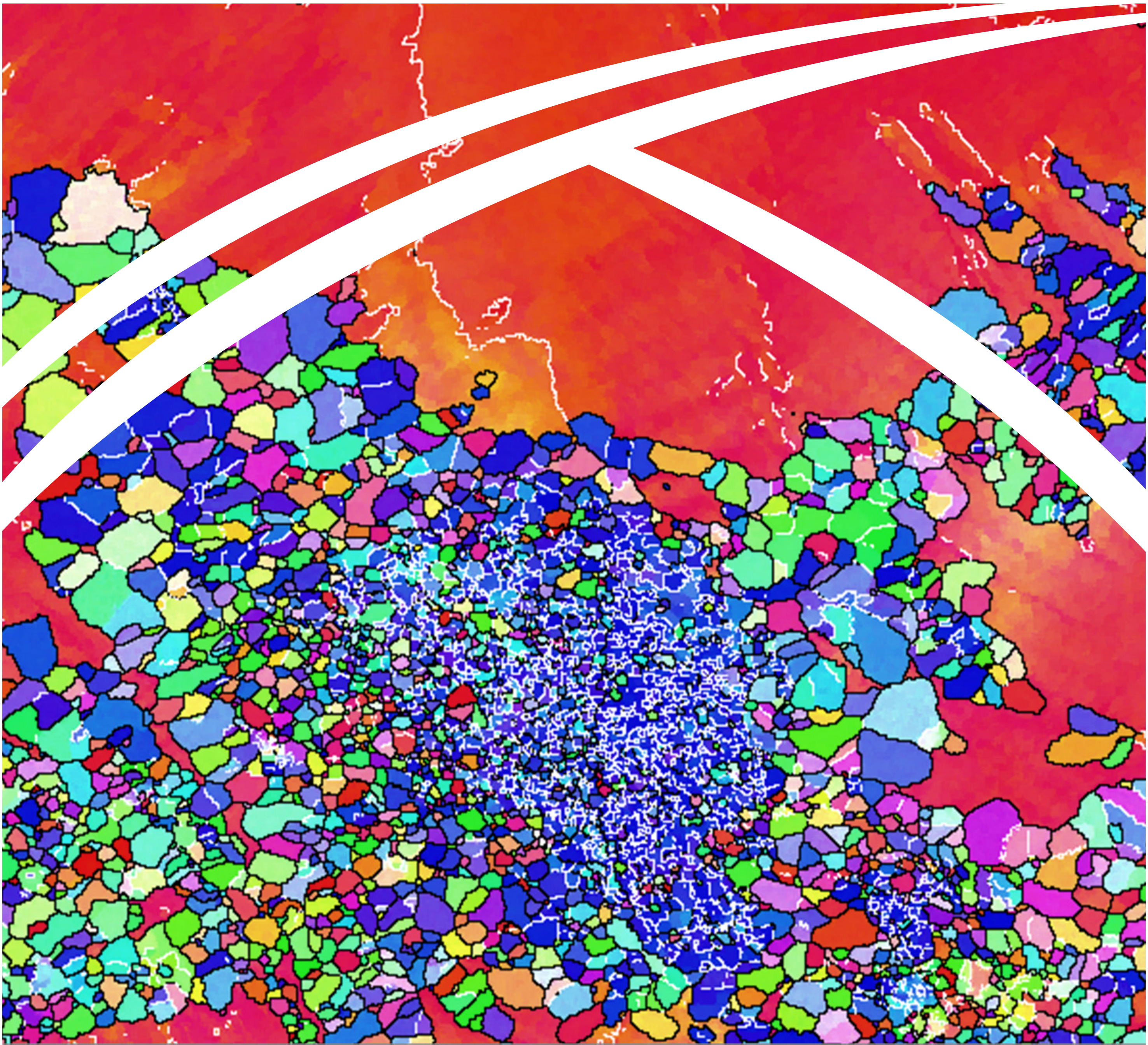
LIGHT FORM

YEAR TWO REPORT



MANCHESTER 1824
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Imperial College London

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CONTENTS

LIGHT FORM

MESSAGE FROM THE DIRECTOR

At the end of our second year, it is now clearer than ever that our future economy will have to be more sustainable, with lower carbon emissions. This brings home, more and more, the importance of advancing the UK's research capability in the more efficient use of light metals technologies. Forming components from light alloys (aluminium, titanium and magnesium) is extremely important to sustainable transport because they can save over 40% weight, compared to steel, and are far cheaper and more recyclable than composites. This is leading to rapid market growth in the automotive sector and increased demand for manufacturing with more specialised alloys in the aerospace and defence industries, particularly with titanium.

