a Mg_2Sn phase. With an increase in the Mg/Sn ratio, the content of the Mg_2Sn phase gradually increased, accompanied by the morphological conversion of the Mg_2Sn phase from an irregular block to a petal-like structure. The Al_3Mg_2 phase appeared when the Mg/Sn ratio was greater than 2/1. In addition, when the Mg/Sn ratio in the Al–Mg–Sn–Ga alloy increased from 1/4 to 3/1, the corresponding hardness improved from HV 64.9 to HV 152, and the compressive strength increased to 540 MPa from 382 MPa, respectively.

Recycling Materials

The inclusion of recycled and secondary materials was explored by several research groups [61–66]. The incorporation of aluminum shavings from machining chips within a foundry plant was carried out, and the efficiency of the recycling depended on the conditioning of the material, melting technique, and treatment methodology of the melted metals. In addition, minimum rates of slag formation and utilization of approximately 90% of the recycled material without the use of salts and scorifying flows was possible [59].

Wei et al. [60] conducted a review of recycling aluminum alloy waste. Due to their low density, high strength, good corrosion resistance, and other excellent properties, aluminum alloys have become the second most commonly used metal material. In recent years, increasing attention has been given to recycling aluminum alloy waste, which not only effectively alleviates the global scarcity of bauxite resources but also contributes to the sustainable development of the economy. In the aerospace industry, there are high performance requirements for aluminum alloys, and aluminum alloys used for aerospace applications contain many types of alloy elements and have a high recycling value. With decades of research and exploration, there are still problems that limit recycling, such as unstable product quality, high burning rate, and severe oxidation. The technologies of heavy-medium separation, fusion of double-chamber furnaces, metamorphic treatment equipment, and laser reading equipment were successively developed.

Recently, the production of alloys with recycled aluminum from cans that incorporate rice husk ash, magnesium, and copper was studied with excellent results and demonstrated potential for use. The results showed the use of 52% (w/v) cast aluminum cans. Due to the incorporation of rice husk ash (RHA), there was a reduction in the density of the melt, but the hardness of the formed alloy increased (23%). In addition, this increase in the addition of RHA decreased the fragility of the material, according to Charpy impact force analysis [5].

A summary of the commonly used aluminum alloy types, the equipment, and technologies used in the recycling process, including pretreatment, reflow regeneration, and refining, is shown in Fig. 8. The main authors associated with aluminum alloy residue pretreatment are also associated aluminum casting [48–58] aluminum recycling [5, 59, 60] automotive boards [23, 25–27], and especially aluminum alloys [34, 40–47].

According to Wei et al. [60], the material previously selected by the pretreatment phase proceeds to the casting process. Casting occurs individually by the type of material, generating secondary aluminum ingots according to the properties of the recycled material. Figure 9 presents the casting process diagram.

Proposals for Applications in the Automotive Sector

The automobile sector is the target of research by several authors, and we detected research that presented solutions involving the production of cast aluminum alloys.

Han et al. [27] developed a technology for the production of aluminum alloy inserts reinforced with the addition of steel, nickel, and copper in addition to steel, nickel, and silver. The authors performed a push-out experiment that indicated improved results in terms of the strength and prevented direct contact between the aluminum and steel; however, during the casting process, undesirable phases formed. González et al. [26] evaluated the fatigue strength of an aluminum alloy removed from engine blocks. The stress-compression tests indicated that the fatigue cracks originated in the pores, where they started cracking below a nominal stress of 120 MPa.

