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Magali Brunet et Clair Juilliet

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PLAN

TEXTE

1 Materials [1] -whether natural or artificial- and the technical progress of human societies are inextricably linked. [2] A typical example of this rule, aviation is no exception. This human and societal adventure finds its source in the most far-off times, as evidenced by the myth of Daedalus making wings out of feathers and wax for his son, Icarus, [3] the automaton (flying pigeon) of Archytas of Tarantoin in the 5th century BCE, [4] Abbas Ibn Firnas's attempt at flight in the Emirate of Cordoba around 853 CE, or the flying machines designed in the 15th century by Leonard de Vinci. [5] There are numerous examples where humans have attempted to fly or have designed self-propelled flying machines, and natural materials such as wood, canvas or ropes were at the heart of construction of the first flying machines. [6] Subsequently, metals and their historical alloys [7] -ferrous alloys (steels or cast irons), copper alloys (bronzes, brass, etc.)- were quickly used for the manufacture of "heavier than air" [8] engines.

2 If the integration of these materials allowed the forerunners of aviation to make the first tests at the turn of the 20th century, [9] thus triggering the inception of aeronautics, [10] it was not until the First World War that aviation was developed on an industrial scale. [11] This industrialization was the consequence of decision-making factors driven by a rapidly changing military context but also by dint of technical innovations in the fields of motorization, aerodynamics, struc-

tures and, therefore, materials. The new availability of certain metals (aluminum, titanium) at the time was an important factor in this industrialization. Consequently, the need to solidify or make aircraft lighter encouraged research on metallurgy and allowed for the development of new alloys and associated manufacturing processes such as precision forging, stamping, extrusion.[12] Moreover, ever since aeronautics began the materials industry has innovated steadfastly in order to meet increasing constraints: lightness, hardness, tensile strength, fatigue resistance, corrosion resistance, etc.

3 This issue aims to address the modern period using articles that focus on some of the metallic materials that revolutionized aviation and aeronautics in the 20th century. By offering a history of aeronautics applied through the lens of materials, we wish to contribute to the broader notion of “Aeronautical Heritage”.

1. Strategic materials for aeronautics

4 It would be impossible to think about the rapid development of aviation without mentioning aluminum-based light alloys and, more rarely, those based on magnesium. It was with the discovery of aluminum in 1854 and the development of Duralumin in 1906,[13] that aeronautics as a science was able to take off and, indeed, aluminum-based alloys were triggers for "heavier than air" machines, combining weight reduction and mechanical resistance at the same time. They proved to be the materials of choice for the manufacture of airframes (wings, empennage, fuselage) to replace wood and canvas -the latter being considered too fragile to withstand the stresses exerted on the structures during flights- or to replace steel-based alloys which were considered as being too heavy.

5 Very soon after, additional properties which were resistant to heat or resistant to corrosion led to the development of new alloys. Titanium-based alloys, were developed for this purpose and quickly found their place in aeronautics.[14] They combine medium-to-low density, toughness, high-temperature strength retention (up to 600°C) and excellent resistance to corrosion. Specific alloys have also emerged for engine parts: nickel-based superalloys (the first versions

of which date from 1906)[15] are able to resist harsh conditions such as very high temperatures (approaching 1000°C), high loads, and oxidative vapors all with mechanical properties superior to those of all the metal alloys mentioned above. In the quest for new properties adapted to the demands of aeronautical industry, we must not forget the improvement of older alloys -special steels, for example- with high mechanical and corrosion resistance developed for high load bearing and therefore used in the manufacture of crankshafts and aerostructures such as landing gear.

6 Lastly, since the early 1960s[16] composite materials (fibre/matrix) have played a role in aeronautics -as in many other fields-[17] by replacing metal alloys due to their possessing high resistance qualities (strength to volume mass ratio), their being better able to resist corrosion, or it being possible to produce them in a single go. Doing so allows for a reduction in production costs.[18] Composites with a polymer matrix (or PMC)[19] were the first to be introduced into aircraft structures. First, these were composites reinforced with glass fibres,[20] and then, from the beginning of the 1970s, composites were reinforced with carbon fibres. Composites with a ceramic or metallic matrix (CMC, MMC)[21] are currently at the heart of numerous studies[22] due to their excellent properties namely mechanical resistance and rigidity. CMCs also exhibit the dimensional stability to be able to resist the very high temperatures found in engine combustors or exhaust nozzles.

7 In all these cases, there is a very high variant of metal alloys (of different chemical composition or of composite materials), all of which allow particular mechanical properties to be obtained and act in accordance with precise specifications defined by actors from the aeronautical sector.