Professor Phil Pragnell

The philosophy behind LightForm is to adopt a more holistic approach to the engineering of formed light-alloy wrought components, so that we can simultaneously increase precision, process efficiency, and performance, through more intelligently embedding metallurgical design into the manufacturing cycle. Within LightForm we are developing a deeper understanding of the microstructure and texture evolution in materials under forming and forging conditions, where there is complex dynamic coupling between the material behaviour and the process. The overall aim is to capture the material behaviour in more physically based models that can be used to inform simulations performed in component scale engineering codes. This will allow embedded materials engineering to be more fully exploited by industry, by developing the capability to more accurately predict shape, the material behaviour and properties. The project is organised across three Challenge Themes, encompassing: (1) the essential enabling science; (2) developing more material informed computationally efficient simulation; and (3) implementation and process innovation.

Since last year major progress has been made which is summarised by each Theme Leader. Significant advances include: developing physical models to capture the dynamic, strain rate-dependent precipitation behaviour that dominates strengthening in high strength aluminium alloys for implementation in crystal plasticity, FE, 'virtual microstructure simulations' of sheet forming; developing robust high throughput lab-scale process physical simulations and the work flow for automated analysis of the data. For example, within a synchrotron beamline it is now possible to obtain diffraction data at over 100 Hz, which gives information at close to 'real time' rates for forging processes, and automatically analyse the data to generate full texture descriptions for each time frame. In Challenge 3 this work is already starting to have significant impact on solving commercially driven problems, such as reducing the component cycle time in hot press quench forming (HFQ) of aluminium sheet, extending the formability of magnesium alloys, and understanding the origin of abnormal grain structures, which currently cause unacceptable scrap rates in high-value titanium aerospace forgings.

Within the overall project we now have 41 projects and £5.6M of leveraged direct support from industry and other government funded projects. This includes 29 PhD students, based at Manchester and our partner institutions. We have also now launched our first 'club model' pre-competitive research consortium, TIFUN, comprising a cluster of PhDs jointly supported by 6 companies on the fundamentals of texture development in titanium forging. In addition, due to demand from industry, we have added a new work package focusing on environmental performance, which includes major projects on understanding environmentally assisted cracking in aluminium alloys, which is a key 'show stopper' for increasing the strength of these materials.

Our plans for developing large accessible data-bases for the community are also well on their way with a structured repository now being populated on Zenodo (hosted by CERN, through the 'LightForm community' group) linked to the analysis scripts and models the team are developing which are hosted at Github. We have also increased our capacity to up-scale our research by installing an instrumented pilot scale Interlaken hot forming press within the Advanced Metals Processing theme of the Sir Henry Royce Institute, which is being established at Manchester with its partner Universities, and are also in the process of procuring an instrumented forging facility.

This year the team have continued to be active in outreach with the community in the UK and internationally. Team members have given numerous invited talks at conferences and we hosted LightMAT2019 at Manchester, a 4 day international conference on light alloys with over 200 delegates and high quality international keynote lectures from as far afield as Australia.

If you would like to get involved in LightForm, please contact us through our Project Manager, Natalie Shannon (natalie.a.shannon@manchester.ac.uk).

Please also visit our website for more details on the project and news updates.
http://lightform.org.uk

LIGHTFORM AT A GLANCE

- 71 PUBLICATIONS
- CONFERENCES ATTENDED 57
- KEYNOTE INVITED 36
- 59 INDUSTRIAL ENGAGEMENTS

OUR TEAM

- 7 PDRA'S
- ASSOCIATED PDRA'S 5
- 1 REPRODUCIBILITY AND DATA MANAGEMENT OFFICER
- PHD'S ENGAGED IN INDUSTRY RELATED PROJECTS 23
- 29 PHD'S

LIGHTFORM OUTREACH

RESEARCH COMMUNITY OUTREACH	7
SCHOOL OUTREACH PARTNERSHIP	2
CONFERENCES ORGANISED	3

LIGHTFORM PROJECTS

41 TOTAL PROJECTS

BREAKDOWN:

Al ALUMINIUM	25
Ti TITANIUM	9

LEVERAGE

TOTAL LEVERAGE	£5,589,698
INDUSTRY	£2,706,373
EPSRC/RESEARCH ORGANISATION	£2,883,325

NEWS

VISITORS

Dr Ying Zeng
Southwest Jiaotong University

As an Assistant Professor, Ying's research at the Southwest Jiaotong University is mainly on understanding/modelling the mechanic behaviours and microstructural evolution of Mg alloys at the microscale and atomic scale. To further her research Ying reached out to The School of Materials due to the specialist HRDIC knowledge, to enable her to further explore the slip activity and strain localization.

Ying's current research through LightForm focuses on quantitative measurement of the slip activity and strain localisation in Mg alloys with Li addition at room temperature and the quantitative measurement of the strain localization in Mg-Sn-Y alloys with different precipitates.

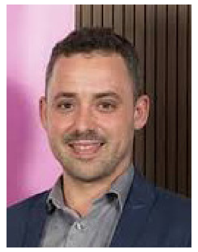
VISITORS

Professor David Fullwood
Brigham Young University

David spent the last year at The University of Manchester using the High Resolution Digital Image Correlation Technique to study metal deformation at the microstructural scale. His work focused on the fundamental role of grain boundaries during polycrystalline deformation, which is essential to the development of computational models of metal deformation.

NEWS

VISITORS



Dr Thomas Dorin
Research Fellow at Deakin University

Thomas's research focuses on the design of high performance aluminium alloys with a particular focus on microstructure characterisation which aims to understand and optimise the microstructure, and in particular the precipitates, in order to develop alloys with enhanced properties.

Over the past few years Thomas has focused his research on the development of the use of scandium as an alloying addition in a range of aluminium alloys.

Thomas was particularly interested to come and work with the renowned metals group at The University of Manchester for a range of reasons, to learn about modelling of microstructure development in alloys, particularly the precipitation kinetics, by collaborating with Prof Joseph Robson.

Thomas's research is the effect of silicon on the formation of the strengthening Al3Sc precipitates to identify the significant impact that Si has on accelerating the formation kinetics of the Al3Sc precipitates. Research it still on-going and will lead to multiple journal papers and continued collaboration with the researchers at The University of Manchester.

LIGHTMAT 2019

The 3rd International Conference on Light Materials – Science and Technology (LightMAT 2019) took place in Manchester from 3 to 5 November 2019, providing a comprehensive overview and new insight into the three most important light metals Aluminium, Magnesium and Titanium and their combinations.

A total of 170 delegates attended, with plenary speakers from both academia and industry including Nick Birbilis from ANU Australia, Blanka Lenczowski from Airbus Germany, Teresa Pérez-Prado from IMDEA Spain, and David Rugg from Rolls Royce.

A total of 20 countries were represented including The United Kingdom, Germany, Austria, France, Norway, Belgium, Canada, United States of America, Japan, Spain, Czech Republic, Australia, Switzerland, China, Italy, Latvia, Poland, Sweden, Slovakia and Turkey.

LightForm contributed significantly to the conference with a total of 13 papers, 8 of which were invited. 4 papers were also from members of LightForm International Advisory Board.

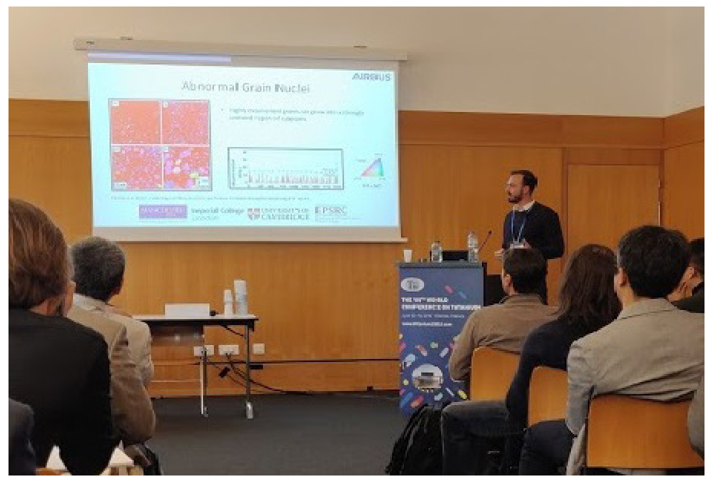
LIGHTFORM AT THE 14TH WORLD CONFERENCE ON TITANIUM

The LightForm research team had a strong presence at the Titanium World conference, which took place in Nantes, France, between the 10th and 14th of June. There were 9 presentations from researchers associated with LightForm , including two talks on the fatigue and creep behaviour of Ti834 and two talks on the additive manufacturing of Ti-6Al-4V with in-process deformation.