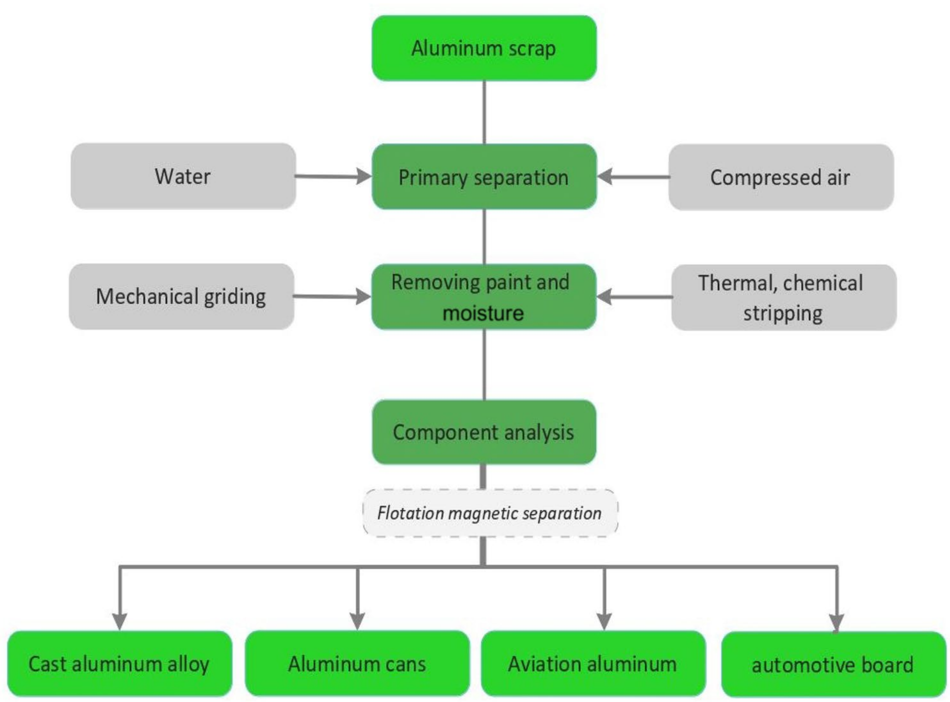


Fig. 8 Aluminum scrap scheme

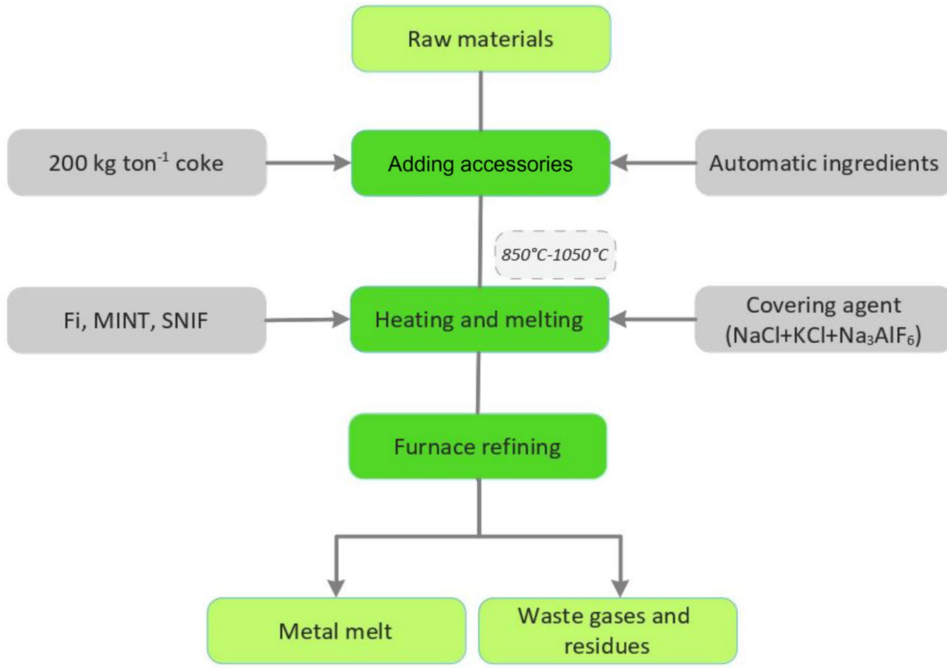


Fig. 9 Remelting regeneration process diagram of the waste aluminum alloys according Wei et al. [60]

Similarly, Carrera et al. [23] analyzed the influence of the quenching rate on the residual stresses in engine blocks. The aluminum cast used a gray iron coating to provide wear resistance in the block holes. The smelting process occurred with the iron coating addition before the liquid aluminum was drained into the cavity. Residual stresses were produced by the difference in the thermal expansion of the iron and aluminum due to different cooling rates being used and were measured by tension meters.

Carrera et al. [24] studied the residual stresses in cast aluminum complexes and the working conditions in the combustion chamber of engine blocks, which forced the use of a liners capable of resisting the pressure and wear caused by the pistons. In this process, the gray iron coating was inserted after the engine block solidified and molded into the block. Depending on the geometry and size of the part, the stresses can be over 150 MPa.

The fatigue resistance was important in the investigations. González et al. [25] predicted the failure cycles that molten aluminum was able to sustain in the engine bulkheads. They also pointed out that cracks occurred in the pores located near the surface of the samples and concluded that resistance to fatigue was affected by microstructural refining. Wang et al. [28] presented the latest advances in cast aluminum parts in structural automotive applications. They reviewed technologies for alloy design, fusion processes, fusion treatments, casting processes, and heat treatments. The robust development of high-integrity aluminum parts was accomplished with the integrated component materials of engineering (ICME) computational approach.

Proposals for Computational and Simulation Models

Simulations using computational models were shown to be representative in the area of casting processes and formation of aluminum-based alloys. The prediction of defects, such as cracks, during the casting process was researched by Long et al. [32], and they achieved results consistent with the cracking index that was established based on the stress/strength ratio in a hot melt of an ingot. Likewise, Allison et al. [29] carried out an integrated approach between materials and component engineering (ICME) in addition to using virtual aluminum casting techniques (VAC) that were implemented at the Ford Motor Company, where they demonstrated the feasibility and benefits of manufacturing processes for engine blocks that pushed aluminum alloys to the limit of their capacities.

Yan and Lin [39] evaluated the predictability of the tendency to hot break for multicomponent aluminum alloys. The calculation interface of the multicomponent phase balance has been extended to models of higher-order systems. The results of the simulations were correlated with experimental results and proved this efficiency. The use of simulation forecasting systems using an ICME approach was used by Gu et al. [30] employing 3D models based on cellular automation (CA). It was developed to predict the grain size of components produced by aluminum die-casting. ProCAST molding process simulation software based on finite elements was used. The tool verified the grain morphology, density, and size by CA modeling. The simulation results were validated by experimental results, and its use in the development of aluminum castings was recommended.

Xu et al. [38] also applied CA modeling; however, they applied a modified simulation model to the microstructural evolution of aluminum alloy castings. The diffusion of solutes in the liquid and solid phases was also considered in the development of a grain growth model. With the models developed, not only the grain structure but also the dendritic microstructure could be predicted during the solidification process.

Liu et al. [67] studied the dendritic morphology of magnesium and aluminum alloy solidification process using cellular automata and phase field methods, mathematical models for the segregation of large steel ingots and microstructural models for the casting of unidirectionally solidified turbine blades.