2. A dialogue between disciplines

8 In order to better understand the development of aeronautics, it would be appropriate to study the contribution of these materials in technical innovations. Conversely, studying the contextual factors (historical, technical, industrial, social or even economic) that have triggered innovation(s) in the materials field is just as important. Beyond the informative content it provides, this issue demonstrates the

need for interdisciplinary dialogue, particularly in the fields of materials sciences, engineering and human and social sciences that are too often separated and dealt with separately. This assertion is coherent with the analysis of technology ethnologist, Pierre Lemonnier,[23] who notes that human sciences are mostly absent from the works of specialists writing on the fundamental principles of aviation, and that historians often describe the economic and political contexts of the aeronautical industry without going into the heart of its technology.

9 Sociologists, historians of science and technology, etc., might see the interest of associating other disciplines when studying complex and multifaceted subjects such as aviation and the aeronautical industry in the mobilization of technical documentation. Technical archives, when conserved, include technical concepts intended for an informed public, e.g. aeronautical engineers of the time. Knowledge of metallurgy is therefore needed and this knowledge includes the science of materials -more precisely of metals- their elaborations, their treatments -more often than not, on an industrial scale- and their properties -mainly mechanical but also chemical-. It is worth devoting time to these aspects as the analysis of these technical archives can provide help in understanding the technological problems and solutions that may have emerged in this area, e.g. around engine, aerodynamics and of course aeronautical materials. It may then be possible to analyse how certain technical progresses or certain inventions may have triggered industrialisation.

10 With regard to the material sciences or the engineering sciences, studying a social, economic or technical context while considering the history of aeronautics can be enlightening and inspiring. In particular, it can be a question of understanding the technical developments introduced by engineers as well as the contribution of scientists in the discovery of particular physical phenomena.[24] The approach, then, consists in going back to the origins of the discoveries through bibliographical research such as consulting early scientific articles and/or patents.[25] Subsequently, by analysing these sources and cross-checking them with other sources such as industrial archives or testimonies, the researcher is able to understand past successes (how technological barriers were overcome, for example) and the failures (how addressing some problems was abandoned due to a lack of technical means to solve them or because of new inven-

tions making it possible to circumvent them).[26] These paths previously considered as dead ends, could raise new interest thanks to modern techniques and could serve overcome current technological obstacles.

11 It is highly interesting, therefore, for researchers to increase collaborative efforts and to produce a collective analysis of past and present sources in order to provide a better understanding and to provide the means of analysis and treatment that can prove useful in the future.

3. A technical history of aeronautics: from multidisciplinarity to interdisciplinarity

12 Crossing various scientific perspectives on a common object of study provides a definition of what is termed as multidisciplinarity.[27] This approach is certainly necessary, but is not sufficient within the framework of a global analysis integrating extrinsic properties (actors, scientific policies, economy) and intrinsic properties (techniques, materials) of a subject such as the technical history of aeronautics. Interdisciplinarity is not only a dialogue between sciences, it must also tend to the hybridization of the methodology itself. This is in line with the proposal by technical historian and epistemologist, Marina Gasnier, on the subject of industrial heritage.[28] In effect, she invites us to think of industrial heritage “not as something multidisciplinary -as four decades of study have concluded- but as interdisciplinary and requiring the intersection between human, social, and the engineering sciences”.[29] An example where this interdisciplinary approach can be found in the development of archaeometry. Created after the Second World War, archaeometry is a discipline which examines past societies using a wide variety of methods such as chemical and physical sciences or earth and life sciences. In this respect, it fully enters the realm of human and social sciences.[30] Archaeological remains are an important source of information for the completion of the often partial or even non-existent archives of ancient civilisations. The study of the materials of which these remains are composed not only makes it possible to learn about past manufacturing processes of ma-

terials thus providing valuable information for historians and archaeologists, but also to discover solutions for more current problems [31].

13 More broadly, heritage sciences are a good illustration of the interdisciplinary approach. Cross-research involving art historians, materials scientists, physicists and chemists allows us to understand the materiality of heritage objects: the materials they are made of or the processes by which they were implemented. [32] The analysis of materials is also essential for understanding the physico-chemical phenomena that develop at the heart of matter as time goes by. This can cause changes in their properties (optical, mechanical or other). But it is also essential to refer to the evolution of techniques through the eras as much as to the raw materials available in a specific historical context and/or geographic space. The use of the historical methods such as research in archives and criticism of sources is therefore a necessary step in delivering the most complete study possible.