Nick Byres spoke about his research on understanding the origins of abnormal grain development in Ti-6Al-4V forgings. In a session with two other presentations on the same topic, Nick showed his detailed characterisation of the abnormal micro structure and new results showing the beta annealing behaviour in-situ using EBSD. Nick's project is sponsored by Airbus.

João Fonseca presented results from Christopher Daniel's in-situ synchrotron work, which show tantalising evidence that phase transformation occurs during hot deformation in Ti-6Al-4V. This preliminary work opens the way to in-situ studies of forging using synchrotron X-ray diffraction, the data from which will be invaluable to the development of new models for texture prediction during forging of Ti alloys.
Associated PDRA Chi-Toan Nguyen presented results of the crystal plasticity modelling of hot uniaxial deformation of Ti-6Al-4V, which aimed to explain the strengthening of the cube fibre component. Chi-Toan's work, a collaboration between Manchester, Otto-Fuchs and Airbus, shows that both grain shape and interactions between the alpha a beta phase can play a role on the development of this undesired texture.

Pre-prints of the conference articles are available through the LightForm Zenodo community.



CHALLENGE 1:
ENABLING SCIENCE FOR MANUFACTURING WITH EMBEDDED MATERIALS ENGINEERING

Challenge Theme 1 is focussed on the fundamental science required to make embedding microstructural engineering in advanced forming a practical reality.

Over the past year, the theme 1 activity has grown substantially through an additional 8 industry supported PhD projects, bringing the total number of PhDs associated with the theme to 13.

New project areas in aluminium have focussed on evaluating the fundamentals of aluminium alloy performance with the HFQ process, understanding the coupling between precipitation and deformation in cold and warm forming of high strength aluminium alloys. The theme has also expanded in response to industrial demand to focus more on critical performance issues. This includes creating a large activity aimed at understanding the fundamentals of environmentally assisted cracking (EAC) in high strength aluminium alloys. This last activity is being conducted in close collaboration with a new major Airbus supported research effort.

In titanium, new activities have started to understand the fundamentals of hot deformation behaviour and its effect on microstructure and texture evolution, utilizing in-situ techniques pioneered in LightForm. In magnesium, there are new projects to understand the micromechanics of deformation in formable magnesium alloys, and to investigate the potential to enhance age hardening response through deformation.

We are also delighted to have attracted two prestigious international visiting academics to work with us in 2019/20. Thomas Dorin from Deakin University, Australia has been collaborating on the fundamentals of microstructure and property development in aluminium alloys strengthened by $L1_2$ Al_3X phases. Ying Zeng from Southwest Jiatong University, China has been working on new magnesium alloy development and the fundamentals of magnesium alloy deformation.

Research Highlights

Hot Forming of Aluminium

In the past year, we have advanced our work on the HFQ process in collaboration with Impression Technologies. This is an attractive forming technique for high strength aluminium parts, particularly for the automotive industry. Focussed initially on 6xxx (Al-Mg-Si) alloys, we have performed detailed microstructural analyses on real HFQ components subject to different process routes. Using a model calibrated with isothermal heat treatment data, we have replicated the microstructures obtained in different regions of the HFQ part. This has enabled us to perform mechanical and corrosion tests that represent the local performance in the HFQ material. It has been demonstrated that although there are microstructural variations in the HFQ part, these do not negatively impact the fracture behaviour or corrosion response for the 6xxx alloy studied.

The project involves all three University partners working closely together and a number of published and submitted papers have arisen from this work (see HFQ spotlight). This activity is ongoing in LightForm, with focus now switched to the higher strength 7xxx (Al-Zn-Mg-Cu) alloys.