In the computational tools used for virtual casting, the cast aluminum requires an improved quality and reliability and a quantifiable performance. The effort was dedicated to the development of robust and accurate computational models, where numerous modeling and simulation techniques could be applied in the practice of aluminum casting and subsequent processing, allowing designers and engineers to develop the components obtained by aluminum casting with minimal costs [35]. The Bayesian analysis method was applied in the optimization of permanent casting mold design. Therefore, the use of statistical methods was applied to measure the effects of mold designs and the operational parameters of the casting process on mechanical properties [37].

A contraction defect model related to the feed flow of aluminum castings was also evaluated [33]. A 3D model was developed and predicts the formation of contraction defects associated with the continuous phenomena in interaction. The model solves the macroscopic conservation equations coupled to the mass, moment and energy with a phase change during solidification. This advanced retraction model was successfully experimentally validated using two Al–Si alloys, a eutectic alloy and a hypoeutectic alloy.

Before this, Liu et al. [68] reviewed the macro- and micro-solidification modeling method for aluminum castings. They used numerical methods to improve and understand on a computational scale the filling of the mold and the solidification of the aluminum alloy. The experimental results showed that the studied models feasibly describe the formation and evolution of the microstructure of the alloy.

Currently, there are analyses of the grain mechanism of the ultrasonic vibration depth in large-diameter aluminum ingots for hot casting. The test results of the solidified microstructure of an aluminum alloy ingot were confirmed by the results of a sound field simulation developed with a finite element software, such as ANSYS. Such software presented the mechanism of the microstructure refinement of the aluminum alloy ingot under different depths of vibration. In addition, with an increase in the vibrational depth of the supersonic radiation rod, the entire cross section of the ingot was refined, and the shape of the grain changed from developed dendrites to equiaxial dendrites. Due to the final faces of the ultrasonic radiation rod, there was a vibrational peak in the fixed position, which led to different ultrasonic cavities under different ultrasonic vibrational depths in the aluminum melt, corresponding to different mechanisms for refining the solidified structure [36].

With casting process simulation, Wang et al. [34] studied the criterion of statistical cracking of silica sand bonded to a resin. Crack mold/core sand can result in many casting defects. A robust cracking criterion is required to predict/control these defects. A crack probability map related to the fracture stress and effective volume was proposed for resin-bonded silica sand based on Weibull statistics. The results of three-point flexion tests of the sand samples were used to generate the crack map and establish a safety line for the crack criterion. The tension and deformation behavior and the effective volume of the molds for the samples were calculated using the ProCAST® finite element code. In addition, a fractographic examination by dispersive energy spectroscopy of the sand samples confirmed the cracking of the silica sand bonded to the resin.

Thus, there is a great possibility of exploring solutions using simulation environments and software, such as ANSYS, and applying numerical models as finite elements, Bayesian analysis, 3D models, as well as in the application of engineering models of computational materials integrated (ICME). Simulation models offer the possibility to conduct research without the need to involve test equipment or materials to carry out the experiments.

General Approach from Research Questions

According to the approach taken, we presented the solutions and innovations regarding the highlighted research priorities. In addition, for the state of the art, we address the production processes and aluminum recycling issues. Figure 10 presents the types of aluminum waste and types of casting processes that exist.

The specific approach to the recycling and casting of aluminum beverage cans was not highlighted in the state-of-the-art approach presented above. However, several important views were presented, which enable innovation in favor of sustainable aluminum recycling, as expected for the study of research topic A described in the methodology. Puga et al. [59] highlighted the reuse of aluminum chips from the metallurgical industry. They emphasized that recycling efficiency depends on the conditioning of the cast material, the melting technique, and the chips treatment methodology. In this industry, the recycled yield was approximately 90%, without the use of scorifying salts, resulting in minimum rates in the formation of slag.

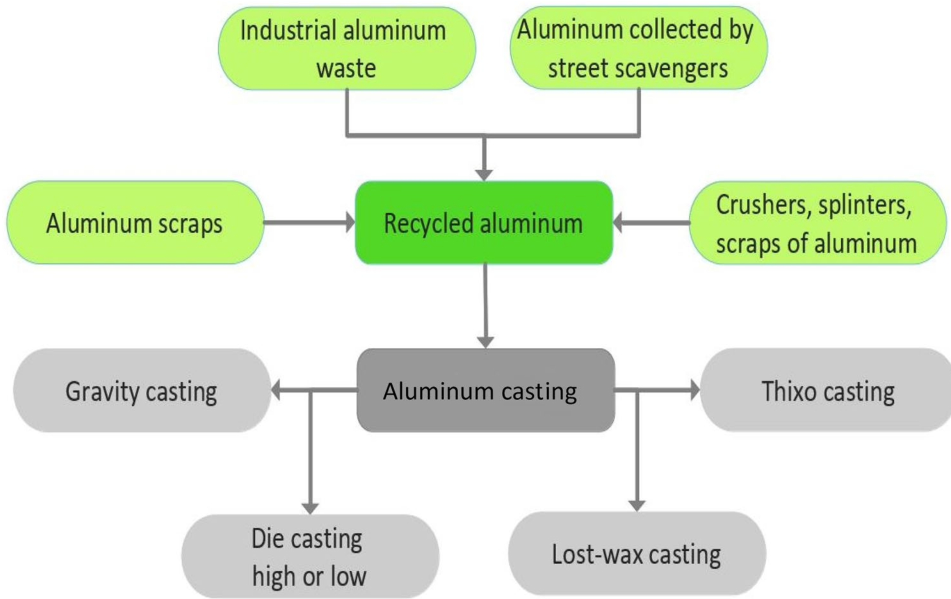


Fig. 10 Types of aluminum waste and types of casting processes

Aluminum recycling effectively alleviates the global scarcity of bauxite resources and contributes to sustainable development in the use of aluminum cans. Due to its low density and high resistance, aluminum alloys have become the second most explored metallic material. With decades of research and exploration, there are still problems that limit recycling, such as unstable product quality, high burning rate, and severe oxidation. Separation technologies therefore need to be developed [60].

