Institution: Brunel University London		
Unit of Assessment: 12 Engineering		
Title of case study: High strength recyclable extrudable aluminium alloys for light-weight automotive structures		
Period when the underpinning research was undertaken: 2010 – 2020		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s):	**Role(s) (e.g. job title):**	**Period(s) employed by submitting HEI:**
1. Prof. Zhongyun Fan (Lead)	1. Director of BCAST	1. 12/1996-present
2. Prof. Geoff Scamans	2. Professor of Metallurgy	2. 07/2007-present
3. Prof. Isaac Chang	3. Professor of Metallic Materials	3. 05/2016-present
4. Prof. Hamid Assadi	4. Professor of Solidification Research	4. 04/2016-present
5. Dr Chamini Mendis	5. Reader in Magnesium Research	5. 06/2016-present
6. Dr Ian Stone	6. Senior Lecturer	6. 02/2010-06/2016
7. Dr Yan Huang	7. Senior Lecturer	7. 06/2010-present
8. Prof. Shouxun Ji	8. Professor	8. 10/2010-present
Period when the claimed impact occurred: 2014 – Dec 2020		
Is this case study continued from a case study submitted in 2014? No		

1. Summary of the impact (indicative maximum 100 words)

BCAST (the Brunel Centre for Advanced Solidification Technology) at Brunel University London has developed fully recyclable high strength aluminium extrusion alloys (HSA6) through a strategic partnership with the Automotive Structures and Industry (AS&I) business unit of Constellium. The new alloys have already been implemented in light-weight crash management systems of 5 vehicles and platforms securing almost GBP200,000,000 in vehicle sales live revenue. Assuming typical annual vehicle sales of 500,000, the weight saving will lead to an estimated saving in CO_2 emissions of 225 kT, and associated saving of 89,500,000 litres of fuel representing a total fuel cost saving of GBP103,000,000 to consumers. These new alloys have contributed to 80% of Constellium AS&I's new business and helped double Constellium's turnover in 5 years. Working with BCAST at Brunel has led Constellium to radically change its R&D, investment and business strategies, and to embark on a plan to on-shore aluminium manufacturing in the UK, creating hundreds of jobs and revitalising the aluminium industry.

2. Underpinning research (indicative maximum 500 words)

The development of HSA6 has been underpinned by the development of BCAST's melt conditioned direct chill (MC-DC) casting technology, which emerged alongside BCAST's fundamental research into heterogeneous nucleation and grain refinement; and design of alloys combining a chemical and process approaches based on strain enhanced precipitation.

Heterogeneous Nucleation: The decades old classical theory of heterogeneous nucleation is physically unrealistic for potent nucleation. The BCAST team has developed ground-breaking new theories for the entire nucleation process using a combination of molecular dynamics simulation, analytical and numerical modelling, and experiment. They have discovered that for solidification, the liquid close to the nucleating substrate becomes layered and ordered as a precursor to nucleation, which has been termed prenucleation [1], and the extent of layering and ordering is determined by the crystallography (misfit) [1], chemistry (chemical templating) [2] and atomic roughness of the nucleating substrate surface [3]. Following prenucleation and further undercooling nucleation then proceeds through templating of the first liquid layer by the substrate to form a solid layer with a 2D crystallographic structure closely matching that of the substrate surface. The second and third solid layers then form through templating the preceding solid layer, but with crystallographic orientation changes such that the third layer closely resembles that of solid phase and nucleation then continues with further undercooling until the solid nuclei grow to a sufficient size to grow freely. Furthermore, the team have developed the concepts of progressive and explosive nucleation [4], leading to predictive mapping of grain size as a function of process condition and alloy chemistry.

MC-DC Casting: Direct chill (DC) casting is the semi-continuous industrial process used for casting large round billets of Al alloys as feedstock for producing extruded profiles. For 60 years, the aluminium industry has been adding inoculants, commonly TiB_2 particles, to refine the grain structure of DC cast materials. However, homogenisation heat treatments are required after casting to improve chemical homogeneity across the billet and to control the size, morphology and type of intermetallic compounds (IMCs) formed in the latter stages of solidification, and the accumulation of TiB_2 particles from secondary scrap hinders continuous closed-loop recycling. The BCAST research team identified some years ago that the application of high shear forces to liquid metal prior to casting ("melt conditioning") has significant effects on the microstructure of the solidified material, and then developed a simple rotor-stator device to provide high shear and distribute the sheared liquid macroscopically. When this device is inserted directly into the DC casting head, we refer to this as MC-DC casting [5,6]. The application of high shear disperses natural oxide films within the liquid metal into well distributed benign nano-scale particles that can act has potent heterogeneous nucleants leading to grain refinement without the need to add TiB_2. The dispersive mixing leads to reduced macrosegregation across the billet.
The microstructure of the DC cast material can also be controlled as a function of the rotational speed of the rotor. At low speeds the resulting microstructure is similar to that of conventional DC casting with coarse grains with coarse dendrite arms. At very high speeds the grains are almost spherical. In these two cases the pools of liquid remaining at the latter stages of solidification are coarse, as are the IMCs that form in them. At intermediate speeds, however, the grains are fine with very fine dendrite arms, and the residual liquid is finely dispersed and the IMCs are therefore highly refined. Together with reduced macrosegregation, this can minimise or even eliminate the expensive homogenisation heat treatment step between casting and extrusion, and lead to tolerance of impurities from recycled feedstock [7].