Dynamic Interactions in Aluminium

Understanding the interaction of deformation and formation of strengthening precipitates is critical to enabling the MEME (Manufacturing with Embedded Materials Engineering) concept envisioned in LightForm. These interactions are also of key importance in other proposed process routes for forming high strength aluminium alloys, such as cold forming after partial precipitation.

Since last year, we have made important advances in understanding dynamic interactions in high strength 7xxx alloys. Data from initial in-situ studies performed on AA7075 deformed at different strain rates have revealed an accelerating effect of strain rate on precipitate growth rate not noted in previous studies. The data have been used to develop and test a model for coupled deformation/precipitation. This model is currently being integrated into our multiscale crystal plasticity framework (Challenge 2).

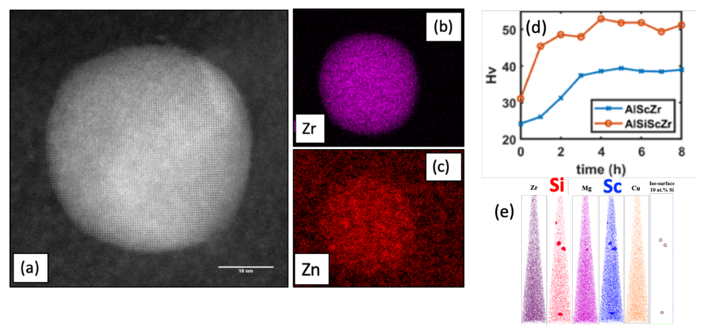
The strain rate used in these studies was a maximum of $10^{-2}s^{-1}$, which is the highest yet reported for such in-situ investigation. However, is still orders of magnitude less than that in a real forming operation, so a key future development will be to develop a higher strain rate in-situ capability. Ongoing work in LightForm is also exploring the effect of more complex strain paths, as experienced in real forming operations.

The models being developed are now also starting to be more widely applied to industrial challenges within Theme 3, including in new projects on creep-age forming of high-energy hydroformed Al-fuselage structures.

Aluminium Strengthened with Dispersoids

An attractive alternative to conventional age hardened aluminium alloys for applications requiring formability, high strength, weldability, and low density is a class of alloys based on solid solution strengthening combined with $L1_2$ Al_3X dispersoids (X = Zr, Sc, Ti...). The challenge with these alloys is to accelerate dispersoid precipitation to reduce heat treatment times and increase the strengthening effect through increasing volume fraction.

We have recently demonstrated that contrary to previous assumptions, the dispersoids are influenced by the other elements used in Al alloys (e.g. Zn, Mg, Cu, Si) and this can profoundly change their behaviour, which can be manipulated to increase their strengthening contribution. We have also discovered a previously unreported form of the dispersoid phase that is formed in 7xxx alloys due to the presence of Zn. This has consequences for the quench sensitivity of such alloys (which is important in processes such as HFQ).



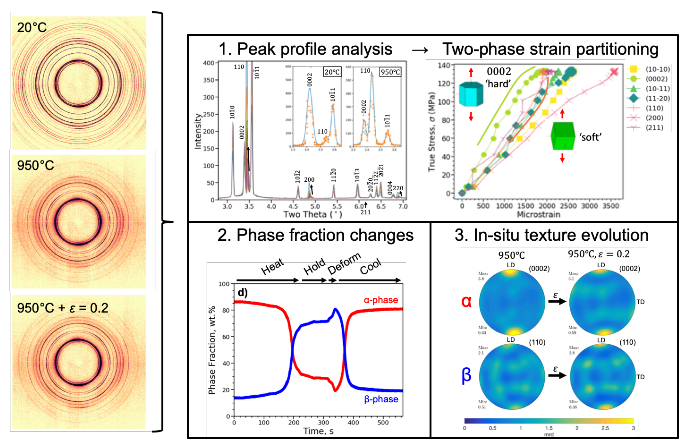
(a) High resolution image of a typical $L1_2$ dispersoid in a 7xxx alloy, showing the expected high concentration of (b) Zr as well as (c) the incorporation of significant Zn, which changes the phase stability. (d) Effect of adding Si to Al-Sc-Zr alloy on accelerating hardening and increasing strength due to $L1_2$ dispersoids. (b) Atom probe showing Si and Sc clusters forming early in the precipitation of dispersoids (collaboration with Deakin University).