Research topic B focused on the aluminum smelting processes, methods and techniques that are necessary to make aluminum exploitation feasible.

Chirita et al. [48] studied the centrifugal effects in castings with functional reinforcements based on silicon particles. Zeng et al. [57] proposed a manufacturing process for aluminum casting with thin and complex walls. In this research, they applied casting techniques against gravity. Xu et al. [56] studied the conditions to verify changes in the hydrogen content of molten aluminum during casting under adjusted pressure (CAP). In a new proposal, the same authors carried out a new low-pressure casting process with a degassing function that employed a pressure adjustment.

Likewise, Wang et al. [55] investigated the production of thin-walled aluminum castings using plaster molds combined with vacuum casting and solidification under pressure. Li et al. [50] developed an electromagnetic aluminum casting system using a double roller with an independently controlled three-phase AC/AC converter. Similarly, Li et al. [51] studied the effect of treating the staggered solution on the mechanical properties and microstructure of an AA7085 alloy and compared the results to those of an AA7050 alloy. In addition, Wang et al. [54] conducted the application of a new coupling agitation in the DC casting process for large aluminum ingots. Zhou et al. [58] evaluated the fusion treatment by mixing with low melting temperature to refine the primary compound of Al_3Fe. Ning et al. [52] evaluated the effect of the initial microstructure of A356 alloys on the mechanical behavior in the semisolid state.

Thus, throughout the research period, there were several attempts in the search for new casting technologies and processes to achieve advances in the casting area. Techniques have been proposed in the area of centrifugal casting, such as a technique against gravity, a technique under low pressure, and leakage methods involving thin walls, vacuum casting, and solidification under pressure.

Research topic C involved the current state of secondary aluminum alloy formation as well as applications after the formation of alloys. The formation of alloys from the use of secondary aluminum as a base still presents many possibilities for exploration. There are numerous possibilities in the area of metal alloy formation with aluminum as the basis for the alloy. The great challenge is to increase the possibilities of applying secondary aluminum and, in addition to the existing applications, to increase the percentage of secondary aluminum in the alloys. The research demonstrated several structures based on primary and secondary aluminum.

We highlighted an Al–Si alloy that was produced by carbothermic melting of aluminum ore by Wang et al. [44]; the influence of Sn addition on microstructural and mechanical proprieties in Al–Si–Cu and Al–Si–Mg by Mohamed et al. [41]; Al–Si–Cu melting alloys thermally treated by Canales et al. [40]; and high-quality casted Al purified by fusion and with inclusions by Samuel et al. [40]. The impact of the resistivity of an alloy was also analyzed, and the use of Ti and Co as a wetting layer to fill the gaps in the aluminum castings was explored [45].

The casting of aluminum from a slag using a radio frequency plasma produced a fine powder of Al_2O_3 that was studied by Yang et al. [46]. The effect of Si addition on the stability of the Al–10Ti–5Cu–*x*Si interface was evaluated by Wang et al. [43] and, similarly, Zhang et al. [47] presented the proprieties and microstructure of Al–Ga alloys with different Mg/Sn ratios.

Therefore, the formation of alloys was widely explored during the research period. The major obstacle is to expand the possibilities for recycling and reprocessing of secondary aluminum to form alloys. Optimization techniques were presented for the formation of alloys and the reduction of slag formation, which is a major concern during aluminum reprocessing.

It was also observed that recycling cans is rarely explored in research, although it is generally explored through the use of secondary aluminum. Indeed, these cans are directed to large recyclers, mixed with the other aluminum scraps, and melted in the same process. Table 3 presents a summary of the main perspectives and challenges in the aluminum recycling area.

Final Considerations

Several possibilities of sustainable applications and solutions for secondary aluminum transforming into new products were presented. Analysis was carried out regarding the longitudinal reach and evolution of the motor themes, the evolution of the publications of the authors who stood out in the research period, and the identification of the networks of connections of the authors with SciMAT. Authors and their relations with other researchers in the scientific community were investigated, providing a broad view in terms of the scope of the area.

The research topics were addressed initially through the keywords. The analysis period was established for the last 15 years of research. At the beginning of the studied period, there was a concentration of research on the topic of aluminum alloys addressed to research topic C (formation of aluminum-based alloys and their applications). In the same way, there was a concentration of research on the word "aluminum," showing the interest of researchers in the exploration of the metal, its physical and mechanical properties, and the conditions of metal fusion.

In the third subperiod from 2011 to 2013, the term “recycling” covered in research topic A (aluminum recycling) began to be investigated in the research field, gained importance in the following periods, and in the final period, was at the same level of significance as the keyword “alloy aluminum." This connection demonstrates a clear interest in the relationship of recycled aluminum to the formation of aluminum-based alloys and connected research topics A to C. Certainly, the keyword "casting" needs to be between recycling metals and forming alloys. The overlaid map demonstrates the relevance of the word “casting” by presenting compound words as connected motor themes. Thus, the keywords “aluminum casting” and “aluminum cast alloys” link

Table 3 Main challenges and perspectives in the area of recycling, casting, and forming aluminum alloys