4. The case of aeronautical heritage

14 The case of aeronautical heritage, which it should be remembered, encompasses intangible dimensions (aviation history, aeronautical industries, etc.) and tangible dimensions (artifacts such as archaeological remains or airplanes in museum collections), should be compared with previous examples. As with industrial heritage or archaeometry, studies on aeronautical heritage must be based on an interdisciplinary approach applying a large crossover of sources (testimonies, archives, materials, experiments). Notably, this allows for the study of materials in the long term.

15 Among the interdisciplinary research already carried out on aeronautical heritage, aluminum alloys -the constitutive materials in almost all of the airframes and structures of aircraft since the 1920s- appear to be the principal and most emblematic illustration of this hybridisation. The first studies led in the 1980s and 1990s focused on aircraft wrecks from the Second World War, and required the contribution of chemists (corrosion specialists) in order to find treatments and conservation protocols. [33] It was during this period that the term "aeronautical archeology" [34] first appeared. Given the complexity of

the alteration phenomena observed on these wrecks, it very soon appeared necessary for researchers to deepen their knowledge of old aeronautical materials, and to study the various nuances and intrinsic characteristics which are linked. Specialized journals like *La Revue de l'Aluminium* created in France in 1924 [35] are, in this respect, invaluable sources of information on the development of aeronautical alloys. Beyond that, we might think that consulting technical archives kept by companies or industrialists responsible for manufacturing these alloys would be sufficient: technological developments made in the 20th century being supposedly well documented. As a matter of fact, industrialists did not always give enough importance to the preservation of technical archives. They may have been destroyed and/or dispersed during company mergers or when depository institutions disappeared.

16 As with archeology, the materials themselves are useful sources for the researcher. It is in this context that certain research teams [36] [37] have approached the study of older aeronautical aluminum alloys based both on the analysis of historical sources (often industrial archives) and on the analysis of materials collected from heritage airplanes or wrecked aircraft. [38]

5. Target and content of the issue

17 This issue brings together contributions written by researchers and engineers from different disciplines but who are all specialists in materials and/or in the aeronautical sector. It gives an initial overview of the metal alloys that were necessary for the development of aeronautics throughout the 20th century. Nihad Ben Salah's article explores the origins and role of each family of metal alloys in aeronautics from their beginnings to the present. The articles by Toufa Ouissi and Christian Degrigny deal more specifically with aluminum alloys. The first shows the handling of this new material at the beginning of the 20th century by countries anxious to develop their military aviation. It provides an explanation for the rapid developments which followed and which were brought on by a complex and strained international context of the pre-Second World War period. The second shows that aluminum was considered a noble material at the time of its discovery and as a potential replacement for silver. The aluminum

objects kept in museum collections -as is the case for the airplanes themselves- raise conservation issues. The author provides examples of the typical alterations which were observed and the need for a sharper understanding of the alloys of which they were constituted. Finally, the article by Jean-Yves Guedou sets out in detail the reasons why nickel-based alloys called "superalloys" were essential to the development of aeronautical propulsion and, in particular, the manufacture of turbojets. In addition to these background articles, a note on the trends and prospects for the market of composite materials, particularly in the aeronautics sector, can be found in the news section.

18 By offering this first issue on the history of aeronautical materials we hope that a cross-view of specialists -whether historians, engineers, physicists, or chemists- will be possible. We also want to open up the field of possibilities for collaborations and new multidisciplinary -even interdisciplinary- studies dealing with materials such as titanium alloys, nickel alloys, or composite materials and even anti-corrosion coatings that have not been discussed in this issue. In this sense, this issue is fully in line with the interdisciplinary approach launched by *Nacelles: Past and present of aeronautics and space* since its foundation. [39]

NOTES

1 The authors would like to thank Med Kechidi, Philippe Sciau, Joël Douin and Stephen Rookes for their advice and corrections.

2 G. Pomey, "Réflexion sur révolution de l'industrie des matériaux", *Revue de Métallurgie* – CIT, Vol. 84 / n°3 (March 1987), p. 195-214.

3 Ovide, *Metamorphoses: Daedalus and Icarus* (VII, 183-235).

4 Philosopher, mathematician, astronomer and politician from ancient Greece.

5 C. Ravaisson-Mollien, *Les Carnets de Leonard de Vinci – Tome 2: Manuscrits B et D (Tactiques, armes et machines militaires, aéronefs… Étude de la vision)*, Manuscripts of the Institut de France, Léopold, 2014.

6 J.-M. Ballu, *Bois d'aviation, Sans le bois, l'aviation n'aurait jamais décollé*, Institut pour le Développement Forestier, 2013, 193 pages; D. Parrochia, *L'Homme volant*, Champ Vallon, 2003, 329 pages.

