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Lighter structures for transports: The role of innovation in metallurgy

Allègement des structures dans les transports : le rôle de l'innovation en métallurgie

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A B S T R A C T

The landscape of energy production and use is facing great challenges in the transportation sectors. The two main means of transportation, automobiles and airplanes, are mainly made from metals. The necessity of reducing their carbon emission translates into major stakes for weight reduction, which can only be the result of an interplay between improving the alloys and the part's geometry. This contribution discusses some of the strategies for structural weight reduction based on innovative alloy design in aluminum alloys and steels and on innovative processing by additive manufacturing.

R É S U M É

Le paysage de la production d'énergie et de son utilisation est confronté à des défis importants dans le secteur des transports. Les deux principaux moyens de transport, automobile et aérien, sont principalement fabriqués avec des métaux. La nécessité de réduire leurs émissions de CO_2 se traduit par une exigence majeure d'allègement, qui ne peut résulter que d'une action conjuguée d'amélioration des alliages et de la géométrie des pièces. Cette contribution discute certaines des stratégies pour l'allègement des structures basées sur la conception innovante d'alliages d'aluminium et d'aciers et sur les procédés innovants par fabrication additive.

1. Introduction

This contribution is part of a thematic volume of the *Comptes rendus Physique*: "The energy of tomorrow". Dealing with our use of energy requires thinking both on energy conversion to a usable energy for society's needs, and on energy use in

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the many devices that we are using in everyday life. Among these, one key issue to improve the footprint of our society is to reduce the emissions of greenhouse gas by the main means of transportations, primarily cars and airplanes, as well as the embedded energy [1]. This requirement seems obvious; however, the ways to get there are not straightforward, especially when cost constraints are taken into account.

Reducing the impact of transports requires an approach towards several directions. The engines must be further optimized, and shift to different energy sources can bring improvements (fully electric, hybrid or hydrogen cars, for instance). However, if vehicles using different sources of energy can be an efficient way to link them to renewable energy sources, or more generally to low-carbon energy, it is not by itself necessarily a good way to reduce the total amount of energy used in transports.

A common target to all transport means is to reduce the weight of the structures [2,3]. By itself, weight reduction is an effective way to reduce the consumption of vehicles per transported passenger. This is particularly true for airplanes and for cars as well, as soon as they travel at non-constant speed. It has to be pointed out that this target becomes somewhat less effective with electric cars where some of the energy of breaking serves to charge back the battery. In fact, while the weight of airplanes per passenger transported has effectively been reduced in the last decades by an improvement in the design and materials used, this is not so true for cars, for which the weight has increased for a long time [4] while a tendency for slow decrease is now slowly arriving. This tendency for making ever heavier cars has been driven by the improvement of comfort and safety, which required the addition of extra weight.

Reducing the weight of a car or an airplane is actually more important than what can be predicted from simply this weight reduction [3,5]. When the weight of the structure is reduced, synergetic effects arise: the engine can be smaller, which reduces its own weight and also reduces consumption. And all other elements can also be designed at lower weight: brakes, suspensions, etc. Such synergetic effects were key to the major shift that was made by the car industry in the USA when Ford decided to make their F150 pickup truck (one of the most sold cars in the USA) entirely of aluminum. This decision made it possible to reduce substantially the engine's size and therefore the truck's gas intake. Obviously, it remains high compared to that of small cars. Therefore, weight reduction has been recognized as a key way to achieve ambitious emission reduction programs such as the target for 2 l/100 km cars in France.

Interestingly, it has been recognized since a very long time that reducing alone the price of using transportation means (which would be a side-effect of reducing consumption) does not necessarily mean that the global emissions will decrease. The contrary can be observed and is known since 1865 as Jevon's paradox [6], from the name of a British economist, William Stanley Jevons, who recognized that an improvement of efficiency could be compensated by an increase in demand due to the reduced cost of the service. Typically, such a mechanism can be observed in the aerospace industry, where from the 1970s to now the consumption of airplanes per passenger per 100 km travelled has gone down by a factor of two (7 l to 3.5 l, approximately), and yet the total consumption of airplanes has increased drastically because of the development of low-cost air transport, which itself has been made possible by the availability of low-consumption airplanes. Therefore, it becomes quite clear that making lighter means of transportation (and more generally, making them more economic to use) cannot alone guarantee a lowering of the total emissions of transport, and the legal framework must be adapted simultaneously (restriction policies) [7].