Researches topics	Challenges
A Aluminum recycling	Improve recycling processes through sustainable technologies
	Increase ecological disposal topics in urban centers
	Increase of secondary aluminum use from casting process and eliminate the bauxite ore mining the earth's crust
	Improve reverse logistics processes in order to increase the return of materials for reuse and reprocessing
	Optimize pretreatment, separation and refining techniques so that production with higher quality occurs
B Aluminum casting process	Carry out casting processes in order to reduce the formation of slag, and thus increase the use of secondary aluminum
	Optimize energy consumption in smelting processes using renewable energies
	Reconcile the properties of aluminum with the casting processes, in order to improve its performance
	Use computational models and simulation and virtual casting in order to verify the most reliable and quantifiable performance of the casting process
C Formation of aluminum-based alloys	Increase the percentage of addition of secondary aluminum in the formation of metal alloys
	Evaluate new applications of metal alloys in order to increase the possibilities of adding secondary aluminum in the formation of alloys
	Conduct research with the aim of promoting the replacement of primary aluminum by secondary, encouraging sustainability
	Evaluate metals to add into of aluminum alloys, can improve its performance and quality of the formed alloy

these themes, proving that research topics A, B, and C are connected in the scientific field. This representativeness is also demonstrated through the connection networks of the motor theme in each studied subperiod.

The engine network connection tool was extremely important for the research. The motor word, highlighted in the center of the network, was connected by all the words that have research links, suggesting future search proposals for new research to be explored. Thus, it was possible to highlight the connections between "aluminum alloys" and "solidification," "microstructure," "metal melting." When the word "aluminum" was indicated as a motor theme, it demonstrated a strong relationship with "metal casting," "aluminum casting," "smelting," and "metal melting" and formed a combination of keywords that could be used to look for aluminum, the formation of alloys, and their properties. Research interested in aluminum smelting processes was also included in this SLR.

The scientific field of the keyword "aluminum casting" also demonstrated a network with the words "metal casting," "microstructure," "chemical properties," "solidification," "porosity," and "casting process." Therefore, it is recommended for future research connected to the melting area focused on the metal microstructure, chemical properties, solidification processes, cooling processes, pore formation in molten metal alloys, and casting process exploration.

It was possible to carry out an in-depth analysis by delving into the state of the art of the research topics. The term “aluminum” was highlighted as a central word connected to several areas of study. In this way, future research will be able to explore the field formed by aluminum and recycling processes that can be from diverse origins, such as machining chips, industrial waste, aluminum cans, and metals from urban recycling, as well as waste from the casting industry itself. It will not be possible to carry out such exploration, without making a connection with the casting processes, since the transformation of the metal goes through the casting processes. Naturally, the casting processes are connected with the alloying processes, including other metals, that form new compositions. These new compositions can be diverse and have similar applications. There are numerous possibilities for the use of metal alloys in commercial applications, the formation of new products, and improving the life cycle of materials.

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Declarations

Conflict of interest The authors declare no conflict of interest.

References

1. Maung KN, Yoshida T, Liu G, Lwin CM, Muller DB, Hashimoto S (2017) Assessment of secondary aluminum reserves of nations. Resour Conserv Recycl 126:34–41. https://doi.org/10.1016/j.resconrec.2017.06.016
2. Mahinroosta M, Allahverdi A (2018) Hazardous aluminum dross characterization and recycling strategies: a critical review. J Environ Manage 223:452–468. https://doi.org/10.1016/j.jenvman.2018.06.068
3. Tsakiridis PE (2012) Aluminium salt slag characterization and utilization: a review. J Hazard Mater 217–218:1–10. https://doi.org/10.1016/j.jhazmat.2012.03.052
4. Wan B, Chen W, Lu T, Liu F, Jiang Z, Mao M (2017) Review of solid state recycling of aluminum chips. Resour Conserv Recycl 125:37–47. https://doi.org/10.1016/j.resconrec.2017.06.004
5. Holzschuh GG, Dörr DS, Moraes JAR, Garcia SB (2020) Metal matrix production: casting of recycled aluminum cans and incorporation of rice husk ash and magnesium. J Compos Mater
6. Capuzzi S, Timelli G (2018) Preparation and melting of scrap in aluminum recycling: a review. Metals 8(4):24. https://doi.org/10.3390/met8040249
7. Zupic I, Čater T (2015) Bibliometric methods in management and organization. Organ Res Methods 18(3):429–472
8. Cobo MJ, Jürgens B, Herrero-Solana V, Martínez MA, Herrera-Viedma E (2018) Industry 4.0: a perspective based on bibliometric analysis. Proc Comput Sci 139:364–371. https://doi.org/10.1016/j.procs.2018.10.278
9. Kipper L, Bertolin Furstenau L, Hoppe D, Frozza R, Iespen S (2019) Scopus scientific mapping production in industry 40 (2011–2018): a bibliometric analysis. Int J Prod Res 10:1–24. https://doi.org/10.1080/00207543.2019.1671625
10. Hermansson F, Janssen M, Svanstrom M (2019) Prospective study of lignin-based and recycled carbon fibers in composites through meta-analysis of life cycle assessments. J Clean Prod 223:946–956. https://doi.org/10.1016/j.jclepro.2019.03.022
11. Thomé AMT, Scavarda LF, Scavarda AJ (2016) Conducting systematic literature review in operations management. Prod Plan Control 27(5):408–420. https://doi.org/10.1080/09537287.2015.1129464
12. Kitchenham B, Charters S (2007) Guidelines for performing systematic literature reviews in software engineering (Version 2.3)-EBSE Technical Report. Keele University and University of Durham. http://citeseerx.ist.psu.edu/viewdoc/summary?doi=10.1.1.117.471
13. Neto ACD, Subramanyan R, Vieira M, Travassos GH (2007) A survey on model-based testing approaches: a systematic review. In: Proceedings of the 1st ACM international workshop on Empirical assessment of software engineering languages and technologies: held in conjunction with the 22nd IEEE/ACM International Conference on Automated Software Engineering (ASE) 2007. ACM, Atlanta, pp 31–36. https://doi.org/10.1145/1353673.1353681
14. Cobo M, López-Herrera AG, Herrera-Viedma E, Herrera F (2012) SciMAT: a new science mapping analysis software tool. J Am Soc Inform Sci Technol 63:1609–1630. https://doi.org/10.1002/asi.22688