Strain Enhanced Precipitation: Development of the HAS6 alloy is underpinned by the deep understanding of nucleation in the liquid state applied to the solid state to providing new insight into the precipitation strengthening (ageing) process in combination with deformation during alloy processing such as extrusion. The alloying elements for precipitation strengthening selected were those with wide availability and low cost, such as Mg, Si, Cu and Zn, and minor alloying elements have been shown to achieve specific functions: precipitation strengthening of the alloys could be enhanced by adding Sn which delays detrimental natural ageing; Mn improves tolerance to Fe impurities providing the opportunity for closed-loop recycling; and rare earths reduce secondary dendrite arm spacing compared with the MC-DC yardstick.

Both the strength and toughness of HSA6 alloys can be significantly increased by providing a microstructure based on an optimised level of precipitation and dislocation network. This has provided the way forward for both the development of stronger alloys and novel processing techniques and to closed-loop recyclable alloys.

All of the research described was taken forward through studentships and fundamental and applied research projects directly funded by Constellium, and through collaborative projects funded by Innovate UK, the EPSRC, and the Advanced Propulsion Centre.

3. References to the research (indicative maximum of six references)

Key Publications

1. H. Men, Z. Fan, Prenucleation induced by crystalline substrates, *Metall. Mater. Trans. A*, 49 (2018) 2766-77. [https://doi.org/10.1007/s11661-018-4628-x]
2. C.M. Fang, H. Men, Z. Fan, Effect of substrate chemistry on prenucleation, *Metall. Mater. Trans. A*, 49 (2018) 6231-42. [https://doi.org/10.1007/s11661-018-4882-y]

3. B. Jiang, H. Men, Z. Fan, Atomic ordering in the liquid adjacent to an atomically rough solid surface, *Comput. Mater. Sci.*, 153 (2018) 73-81. [https://doi.org/10.1016/j.commatsci.2018.06.005]
4. Z. Fan, F. Gao, B. Jiang, Z.P. Que, Impeding nucleation for more significant grain refinement, *Scientific Reports* 10 (2020) 9448. [https://doi.org/10.1038/s41598-020-66190-8]
5. J.B. Patel, X. Yang, C.L. Mendis, Z. Fan, Melt conditioning of light metals by application of high shear for improved microstructure and defect control, *JOM*, 69 (2017) 1071-1076. [https://doi.org/10.1007/s11837-017-2335-5]
6. G.S. Bruno Lebon, H.-T. Lia, J.B. Patel, H. Assadi, Z. Fan, Numerical modelling of melt-conditioned direct-chill casting, *Applied Mathematical Modelling*, 77 (2020) 1310-1330. [https://doi.org/10.1016/j.apm.2019.08.032]
7. K. Al-Helal, J.B. Patel, G.M. Scamans, Z. Fan, Melt conditioned direct chill (MC-DC) casting and extrusion of AA5754 aluminium alloy formulated from recycled taint tabor scrap, *Materials*, 13 (2020) 2711. [https://doi.org/10.3390/ma13122711]

Key Research Grants

- EPSRC Centre for Innovative Manufacturing in Liquid Metal Engineering (EP/H026177/1), 01/05/10-31/10/15, GBP5,119,391.
- EPSRC Future Liquid Metal Engineering Hub (EP/N007638/1), 01/11/15-31/10/22, GBP10,138,665.
- EPSRC Prosperity Partnership – STEP Aluminium (EP/S036296/1), 01/03/19-29/02/24, GBP2,249,250

4. Details of the impact (indicative maximum 750 words)

Developing Constellium's Strategy: As a global supplier of aluminium and aluminium products, Constellium has long had major businesses in supplying sheet aluminium to the aerospace sector. A key strategy for growth of the company has been to grow the Automotive Structures and Industry (AS&I) business unit providing extruded aluminium and products based on extrusions to the automotive sector.

Working with BCAST at Brunel has had a fundamental impact on Constellium AS&I's business strategy. They are now taking a more targeted and strategic approach to R&D operations and investment; they have now based their R&D operations at Brunel and have invested more than GBP40,000,000 in cash in BCAST at Brunel, and worked in collaboration with BCAST on GBP23,700,000 of government funded research programmes. Working in this targeted and strategic way has allowed Constellium to ramp up the scale, focus and delivery of its R&D investment. Over 30 Constellium technical staff have benefited from working alongside Brunel academic researchers, increasing their technical skills whilst supporting direct and rapid knowledge transfer. Consequently, Constellium have benefited from a step change in the speed at which they can produce working prototype systems from months to 6 weeks, enabling its new products to break into current cycles of vehicle design for the first time.