Improving the weight of structures is a never-ending interplay between material properties and structural design. In this contribution, we will restrict ourselves to the metallic subset of materials used in the transport sector. Traditionally, these two areas were relatively separate: the material's supplier would provide a material with a set of properties, and the designer would try to make the most out of them. However, such a separation is nowadays outdated, because the development of new alloys needs to take into account the complexity of the property sets required for each application. Nowadays, each part of a car or an airplane, submitted to different combinations of mechanical loading and environmental constraints (temperature, corrosive agents), should have a different optimal set of properties, which should lead to a specific material design. Consequently, the diversity of the alloys used in transports has dramatically increased, and to reach this goal the material's producer and the material's user need to work in close collaboration, so that new materials match the property sets required by new applications.

More recently, the development of additive manufacturing in the metallurgy community has led to another paradigm shift: in this case, the material and the structure are only one single concept, which needs to be optimized as a whole: changing the structure of an additive manufactured part requires changes in processing parameters that necessarily impact the material's properties.

In the following, we will present a few examples of how material's research and innovation can lead to improved sets of material properties and architectures. First, we will present some aspects of the development of the new family of Al–Cu–Li alloys for aerospace applications; secondly, we will present the progress brought by the new generations of high-strength steels under development for automotive applications; thirdly, we will present some of the benefits and challenges of metal additive manufacturing using a fast-developing methods, namely Electron Beam Melting.

2. Al–Cu–Li alloys for aerospace applications

The construction of airplanes relies, since the beginning of the 20th century, largely on the use of aluminum alloys, since the discovery by A. Wilm of age hardening brought by alloying soft aluminum by Cu atoms (see [8] for a historical perspective). At that time, age-hardened aluminum alloys with improved strength were rapidly used in industrial appli-

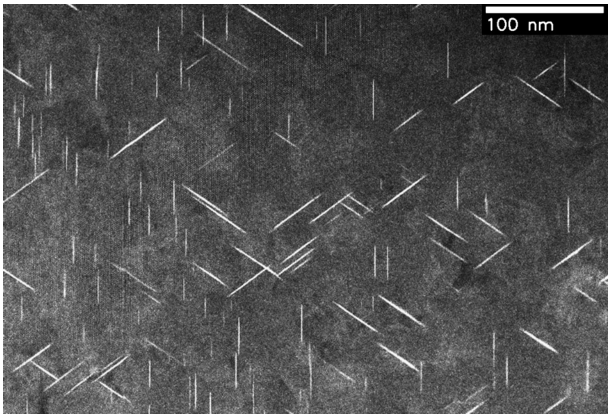

Fig. 1. STEM-HAADF image (scanning transmission electron micrograph in High Angular Annular Dark field mode) of the microstructure of an Al–Cu–Li–Mg–Ag alloy in fully precipitated conditions, showing in white the projection of the platelet nanometric precipitates that act as obstacles to the motion of dislocations and thus harden the material [17].

cations, without knowing the physical phenomena underlying this change in their mechanical properties. Only after the discovery of dislocations in the 1930s and that of Guinier–Preston zones in 1936 [9] did it become clear that the strength increase was due to the formation of nanometer-size precipitates in the Al matrix, which impede the movement of the linear defects responsible for the plastic deformation of metals, namely dislocations. Nowadays, many alloy systems exist, which take advantage of precipitation strengthening to increase the yield strength of aluminum from about 10 MPa to more than 700 MPa. This strength increase, if properly taken into account in design, can be translated in a weight reduction of the structure. The planes designed until the end of the 20th century used massively the Al–Zn–Mg–Cu alloy system (designated as 7000 series alloys), where the precipitation of the $MgZn_2$ phase and its metastable precursors lead to some of the highest strength in aluminum alloys. However, in many applications, the full strength potential of these alloys could not be exploited because of constraints on other properties. Namely, the so-called peak strength temper (designated T6) where the precipitate characteristics in terms of nature, size, and volume fraction are such that they impede most efficiently the dislocations' movement, presents severe limitations in many other properties. In particular, peak strength alloys usually show limited ductility, toughness, and are prone to localized corrosion [10]. Therefore, the mechanical properties (and consequently the potential for weight reduction) have to be degraded to ensure the safety of the components with respect to crack propagation resistance or to resistance to environmental degradation.

The shift of the aerospace industry to carbon-based composites, accelerated by Boeing's decision of to construct the 787 mostly with composites, has been a powerful driver to design new aluminum alloys. Long-standing candidates for Al alloys with desirable properties were based on the Al–Li alloy system. In fact, adding Li to Al improves simultaneously the elastic properties (increase in Young's modulus), the strength (due to nano-precipitation of Al_3Li precipitates) and reduces the alloy's density. However, despite developments in the 1980s of Al–Li based alloys for space applications, their widespread use remained limited for a long time, partly due to cost issues and processing difficulties, and to issues linked to their properties change during long-term ageing in service at moderate temperatures. At the turn of the new century, the pressure for finding new alloy solutions that compete with composites for airplane weight reduction while maintaining the advantages of metals (high productivity, resistance to thunder and impacts, recyclability,...) led to revisit the Al–Li alloy system with the addition of other species: Cu, Mg and some small amounts of Ag or Zn. The change in alloy composition triggers new paths of phase transformations, including the T_1–Al_2CuLi phase [11], but also other phases such as S–Al_2CuMg and its precursors, or Cu–GP zones [12,13], resulting in a dense distribution of obstacles to dislocation movement, as shown in Fig. 1. These alloys present high strength, similarly to 7000 series, slightly lower density, but their success, and their weight-reduction potential relies more importantly on an improved balance of properties, namely their high ductility/toughness and good anticorrosion potential [14].