15. Donato H, Donato M (2019) Stages for undertaking a systematic review. Acta Med Port. 32(3):227–235. https://doi.org/10.20344/amp.11923
16. Dyba T, Dingsoyr T, Hanssen GK (2007). Applying systematic reviews to diverse study types: an experience report. In: First international symposium on empirical software engineering and measurement (ESEM 2007). IEEE, pp 225–234. https://doi.org/10.1109/ESEM.2007.59
17. Kitchenham B, Brereton OP, Budgen D, Turner M, Bailey J, Linkman S (2009) Systematic literature reviews in software engineering: a systematic literature review. Inf Softw Technol 51(1):7–15. https://doi.org/10.1016/j.infsof.2008.09.009
18. Sampaio R, Mancini M (2007) Systematic review studies: a guide for careful synthesis of the scientific evidence. Braz J Phys Ther 11:83–89. https://doi.org/10.1590/S1413-35552007000100013
19. Callon M, Courtial JP, Laville F (1991) Co-word analysis as a tool for describing the network of interactions between basic and technological research: the case of polymer chemistry. Scientometrics 22(1):155–205. https://doi.org/10.1007/bf02019280
20. Cobo MJ, Chiclana F, Collop A, de Ona J, Herrera-Viedma E (2013) A bibliometric analysis of the intelligent transportation systems research based on science mapping. IEEE Trans Intell Transp Syst 15(2):901–908. https://doi.org/10.1109/TITS.2013.2284756
21. Cobo MJ, López-Herrera AG, Herrera-Viedma E, Herrera F (2011) Science mapping software tools: review, analysis, and cooperative study among tools. J Am Soc Inform Sci Technol 62(7):1382–1402. https://doi.org/10.1002/asi.21525
22. He Q (1999) Knowledge discovery through co-word analysis. Library Trends - University of Illinois, vol 48, pp 133–159. ISSN: 0024-2594. http://hdl.handle.net/2142/8267
23. Carrera E, González A, Vázquez JL, Colás R, Valtierra S (2012) Influence of quenching rate on residual stresses in aluminum casting engine blocks. In: 70th World Foundry Congress 2012, WFC 2012, pp 314–317. ISBN: 978-162276382-5. http://www.scopus.com/inward/record.url?partnerID=HzOxMe3b&scp=84872543611&origin=inward
24. Carrera E, Rodríguez A, Talamantes-Silva J, Gloria D, Valtierra S, Colás R (2012) Study of residual stresses in complex aluminium castings. Int J Cast Metals Res 25(5):264–269. https://doi.org/10.1179/1743133612Y.0000000028
25. González R, González A, Talamantes-Silva J, Valtierra S, Mercado-Solís RD, Garza-Montes-De-Oca NF, Colás R (2013) Fatigue of an aluminium cast alloy used in the manufacture of automotive engine blocks. Int J Fatigue 54:118–126. https://doi.org/10.1016/j.ijfatigue.2013.03.018
26. González R, Martínez DI, González JA, Talamantes J, Valtierra S, Colás R (2011) Experimental investigation for fatigue strength of a cast aluminium alloy. Int J Fatigue 33(2):273–278. https://doi.org/10.1016/j.ijfatigue.2010.09.002
27. Han Q, Viswanathan S, More KL, Myers MR, Warwick MJ, Chen YC (2008) Bonding of steel inserts during aluminum casting, TMS 2008 Annual Meeting Supplemental: Materials Processing and Properties. New Orleans, vol. 3, pp 339–344. ISBN: 978–087339718–6. http://www.scopus.com/inward/record.url?partnerID=HzOxMe3b&scp=51649102524&origin=inward
28. Wang Q, Jones P, Wang Y, Gerard D (2017) Latest advances in aluminum shape casting. SAE Technical. https://doi.org/10.4271/2017-01-1665
29. Allison J, Li M, Wolverton C, Su X (2006) Virtual aluminum castings: an industrial application of ICME. JOM 58(11):28–35. https://doi.org/10.1007/s11837-006-0224-4
30. Gu C, Lu Y, Cinkilic E, Miao J, Klarner A, Yan X, Luo AA (2019) Predicting grain structure in high pressure die casting of aluminum alloys: a coupled cellular automaton and process model. Comput Mater Sci 161:64–75. https://doi.org/10.1016/j.commatsci.2019.01.029