In support of the automotive sector's drive for electrification, Constellium, with BCAST at Brunel as the academic research partner, has developed a technology roadmap for the implementation of HAS6 for the design and manufacture of light-weight recyclable electric vehicle battery enclosures with integrated thermal management as well as the primary function of crash resistance to replace multi-material solutions with complex additional thermal management systems. Initially demonstrating the feasibility of technology in vehicles defined by BMW (Mini E) and Volvo (XC40) (Innovate UK, LIBERATE), a further investment of GBP15,000,000 by the Automotive Propulsion Centre in 2020 (ALIVE) will ensure scalability of design and manufacturing capability.

Building on the technologies being developed with Brunel, Constellium now intends to create a new Applications Centre in the UK to provide full-scale prototypes to car makers and to refine production methods for advanced manufacturing. Its ultimate aim is to on-shore manufacturing to the UK, reigniting UK aluminium extrusion capability and creating hundreds of jobs.

Personnel Development: Prior to working with Brunel, Constellium had neither a manufacturing nor a technical/R&D facility in the UK, and only a small number of UK-based personnel travelling between global facilities. To support their R&D strategy, Constellium have employed and seconded over 30 personnel to be based at Brunel, including highly experienced engineers, project managers, and plant managers, investing over GBP1,000,000 per year in doing so. Constellium have taken advantage of the research programme in BCAST to shape their next generation of engineers and scientists, promoting knowledge transfer and increasing the technical skills of their staff. They have also developed an apprenticeship programme for developing technical staff for onward sustainability of the R&D centre, in partnership with the local FE college, building a pipeline of talented staff entering the aluminium industry whilst benefitting members of the local community.

Financial Impact: 80% of Constellium AS&I's new business has been based on the availability of the HSA6 alloy they developed with Brunel, contributing to the doubling of Constellium's automotive business to GBP1,000,000,000 in the 5 years to 2017 with an aim to double it again over the following 5 years. Key business won to date, based on the availability of HSA6, has been in the sale of automotive crash management systems (CMS), in combination with Constellium's HCA6 crush alloys, and examples include:

- Tesla 3 (GBP91,000,000)
- JLR Range Rover Evoque (GBP37,800,000)
- JLR Discovery Sport (GBP14,100,000)
- BMW UKL Platform Mini/Series 1 & 2 (GBP41,000,000)
- Audi Q3 (GBP15,000,000).

[Figures in parentheses represent the value of new business secured by Constellium over the sales life of the model].

Environmental Benefits: Legislation on the reduction of CO_2 emissions from the automotive fleet has been a key driver for change in the automotive industry to improve fuel consumption move towards electrification. For instance, the reduction of the EU's 2015 target of 130 gCO_2/km to the 2021 target of 95 gCO_2/km, represents approximate improvements in fuel economy of 5.6 l/100km (petrol) and 4.9 l/100km (diesel) to 4.1 l/100km and 3.6 l/100km respectively. Reducing the weight of vehicles is an important contributor to reduce fuel consumption and CO_2 emissions. This is equally true of fully electric vehicles for which the electric power is derived from fossil fuel sources. Reducing the weight of body structures has the additional benefit of secondary weight savings through the need for smaller powertrains and braking systems.

The weight saving achieved by the HSA6 CMS designs is 20-30%, equivalent to 4-10kg per vehicle depending on the system replaced. For internal combustion (IC) engine vehicles, CO_2 emissions decrease linearly with reduced vehicle kerb weight at a rate of approximately 0.09 gCO_2 per km driven per kg weight saving. The number of the above IC vehicles sold is approximately 500,000 per year. Assuming a model is marketed for 5 years and each vehicle is driven for approximately 200,000km over its lifetime and the weight saved per vehicle is 5kg, then the total CO_2 emission saved is 225,000 tonnes.

Benefits to Customers & Consumers: Constellium's customers include important OEMs of the UK automotive sector, particularly in prestige marques. By incorporating high strength aluminium body structures, OEMS are not only able achieve direct light-weighting, but also facilitates indirect light-weighting because smaller, lighter drive chains and braking systems can be used to achieve the same overall performance. Reducing body mass, lowers the centre of gravity of vehicle, which in turn improves driving dynamics, and therefore allows the OEMs to offer consumers a vehicle that is more fun and safer to drive. Innovation is a vital marketing tool for maintaining and growing market share, and is crucial to the UK market sector, which has been affected by political uncertainty in recent years.

Consumers will benefit through savings in fuel costs. Petrol and diesel produce 2,392 gCO_2 per litre and 2,640 gCO_2 per litre, respectively; say an average of 2,516 gCO_2/l. Based on the analysis above and the total CO_2 emissions saving of 225,000 tonnes, the total fuel saving is slightly less than 89,500,000 litres. At an approximate fuel price of GBP1.15 per litre, this translates to a total fuel cost saving for consumers of slightly less than GBP103,000,000.

5. Sources to corroborate the impact (indicative maximum of 10 references)

Corroborating letter from Global Technical Director, Auto Structures & Industry, Constellium.