This high ductility and toughness has remained a puzzle for some time: in two high-strength alloys, how can it be explained that some precipitates degrade less ductility and toughness than others? To answer this question, one has to first point out that close to peak strength, precipitates are usually shearable, meaning that when the alloy enters the plastic regime, dislocations cross through them and induce a shear step. The second point is that usually dislocations, issued from sources within the crystal, multiply in large numbers and travel in groups on a given slip plane. When crossing a very small precipitate (T_1 particles are only 1.3 nm thick! [15,16]), just a few dislocations should result in its full shear, which subsequently should lead to the formation of easy "channels" for dislocation glide where no obstacle is there anymore to impede their movement. This argument is classically given to justify the poor ductility of alloys strengthened by shearable precipitates.

In the case of T_1 precipitates, atomic resolution transmission electron microscopy images have been acquired after plastic straining to identify the mechanisms of dislocation–precipitate interactions. The result shown in Fig. 2 was intriguing: only single shearing steps were observed, and never multiple shearing steps have been pointed out, as could be expected from

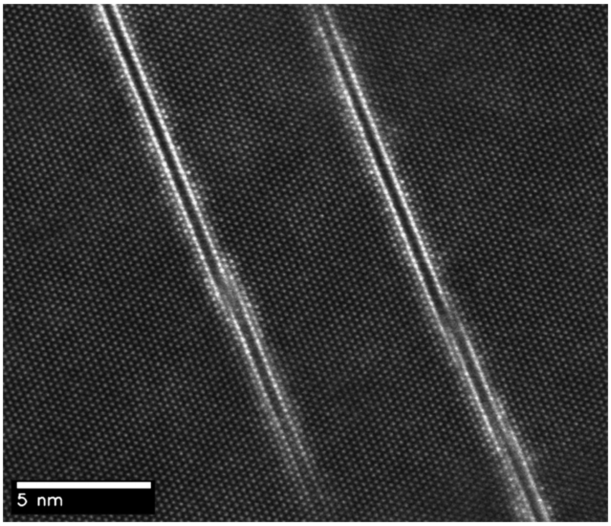

Fig. 2. High-resolution STEM–HAADF image of a plastically deformed Al–Cu–Li alloy. Shearing steps are observed on T_1 *precipitates* [4].

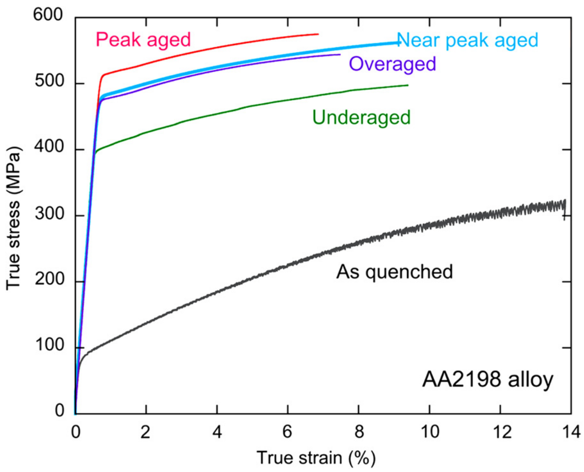

Fig. 3. Stress–strain curves of an Al–Cu–Li alloy for different ageing conditions: peak aged corresponds to the highest condition of strength. Under-aged conditions correspond to shorter ageing times, and overaged conditions correspond to longer ageing times.

the localization of plasticity [17]. An explanation of this peculiar behavior was found in a paper on a slightly different alloy system (Al–Cu–Ag) [18], where the authors argued that if the slip plane in the precipitate were different from that of the matrix, then one shearing event would result in a costly defect at the interface because of the mismatch. A second shearing event would lead to an even greater defect, so that it becomes more attractive for the next dislocation to shear the precipitate in a different location. This microscopic mechanism results in a better spread of plasticity and explains the exceptional ductility and toughness shown by these alloy series, translating in a weight reduction up to 20% with respect to traditional Al alloy design. Fig. 3 shows stress–strain curves of an Al–Cu–Li alloy in different conditions of ageing, resulting in different levels of strength. This figure illustrates that the strength improvement obtained close to peak strength does not come along with a large reduction of ductility.