31. Liu X, Li K (2011) Simulation of the dendritic growth of aluminum casting during solidification based on CA method. In: 2010 international conference on advances in materials and manufacturing processes, ICAMMP 2010. Shenzhen, pp 376–380. https://doi.org/10.4028/www.scientific.net/AMR.154-155.376
32. Long ZD, Han Q, Viswanathan S, Ningileri S, Das SK, Kuwanan K, Hassan MI, Khraishen M, Sabau A, Saito K (2005) Integrated 3D model to simulate solidification and predicate hot cracking during DC casting of aluminum alloys, pp 1057–1062 in Light Metals 2005 (Warrendale, Penn.: The Minerals, Metals & Materials Society). ISBN: 978-087339580-9. http://www.scopus.com/inward/record.url?partnerID=HzOxMe3b&scp=23244454975&origin=inward
33. Reis A, Xu Z, Tol RV, Neto R (2012) Modelling feeding flow related shrinkage defects in aluminum castings. J Manuf Processes 14(1):1–7. https://doi.org/10.1016/j.jmapro.2011.05.003
34. Wang H, Lu Y, Ripplinger K, Detwiler D, Luo AA (2016) A statistics-based cracking criterion of resin-bonded silica sand for casting process simulation. Metall Mater Trans B 48(1):260–267. https://doi.org/10.1007/s11663-016-0865-9
35. Wang Q, Jones P, Wang Y, Gerard D (2011) Advances in computational tools for virtual casting of aluminum components. In: 1st world congress on integrated computational materials engineering, ICME. Seven Springs, pp 217–222. https://doi.org/10.1002/9781118147726.ch30
36. Wang Y, Li XQ, Li RQ, Tian Y (2019) Fine grain mechanism of ultrasonic vibration depth in large diameter aluminum ingot hot-top casting. Gongcheng Kexue Xuebao 41(1):96–103. https://doi.org/10.13374/j.issn2095-9389.2019.01.010
37. Wang Y, Schwam D (2012) Application of bayesian analysis method in the design optimization of permanent casting mold, ASME 2012 International Mechanical Engineering Congress and Exposition, IMECE 2012, PARTS A, B, AND C ed., Houston, pp 17–21. https://doi.org/10.1115/IMECE2012-86413
38. Xu Q, Li B, Liu B (2009) Application of microstructure simulation by modified CA method to Al alloy casting production. In: 4th international conference organised by the CAST CRC, on behalf of the global light metals alliance. Gold Coast, pp 199–202. https://doi.org/10.4028/www.scientific.net/MSF.618-619.199
39. Yan X, Lin JC (2006) Prediction of hot tearing tendency for multicomponent aluminum alloys. Metall Mater Trans B 37(6):913–918. https://doi.org/10.1007/BF02735013
40. Canales AA, Carrera E, Silva JT, Valtierra S, Colás R (2012) Mechanical properties in as-cast and heat treated Al-Si-Cu alloys. Int J Microstruct Mater Prop 7(4):281–300. https://doi.org/10.1504/IJMMP.2012.048518
41. Mohamed AMA, Samuel FH, Samuel AM, Doty HW, Valtierra S (2008) Influence of tin addition on the microstructure and mechanical properties of Al-Si-Cu-Mg and Al-Si-Mg casting alloys. Metall Mater Trans A 39(3):490–501. https://doi.org/10.1007/s11661-007-9454-5
42. Samuel AM, Doty HW, Valtierra S, Samuel FH (2018) Metallurgical aspects of inclusion assessment in Al–6%Si casting alloy using the LiMCA technique. Int J Metalcasting. 12(3):643–657. https://doi.org/10.1007/s40962-017-0203-2
43. Wang W, Du A, Zhao X, Fan Y, Wang X, Ma R, Cao X, Li Q (2018) Effect of Si addition on the stability of Al-10Ti-5Cu-xSi alloy/SiC interface. Compos Interfaces 25(9):761–770. https://doi.org/10.1080/09276440.2018.1439627
44. Wang Y, Yang M, You J, Zheng W, Di Y, Feng N, Ma S (2007) Study of making casting grade Aluminum-silicon alloy with coarse aluminum-silicon alloy produced by carbothermal reduction of aluminous ore, TMS 2007 Annual Meeting and Exhibition. Orlando, pp 477–482. ISBN: 978-087339659-2. http://www.