7 Alloys are defined as “A mixture containing two or more metallic elements or metallic and non-metallic elements usually fused together or dissolving into each other when molten.” See: http://dictionary.sensagent.com/ [accessed 29/04/2020].

8 Expression invented in 1863 by the photographer Nadar (1820-1910) to designate flying machines in opposition with hot air balloons and airships sometimes called “lighter than air”.

9 Clément Ader (1841-1925), Octave Chanute (1832-1910), Otto Lilienthal (1848-1896), or the Wright brothers: Wilbur (1867-1912) and Orville (1871-1948), in J. Carpentier, *Cent vingt ans d’innovations en aéronautique*, (Paris: Hermann, 2011), 734 pages.

10 Aeronautics is defined as “the science of designing, building and operating aircraft”. See: https://dictionary.cambridge.org/dictionary/english/aeronautics [accessed 29/04/2020].

11 E. Chadeau, *Le rêve et la puissance. L’avion et son siècle* (Paris: Fayard, 1996), 440 pages; E. Chadeau, “État, industrie, nation: la formation des technologies aéronautiques en France (1900-1950)”, *Histoire, économie et société*, n° 2, 1985, p. 275-300.

12 G. Pomey, “Réflexion sur révolution de l’industrie des matériaux”, *op.cit.*

13 O. Hardouin-Duparc, “Alfred Wilm et les débuts du Duralumin”, *Cahiers d’histoire de l’Aluminium*, Institut pour l’Histoire de l’Aluminium, Paris, 2005, p. 63-77.

14 Titanium was another modern material of the 20th century. It was first extracted in 1910 but only produced industrially from the 1950s. Y. Combres, “Métallurgie et recyclage du titane et de ses alliages”, *Techniques de l’ingénieur – Métallurgie extractive*, T.I., M2 355, 2016.

15 S. J. Patel, “A Century of Discoveries, Inventors, and New Nickel Alloys”, *Journal of the Minerals, Metals & Materials Society* (Vol. 58 / n° 9, 2006), p. 18-20.

16 J. Cinquin, “Les composites en aérospatiale”, *Techniques de l’ingénieur – Traité Plastiques et Composites*, T.I., AM 5 645, 2002.

17 J.-F. Lemettre, “Une révolution des matériaux”, *Revue d’économie industrielle* (n° 31, 1985), p. 118-131.

18 Less elements are needed and there is a suppression of rivets (G. Pomey *op. cit.*)

19 PMC: Polymer-Matrix Composite (thermoplastic or thermosetting).

20 On Airbus A300 or on Boeing 707 and 747.

21 CMC: Ceramics-Matrix Composite (the matrix is generally silicon carbide or alumina); MMC: Metallics-Matrix Composite (the matrix is generally aluminum, titanium and sometimes magnesium).

22 F. J. Lino Alves, A. M. Baptista, A. Marques, "T. 3 – Metal and ceramic matrix composites in aerospace engineering", in S. Rana, R. Fangueiro, *Advanced Composite Materials for Aerospace Engineering* (Woodhead Publishing, 2016), p. 59-99.

23 P. Lemonnier, "Y a-t-il un chamane dans le cockpit? Sur quelques travaux d'histoire et de sociologie de l'aéronautique", Techniques & Culture (n° 42, 2004), p. 141-164.

24 Structural hardening of aluminum alloys for instance with the works of the American Paul D. Merica (*Sci. Pap. Bur. Stand.* 1919), or of the French André Guinier (*Nature* 1938) or the English George D. Preston (*Philos. Mag. J. Sci.* 1938).

25 Articles and patents must be considered in this case as primary sources.

26 To explain this phenomenon, Jean Carpentier makes the link with the processus of "creative destruction" proposed by Joseph Schumpeter (See: Chapter 4, "Les modalités de l'évolution de l'aéronautique", in *Cent vingt ans d'innovations en aéronautique* (Paris: Hermann, 2011), 734 pages).

27 Or "codisciplinarity" when only two disciplines are concerned.

28 M. GASNIER, "Réflexion épistémologique sur le patrimoine industriel: de la pluridisciplinarité à l'interdisciplinarité", *Revue d'histoire des sciences* (vol. 72 / n° 2, 2019), p. 309-347. Gasnier defines Industrial Heritage as an extension of the industrial archeology initiated in Great Britain in the 1940s, and at the end of the 1970s in France.

29 M. Gasnier, "Réflexion épistémologique sur le patrimoine industriel: de la pluridisciplinarité à l'interdisciplinarité", *op. cit.*, p. 313.