3. New generations of advanced high-strength steels for automotive applications

Dating back to the very first internal combustion vehicles, steel has always been the prevalent material in the automotive industry [19]. Even if some recent examples of vehicles like 2015 Ford F-150 depart from this long-standing rule, the average modern car is still mainly made out of steel [20]. This is in no small part owed to the extreme versatility that is unique to steel. Indeed, slight variations in composition and/or thermal treatments can lead to alloys that feature radically different properties, from very ductile but soft (uniform elongation above 50% for interstitial free (IF) steel) to very strong but brittle (ultimate tensile strength in excess of 2 GPa for martensitic grades), while newer metallurgical designs allow combinations of both [21].

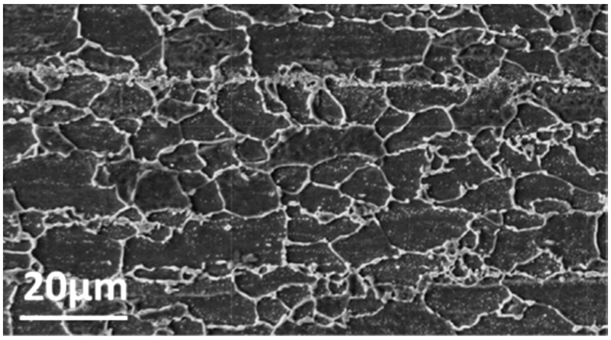

Fig. 4. Microstructure of a dual-phase steel containing 15% of martensite, mostly located at ferrite grain boundaries. Reproduced from [22].

The breadth of properties that can be covered by steel with only very subtle changes in processing is best illustrated by the success of one of the first concept of advanced high-strength steel (AHSS): dual-phase (DP) steel. In DP grades, a controlled amount of strong martensite is dispersed in a matrix of ductile ferrite, as illustrated in Fig. 4. The crucial processing step for those grades is intercritical annealing, during which time and temperature must be precisely controlled so as to obtain the required amount of ferrite. Small adjustments in process temperature and alloy composition can be used to vary the phase fractions. This flexibility in microstructure design permits the attainment of a very broad range of properties. Thus many declinations of DP steels are in use in different part of today's cars, including panels and reinforcements for floors, doors and roofs as well as safety cage components [21]. Adoption of DP steels was exceptionally rapid, notably owing to the fact that it required little to no change to the manufacturing equipment. It has, in particular, an excellent spot weldability with itself and most other advanced high-strength steel (AHSS). As a consequence, DP grades are now found in practically all contemporary cars, where they enable considerable weight savings over former non-AHSS designs.

The microstructure concept introduced in DP steels was further enhanced by tuning the composition to stabilize a significant amount of austenite at room temperature, in addition to the ferrite and martensite/bainite. This metastable austenite is liable to transform into martensite under mechanical load, improving work hardening and thus the formability of this class of alloys labeled TRIP (transformation induced plasticity) steels. These AHSS grades used in combination with other recent metallurgical products such as press-hardened steel (PHS) have for instance enabled 39% weight savings against the baseline during the Future Steel Vehicle program that ended in 2013 [23].

Besides the design of new alloys, innovative processing of steel sheets can lead to dramatic light-weighting as well. Such is the case of tailor welded blanks (TWB), in which sheets of various thicknesses and grades are laser welded together to be jointly formed in a single operation decreasing the number of parts to be joined during manufacturing. This increase in performance can be exemplified by the TWB door ring concept brought forth by ArcelorMittal that lead to a 20% weight saving against the reference assembly and enhanced the resistance to small offset crashes [24].

AHSS will keep contributing to automotive product light weighting, as many new metallurgical designs are being developed. One of the explored avenue is the propensity of austenite to transform at a given stress, which is affected by its chemical composition, notably its carbon content. This lead to one of the latest AHSS concept called Q&P (quench and partitioning) steels. In those grades, the alloy is quenched from either the austenitic or the intercritical range to a temperature at which the austenite has yet to fully transform into martensite (below M_S but above M_F) and held at that temperature (or slightly higher) to allow carbon partitioning from martensite to austenite. Following the partitioning step, carbon-enriched austenite is retained after the alloy has been brought down to room temperature. Variations of the quenching temperature as well as partitioning duration and temperature afford a fine control over the local chemistry in the alloy, which will be leveraged to push further the envelope of properties on the formability diagram.