scopus.com/inward/record.url?partnerID=HzOxMe3b&scp=34547922094&origin=inward
45. Xu K, Wang Y, Shen SH, Xia X, Tu WC, Karuppiah L, Yang H, Ge Z, Lei Y, Allen M, Yoshida N, Chang LW, Liu B, Okazaki M, Brand A (2012) Aluminum alloy formation and impacts in advanced replacement metal gate process. In: 20th international materials research congress, IMRC 2011. Cancun, pp 107–115. https://doi.org/10.1557/opl.2012.113
46. Yang S-F, Wang T-M, Shie Z-YJ, Jiang S-J, Hwang C-S, Tzeng C-C (2014) Fine Al_2O_3 powder produced by radio-frequency plasma from aluminum dross. IEEE Trans Plasma Sci 42(12):3751–3755. https://doi.org/10.1109/TPS.2014.2333543
47. Zhang J, Liu J, Li Q (2019) Microstructure and properties of Al-Ga alloys with different Mg/Sn ratios. Xiyou Jinshu 43(6):592–597. https://doi.org/10.13373/j.cnki.cjrm.XY18060008.html
48. Chirita G, Stefanescu I, Soares D, Cruz D, Silva FS (2008) Centrifugal casting features/metallurgical characterization of aluminum alloys. In: 9th international conference on multiscale and functionally graded materials, FGM IX. American Institute of Physics Inc., Oahu Island, pp 598–603. https://doi.org/10.1063/1.2896847
49. Chirita G, Stefanescu I, Soares DF, Silva FS (2010) On the ability of producing FGMs with an AlSi12 aluminium alloy by using centrifugal casting. Int J Mater Prod Technol 39(1/2):30–43. https://doi.org/10.1504/IJMPT.2010.034258
50. Li Q, Wu Y, Deng H, Mao D (2008) Harmonic analysis of electromagnetic casting system. In: 7th world congress on intelligent control and automation, WCICA'08. Chongqing, pp 691–696. https://doi.org/10.1109/WCICA.2008.4593005
51. Li CM, Chen ZQ, Zeng SM, Cheng NP, Geng ZH, Li Q (2011) Effect of stepped solution treatment on microstructure and properties of AA7085 aluminum alloy, 2011 International Conference on Chemical Engineering and Advanced Materials, CEAM 2011. Changsha, pp 786–792. https://doi.org/10.4028/www.scientific.net/AMR.239-242.786
52. Ning Z, Wang H, Sun J (2006) The effect of initial microstructure of A356 alloys on the mechanical behavior in the semisolid state. In: 9th international conference on semi-solid processing of alloys and composites, S2P 2006. Trans Tech Publications Ltd, Busan, pp 449–452. https://doi.org/10.4028/www.scientific.net/SSP.116-117.449
53. Qingming C, Xia C, Changjun C, Siqian B, Schwam D (2009) Characteristics and influnce factors of mold filling process in permanant mold with a slot gating system. China Foundry. 6(4):328–332. http://www.scopus.com/inward/record.url?partnerID=HzOxMe3b&scp=77953854879&origin=inward
54. Wang HJ, Xu J, Zhang ZF, Liang B, Gao MW (2015) Application research of a new coupling stirring on DC casting process for large-sized aluminum ingots. In: Han Y, Wu Y, Liu X (eds) Chinese materials congress, CMC 2014. Trans Tech Publications Ltd, pp 48–54. https://doi.org/10.4028/www.scientific.net/MSF.817.48
55. Wang T, Chen C, Zhang X, Tang Y (2012) Production of thin-walled aluminum castings with gypsum mold casting combining with vacuum pouring and solidification under pressure. Tezhong Zhuzao Ji Youse Hejin 32(3):264–266. http://www.scopus.com/inward/record.url?partnerID=HzOxMe3b&scp=84861771143&origin=inward
56. Xu Z, Zou Y, Gu H, Zeng J (2007) Investigations on hydrogen content change in melt aluminum during casting under adjusted pressure. In: Zhou Y, Tu ST, Xie X (eds) Progresses in fracture and strength of materials and structures, 1–4. Trans Tech Publications Ltd, Stafa-Zurich, vol. 353–358, PART 4, pp 3059–3062. http://www.scopus.com/inward/record.url?partnerID=HzOxMe3b&scp=36049028991&origin=inward
57. Zeng J, Hu Z, Xu Z, Yan Y, He C, He H (2014) An additive manufacturing process combined with investment casting, SAMPE Tech Seattle 2014 Conference. Soc. for the Advancement of Material and Process Engineering. ISBN: 978-193455116-5. http://www.scopus.com/inward/record.url?partnerID=HzOxMe3b&scp=84907766293&origin=inward
58. Zhou ZP, Li RD, Ma JC, Wang Y (2005) Effect of melt mixing on the microstructure in Al-5%Fe alloy. Hangkong Cailiao Xuebao/J Aeronaut Mater 25(4):6–9. http://www.scopus.com/inward/record.url?partnerID=HzOxMe3b&scp=23944476874&origin=inward
59. Puga H, Barbosa J, Soares D, Silva F, Ribeiro S (2009) Recycling of aluminium swarf by direct incorporation in aluminium melts. J Mater Process Technol 209(11):5195–5203. https://doi.org/10.1016/j.jmatprotec.2009.03.007
60. Wei X, Wang H, Liu C, Cao H, Yan P, Sun Z (2019) A review on recycling of waste aluminum alloy. Guocheng Gongcheng Xuebao/Chin J Process Eng 19(1):45–54. https://doi.org/10.12034/j.issn.1009-606X.218180
61. Cullen JM, Allwood JM (2013) Mapping the global flow of aluminum: from liquid aluminum to end-use goods. Environ Sci Technol 47(7):3057–3064. https://doi.org/10.1021/es304256s
62. Gaustad G, Olivetti E, Kirchain R (2012) Improving aluminum recycling: a survey of sorting and impurity removal technologies. Resour Conserv Recycl 58:79–87. https://doi.org/10.1016/j.resconrec.2011.10.010
63. Liu G, Müller DB (2012) Addressing sustainability in the aluminum industry: a critical review of life cycle assessments. J Clean Prod 35:108–117. https://doi.org/10.1016/j.jclepro.2012.05.030
64. Løvik AN, Modaresi R, Müller DB (2014) Long-term strategies for increased recycling of automotive aluminum and its alloying elements. Environ Sci Technol 48(8):4257–4265. https://doi.org/10.1021/es405604g
65. Nakajima K, Takeda O, Miki T, Matsubae K, Nakamura S, Nagasaka T (2010) Thermodynamic analysis of contamination by alloying elements in aluminum recycling. Environ Sci Technol 44(14):5594–5600. https://doi.org/10.1021/es9038769
66. Paraskevas D, Kellens K, Dewulf W, Duflou JR (2015) Environmental modelling of aluminium recycling: a Life Cycle Assessment tool for sustainable metal management. J Clean Prod 105:357–370. https://doi.org/10.1016/j.jclepro.2014.09.102
67. Liu B, Xu Q, Jing T, Shen H, Han Z (2011) Advances in multiscale modeling of solidification and casting processes. JOM 63(4):19–25. https://doi.org/10.1007/s11837-011-0054-x
68. Liu B, Xiong S, Xu Q (2007) Study on macro- and micromodeling of the solidification process of aluminum shape casting. Metall Mater Trans B 38(4):525–532. https://doi.org/10.1007/s11663-007-9073-y