30 L. Bellot-Gurlet, P. Dillmann, "L'archéométrie une discipline du passé ou un enjeu interdisciplinaire pour l'avenir?", *ArcheoSciences* (vol. 42 / n° 1, 2018), p. 77-83.

31 L. Bertrand, C. Gervais, A. Masic, L. Robbiola, "Paleo-Inspired Systems: Durability, Sustainability and Remarkable Properties", *Angewandte Chemie International Edition*, n° 57, 2018, p. 7 288-7 295; C. Dejoie, P. Sciau, W. Li *et*

al., "Learning from the Past: Rare E-Fe_2o_3 in the Ancient Black-Glazed Jian (Tenmoku) Wares", *Scientific Reports* (n° 4, 2015), p. 4 941.

32 See for instance reviews and journals *Technè*, *Studies in Conservation*, *Journal of Cultural Heritage*, etc.

33 See: C. Degrigny, "Conservation et stabilisation d'alliages d'aluminium prélevés sur des épaves aéronautiques immergées en eau douce", *Conservation Restauration des Biens Culturels*, CRBC, 1991; C. Adams, D. Hallam, "Finishes on Aluminium – A Conservation Perspective", in *Symposium '91: Saving the Twentieth Century: The Conservation of Modern Materials*, Canadian Conservation Institute, Ottawa, 1991, p. 273-286; I. D. MacLeod, "Stabilization of Corroded Aluminium", *Studies in Conservation*, n° 28 (1),1983, p. 1-7.

34 See: C. Degrigny, "L'archéologie aéronautique à travers l'évolution des alliages d'aluminium", *Cahiers d'histoire de l'aluminium* (n°3, 1988), p. 25-33; Y. Roumegoux, "Entre ciel et terre. Histoire de l'aéronautique militaire et archéologie: l'exemple d'Hazebrouck", *In Situ* [available online] (n° 35, 2018), http://journals.openedition.org/insitu/16543 [accessed 24/03/2020]; J.-P. Legendre, "Un exemple d'archéologie de l'aéronautique: la fouille de l'épave du bombardier de Fléville-devant-Nancy (Meurthe-et-Moselle)", *In Situ* [available online] (n° 35, 2018), http://journals.openedition.org/insitu/16583 [accessed 24/03/2020].

35 Most issues can be accessed on the website of *l'Institut de l'Histoire de l'Aluminium* (IHA): https://www.culturalu.org/biblio_numerique/fr/index.php [accessed 05/04/2020].

36 See: E. Rocca, F. Mirambet, C. Tilatti, "Long Term Corrosion of Aluminium Materials of Heritage: Analysis and Diagnosis of Aeronautic Collection", *Corrosion Engineering Science and Technology*, 45 (5), 2010, p. 345-349; É. Guilminot, Y. Tissier, "Étude des alliages aluminium pour la mise au point des traitements de conservation des avions", *Journal of the History of Aluminium* (Vol. 54, 2015), p. 82-93; *Aluminum: History, Technology, and Conservation*, Proceedings from the 2014 International Conference, C. Chemello, M. Collum, P. Mardikian, J. Sembrat and L. Young (eds.), Washington DC, 2019.

37 The laboratories FRAMESPA (UMR 5136 CNRS – University Toulouse-Jean Jaurès and CEMES (UPR 8011 CNRS) have co-directed two PhDs since 2013: A. Cochard, *Microstructures et propriétés mécaniques des alliages de type Duralumin du Breguet 765 n°504 64-PH. Approche historique et sciences des matériaux*, PhD in Material Science, under the direction of Philippe

Sciau and Jean-Marc Olivier, UPS, Toulouse, 2016; T. Ouissi, *Étude des alliages aéronautiques entre 1930 et 1945: apogée des matériaux au service de l'aviation militaire*, PhD in Aeronautics and Astronautics, under the direction of Magali Brunet and Jean-Marc Olivier, UPS, Toulouse, [started in 2017].

38 Wrecks discovered by the association *Aerocherche*. See: *le Fana de l'aviation*, Larivière [on line]: https://www.editions-lariviere.fr/le-fana-de-l-aviation/ [accessed 26/03/2020].

39 C. Juilliet, J.-M. Olivier, "For a Social and Cultural History of Aeronautics in the Twentieth Century", *Nacelles. Past and Present of Aeronautics and Space*, n° 1, 2016.

AUTEURS

Magali Brunet
Research scientist, membre of the Centre d'Elaboration des Matériaux et d'Etudes Structurales (CEMES-CNRS), magali.brunet@cemes.fr.

Clair Juilliet
Independent research scientist, membre of the laboratory FRAMESPA, clairjuilliet@gmail.com.