As the efficiency of powertrain increases and the advent of low-carbon fuels draws closer, it is important to keep in mind that the use phase of automotive vehicles will account for a decreasing fraction of the total emissions of their life cycle [25]. Conversely, the production and disposal phase will represent a growing share of those emissions. Thus, it implies that light weighting and the fuel economy it enables are only desirable as long as the greenhouse gas (GHG) footprint of the new materials involved does not increase. Since the production of steel is one of the lowest GHG emitter amongst automotive structural materials [26], it implies that steel will remain a central material in the production of future cars including battery electric vehicles, even if its use does not lead to the lightest design. This makes innovation in steel a key contributor to the future of transportation.

4. Development of additive manufacturing for the transportation industry

As previously illustrated, driving forces for weight saving in aerospace applications still lead to the development of new alloys or hybrid composites. Another way of saving weight relies on design or (re)design approaches using architectured materials as elementary unit cells. The objective is to substitute bulk parts where this is mechanically allowed by an assembly of lattice or cellular structures, such as in the example shown in Fig. 5.

Fig. 5. Rocket nozzle with a lattice structure (source ARCAM).

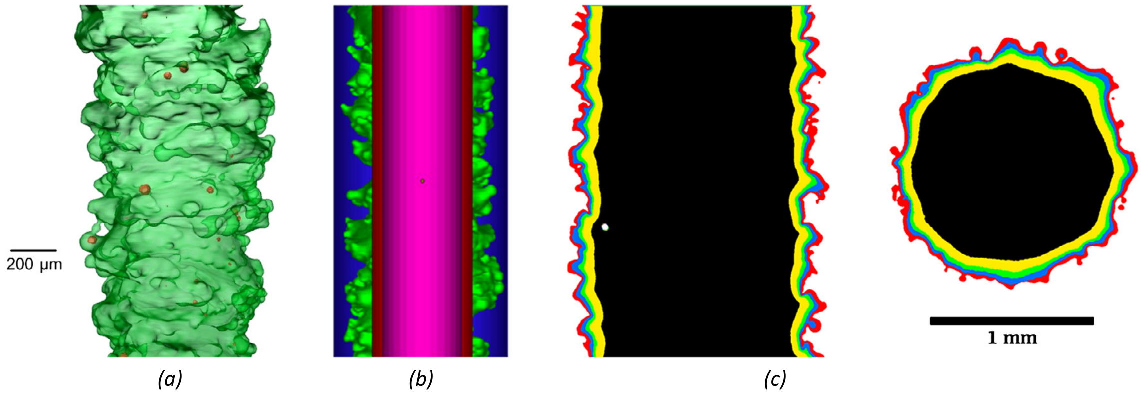

Fig. 6. (a) 3D reconstructed volume of a 1 mm-diameter strut built vertically (residual porosity in red). From [29]. (b) Longitudinal cross section of the CAD-nominal diameter (blue), the fabricated strut (green), and the mechanically equivalent cylinder (red). (c) 2D cross sections of a strut built vertically. The color code refers to the material dissolved after 10 min (red), 20 min (blue), 30 min (green), 60 min (yellow) of chemical etching time. The material remaining after 60 min etching appears in black (from [30]).

Such solutions emerge in particular through topological optimization approaches. These numerical approaches identify where material should be moved or removed in a predefined domain to achieve a specific objective (e.g., minimal mass) for a given set of constraints or desired properties. However, the resulting shapes turn out to be rather complex and difficult (if not impossible) to be fabricated by conventional manufacturing processes, especially for metallic components.

Additive Manufacturing and in particular powder-bed processes make possible the fabrication of such sophisticated geometries. Electron Beam Melting (EBM) is one of the newest and fast-developing technologies [27,28]. It uses a high-energy electron beam to selectively melt successive layers of metallic powders. The process takes place under a controlled vacuum (of about 10^{-3} mbar in the build chamber) and at constant high temperature (depending of the material, typically 700 °C for a Ti–6Al–4V titanium alloy). In comparison with Laser Beam Melting, high-temperature processing leads to very low residual stresses, but the inherited microstructures are often coarser because of the reduced cooling rates and thermal gradients. For each layer, a slight sintering of the powders is required to create necks between powder grains in order to prevent the accumulation of negative charges. This sintering also helps to limit the use of supports, thus giving access to more complex architectures.

EBM is therefore particularly well suited for fabricating lattices structures, where internal supports would be impossible to remove. Of course, it is also well suited for fabricating hybrid parts containing bulk parts coexisting with lattices.

Regarding lattice structures, the characteristic sizes involved are small (in the order of 1–3 mm for the diameter of single struts). Dimensional accuracy and surface quality are then particularly challenging.

These characteristics have been extensively studied in Suard et al. [29] at the scale of single struts. Single struts with different diameters (from 1 to 4 mm) and different orientations with respect to the build direction (0, 45° and 90°) were produced with standard process parameters. They were characterized using X-ray tomography (Fig. 6a). The porosity level was found to be very low (under 0.1%). The few remaining pores exhibited a spherical morphology, exactly like it was observed in the initial powders; this corresponds to gas entrapping during the powder atomization process. From a dimensional point of view, significant discrepancies were found between the ideal computer-aided-designed (CAD) component and the fabricated one. These discrepancies are more pronounced when considering small strut diameters. Moreover, surface irregularities inherited from the process were evidenced by X-ray microtomography: plate-pile like stacking defects related

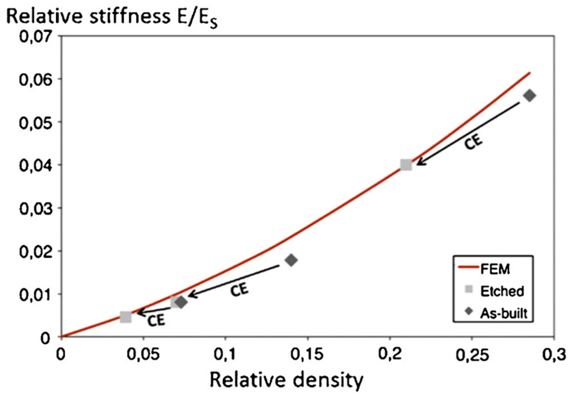

Fig. 7. Relative stiffness of octet-truss lattices as a function of the relative density. Theoretical (FEM) prediction (red curve), experimental values before and after Chemical Etching. From [32].

to instabilities of the melt pool as well as residual powders stuck to the melt pool (see Fig. 6a), but partially melted. These characteristics can be encompassed in the abusive term of "roughness".

Fabricated struts do not transmit load in the same way as bulk material. The different defects described previously induce a decrease in the strut stiffness and, consequently, a decrease in the resulting Young modulus of the lattice structure. Note that the discrepancies seem to be repeatable, making possible systematic corrective strategies. A mechanically equivalent cylinder was estimated from a numerical calculation performed on the X-ray microtomography 3D images of the different struts (see example in Fig. 6b). A downscaling factor can thus be identified as a function of the initial CAD diameter as well as of the orientation respect to the building direction. Using this corrective factor, it is possible to estimate the true mechanical properties (stiffness) of any additively manufactured lattice structure, whatever the architecture or building orientation [29].

For some targeted applications, roughness may be interesting. It is particularly the case for biomedical applications, where the lattice structures become a scaffold, hosting the bone cells. Roughness is known to promote cell growth. It can also be interesting in the field of thermal applications, where roughness may promote turbulence into channels and hence lead to better heat exchanges.

On the contrary, from a mechanical point of view, surface defects turn out to be the most critical limitation for the use of lattice structures in transport applications. In this case, it is important to develop strategies to reduce those surface defects. Given the complex architecture of lattice structures, conventional mechanical post treatments such as conventional machining are prohibited. Even classical blasting treatments are not suitable, because they affect the struts very inhomogeneously. Chemical etching procedures were recently successfully applied to lattice structures [30–32]. The procedure has been proved uniform throughout the entire structure. Effects were quantified by a 3D characterization of single struts using X-ray microtomography. The evolution of the morphology of the struts was investigated during the chemical procedure. An example of surface evolution with etching time is shown in Fig. 6c. During the first 10 minutes, there is a rapid dissolution of the powder particles stuck to the melt pool. This regime is then followed by a slow but real smoothing of the plate-pile-like stacking defects.

As-built and etched lattice structures (octet-truss geometry in this case) have been mechanically tested under uniaxial compression. The experimental relative stiffness values of as-built lattices are reported in Fig. 7 as a function of the relative density. The experimental values depart from the theoretical ones, as mentioned in the previous section. This difference is systematically reduced after chemical etching. Chemical etching removes preferentially the powder particles stuck to the struts, which decreases the relative density. However, these powders, as stated before, do not participate in the stiffness of the lattice. In other words, etching removes the mechanically inefficient material.

Recent works have extended studies on surface defects in lattice structures to failure mechanisms (see, e.g., [33]). The aim of the ongoing works is also to identify and classify the critical defects in the field of fatigue properties, as well as the different ways to reduce them and to remove the most critical ones. It seems that combinations of etching and hot isostatic pressing are very promising. It is the price to pay to popularize the use of lattice structures made by additive manufacturing as structural parts in aerospace applications.

5. Conclusion

Fabricating lighter structures is a key endeavor in meeting tomorrow's challenges of reducing our consumption of both energy and material resources. The materials science community contributes to this effort by developing integrated approaches, spanning from the understanding of fundamental mechanisms to the optimization of component design, exploiting the potential of new processes such as additive manufacturing. Nowadays, materials scientists must think materials development in terms of complex sets of properties and in terms of the interplay between the possibilities offered by physical metallurgy and the limitations of processing. New approaches to materials design are flourishing at both ends of this spectrum: on the one hand, combinatorial methods accelerate the design of new materials and, on the other one, advances in manufacturing enable unprecedented properties and geometries.

Acknowledgements

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References

[1] A. Mayyas, A. Qattawi, M. Omar, D. Shan, Design for sustainability in automotive industry: a comprehensive review, Renew. Sustain. Energy Rev. 16 (2012) 1845–1862, http://dx.doi.org/10.1016/j.rser.2012.01.012.
[2] R. Geyer, Parametric assessment of climate change impacts of automotive material substitution, Environ. Sci. Technol. 42 (2008) 6973–6979, http://dx.doi.org/10.1021/es800314w.
[3] R. Dhingra, S. Das, Life cycle energy and environmental evaluation of downsized vs. lightweight material automotive engines, J. Clean. Prod. 85 (2014) 347–358, http://dx.doi.org/10.1016/j.jclepro.2014.08.107.
[4] E. Zervas, Analysis of CO_2 emissions and other characteristics of new German passenger cars, Energy Fuels 23 (2009) 244–252, http://dx.doi.org/10.1021/ef800723k.
[5] F. Del Pero, M. Delogu, M. Pierini, The effect of lightweighting in automotive LCA perspective: estimation of mass-induced fuel consumption reduction for gasoline turbocharged vehicles, J. Clean. Prod. 154 (2017) 566–577, http://dx.doi.org/10.1016/j.jclepro.2017.04.013.
[6] B. Alcott, Jevons' paradox, Ecol. Econ. 54 (2005) 9–21, http://dx.doi.org/10.1016/j.ecolecon.2005.03.020.
[7] R.-C. Jou, T.-Y. Chen, Willingness to pay of air passengers for carbon-offset, Sustainability 7 (2015) 3071–3085, http://dx.doi.org/10.3390/su7033071.
[8] O. Hardouin Duparc, Alfred Wilm and the beginnings of Duralumin, Z. Metallkd. 96 (2005) 398–404, http://dx.doi.org/10.3139/146.018122.
[9] O. Hardouin Duparc, The Preston of the Guinier–Preston Zones. Guinier, Metall. Mater. Trans. A, Phys. Metall. Mater. Sci. 41A (2010) 1873–1882, http://dx.doi.org/10.1007/s11661-010-0320-5.
[10] T. Marlaud, B. Malki, C. Henon, A. Deschamps, B. Baroux, Relationship between alloy composition, microstructure and exfoliation corrosion in Al–Zn–Mg–Cu alloys, Corros. Sci. 53 (2011) 3139–3149.
[11] E. Gumbmann, F. De Geuser, C. Sigli, A. Deschamps, Influence of Mg, Ag and Zn minor solute additions on the precipitation kinetics and strengthening of an Al–Cu–Li alloy, Acta Mater. 133 (2017) 172–185, http://dx.doi.org/10.1016/j.actamat.2017.05.029.
[12] B. Gault, F. De Geuser, L. Bourgeois, B.M. Gable, S.P. Ringer, B.C. Muddle, Atom probe tomography and transmission electron microscopy characterisation of precipitation in an Al–Cu–Li–Mg–Ag alloy, Ultramicroscopy 111 (2011) 683–689.
[13] V. Araullo-Peters, B. Gault, F. de Geuser, A. Deschamps, J.M. Cairney, Microstructural evolution during ageing of Al–Cu–Li–x alloys, Acta Mater. 66 (2014) 199–208, http://dx.doi.org/10.1016/j.actamat.2013.12.001.
[14] T. Warner, Recently-developed aluminium solutions for areospace applications, Mater. Sci. Forum 519–521 (2006) 1271–1278.
[15] C. Dwyer, M. Weyland, L.Y. Chang, B.C. Muddle, Combined electron beam imaging and ab initio modeling of T(1) precipitates in Al–Li–Cu alloys, Appl. Phys. Lett. 98 (2011) 201909, http://dx.doi.org/10.1063/1.3590171.
[16] P. Donnadieu, Y. Shao, F. De Geuser, G.A. Botton, S. Lazar, M. Cheynet, M. de Boissieu, A. Deschamps, Atomic structure of T-1 precipitates in Al–Li–Cu alloys revisited with HAADF-STEM imaging and small-angle X-ray scattering, Acta Mater. 59 (2011) 462–472, http://dx.doi.org/10.1016/j.actamat.2010.09.044.
[17] A. Deschamps, B. Decreus, F. De Geuser, T. Dorin, M. Weyland, The influence of precipitation on plastic deformation of Al–Cu–Li alloys, Acta Mater. 61 (2013) 4010–4021.
[18] B.Q. Li, F.E. Wawner, Dislocation interaction with semicoherent precipitates (Omega phase) in deformed Al–Cu–Mg–Ag alloy, Acta Mater. 46 (1998) 5483–5490, http://dx.doi.org/10.1016/S1359-6454(98)00188-8.
[19] R. Geyer, The industrial ecology of the automobile, in: R. Clift, A. Druckman (Eds.), Tak. Stock Ind. Ecol., Springer International Publishing, Cham, Switzerland, 2016, pp. 331–341.
[20] B. Smith, A. Spulber, S. Modi, T. Forielli, Technology Roadmaps: Intelligent Mobility Technology, Materials and Manufacturing Processes, and Light Duty Vehicle Propulsion, Center for Automotive Research, Ann Arbor, MI, USA, 2017.
[21] S. Keeler, M. Kimchi, P.J. Mooney, Advanced High-Strength Steels Application Guidelines V6.0, WorldAutoSteel, 2017.
[22] Q. Lai, L. Brassart, O. Bouaziz, M. Goune, M. Verdier, G. Parry, A. Perlade, Y. Brechet, T. Pardoen, Influence of martensite volume fraction and hardness on the plastic behavior of dual-phase steels: experiments and micromechanical modeling, Int. J. Plast. 80 (2016) 187–203, http://dx.doi.org/10.1016/j.ijplas.2015.09.006.
[23] WorldAutoSteel, Steel Eliminates Weight Gap with Aluminum for Car Bodies, http://www.worldautosteel.org/download_files/FutureSteelVehicle%20Results%20and%20Reports/2013/7_PressRel_SteelClosesGapWithAlum__EUGLOBAL_2013416.pdf, 2013 (accessed July 13, 2017).
[24] Laser Welded Blanks for Hot Stamping, ArcelorMittal, 2015, http://automotive.arcelormittal.com/saturnus/sheets/TB2_EN.pdf (accessed July 13, 2017).
[25] A. Kendall, L. Price, Incorporating time-corrected life cycle greenhouse gas emissions in vehicle regulations, Environ. Sci. Technol. 46 (2012) 2557–2563, http://dx.doi.org/10.1021/es203098j.
[26] J.C. Kelly, J.L. Sullivan, A. Burnham, A. Elgowainy, Impacts of vehicle weight reduction via material substitution on life-cycle greenhouse gas emissions, Environ. Sci. Technol. 49 (2015) 12535–12542, http://dx.doi.org/10.1021/acs.est.5b03192.
[27] X. Gong, T. Anderson, K. Chou, Review on powder-based electron beam additive manufacturing technology, Manuf. Rev. 1 (2014) 2, http://dx.doi.org/10.1051/mfreview/2014001.
[28] C. Koerner, Additive manufacturing of metallic components by selective electron beam melting – a review, Int. Mater. Rev. 61 (2016) 361–377, http://dx.doi.org/10.1080/09506608.2016.1176289.
[29] M. Suard, G. Martin, P. Lhuissier, R. Dendievel, F. Vignat, J.-J. Blandin, F. Villeneuve, Mechanical equivalent diameter of single struts for the stiffness prediction of lattice structures produced by Electron Beam Melting, Addit. Manuf. 8 (2015) 124–131, http://dx.doi.org/10.1016/j.addma.2015.10.002.
[30] P. Lhuissier, C. de Formanoir, G. Martin, R. Dendievel, S. Godet, Geometrical control of lattice structures produced by EBM through chemical etching: investigations at the scale of individual struts, Mater. Des. 110 (2016) 485–493, http://dx.doi.org/10.1016/j.matdes.2016.08.029.
[31] G. Pyka, A. Burakowski, G. Kerckhofs, M. Moesen, S. Van Bael, J. Schrooten, M. Wevers, Surface modification of Ti6Al4V open porous structures produced by additive manufacturing, Adv. Eng. Mater. 14 (2012) 363–370, http://dx.doi.org/10.1002/adem.201100344.
[32] C. de Formanoir, M. Suard, R. Dendievel, G. Martin, S. Godet, Improving the mechanical efficiency of electron beam melted titanium lattice structures by chemical etching, Addit. Manuf. 11 (2016) 71–76, http://dx.doi.org/10.1016/j.addma.2016.05.001.
[33] L. Liu, P. Kamm, F. García-Moreno, J. Banhart, D. Pasini, Elastic and failure response of imperfect three-dimensional metallic lattices: the role of geometric defects induced by Selective Laser Melting, J. Mech. Phys. Solids 107 (2017) 160–184, http://dx.doi.org/10.1016/j.jmps.2017.07.003.