Grain Growth and Texture Evolution in Titanium using In-Situ Methods

Understanding the origin of abnormal grain structures formed during processing in the high temperature (β-phase) in titanium alloys is a major industrial challenge, owing to their significance to the inconsistent quality of forged products. Understanding the mechanism controlling this process is difficult since the β-phase transforms to α with a number of different variants on cooling to room temperature, making texture analysis of the β phase problematic. We have developed a novel quasi-in situ method that involves using a heating stage within the microscope combined with EBSD and β-phase reconstruction to track the evolution of the β grain structure over time for a given location. This work is being used to understand the critical conditions that lead to abnormal grain formation, as well as providing data to inform development of models for the process (challenge 2). This work has highlighted the key role of achieving better control of the prior texture present in the materials before β annealing.

More precise control of texture in wrought titanium products is an important long term goal is it is being increasingly recognised as critical to the performance of titanium alloy components. A key area of interest in this context is to better understand how dynamic effects related to phase transformation when processing in the α–β phase field influence the texture development. Using synchrotron X-rays, diffraction patterns can now be captured at high frequency (>100Hz), and used to extract in-situ full texture descriptions and phase fraction transformation information at rates required to replicate industrial processes. We have developed a rig that enables deformation and heating to be carried out on titanium in the beam line, capturing such diffraction patterns throughout processing. The large datasets (>10^3 diffraction patterns) require automated tools to extract the critical information, and we have recently developed the necessary codes and methods to enable this. These tools are being made available to the community through Zenodo.

This work is now proceeding at pace through the TIFUN project, which is a new pre-competitive crowd funded work-package in LightForm, involving 4 PhDs jointly funded by 6 companies across the supply chain, working on fundamental underpinning research.



Examples of raw diffraction patterns and automatically extracted outputs derived from a synchrotron X-ray in-situ heating and deformation study of Ti-64.

Future Plans

In the next year, there are a number of key areas where we will focus our efforts. In aluminium, we now have the tools in place to study dynamic interactions of precipitation and deformation. We will apply these tools to more complex strain paths and extend the strain rate range towards industrial processes. This work will be linked to practical forming studies enabled by new facilities within the Royce institute. The resulting data will be used to improve our new model for dynamic interactions. In titanium, the tools we have developed for rapid in-situ measurement will be applied to provide fundamental insights into abnormal grain growth and texture evolution during forging and heat treatment. In magnesium, we will continue to work on both processing and alloy design strategies to improve formability, along with understanding the effects of local micro-texture on deformation and failure.

Highlighted Publications

Precipitation sequence in Al–Mg–Si–Sc–Zr alloys during isochronal aging, T.Dorin M. Ramajaya S.Babaniaris Lu.Jiang T.J.Langan, (https://doi.org/10.1016/j.mtla.2019.100437)

Experimental investigations of stress-relaxation ageing behaviour of AA6082, Qi Rong Yong Li Zhusheng Shi Lichu Meng Xiaohong Sun Xiaoguang Jianguo Lin, https://doi.org/10.1016/j.msea.2019.02.043)

Effect of Dispersoids on the Microstructure Evolution in Al–Mg–Si Alloys Michael Kenyon Joseph Robson Jonathan Fellowes Zeqin Liang, (https://onlinelibrary.wiley.com/doi/full/10.1002/adem.201800494?af=R)

Dispersoid composition in zirconium containing Al-Zn-Mg-Cu (AA7010) aluminium alloy, A.M.Cassell J.D.Robson C.P.Race A.Eggeman T.Hashimoto M.Besel, (https://doi.org/10.1016/j.actamat.2019.02.047)

Direct Evidence for a Dynamic Phase Transformation during High Temperature Deformation in Ti-64 [Preprint], Daniel, Christopher Stuart, Nguyen, Chi-Toan, Atkinson, Michael D., & Quinta da Fonseca, João. (2019, August 20). . Zenodo. http://doi.org/10.5281/zenodo.3381183

CHALLENGE 2:
COMPUTATIONALLY EFFICIENT MATERIAL AND PROCESS MODELLING

The aim of **Challenge Theme 2** is to develop an efficient computational modelling framework for modelling material behaviour, including microstructural evolution, and embed it into forming process models. The theme's main objectives are:

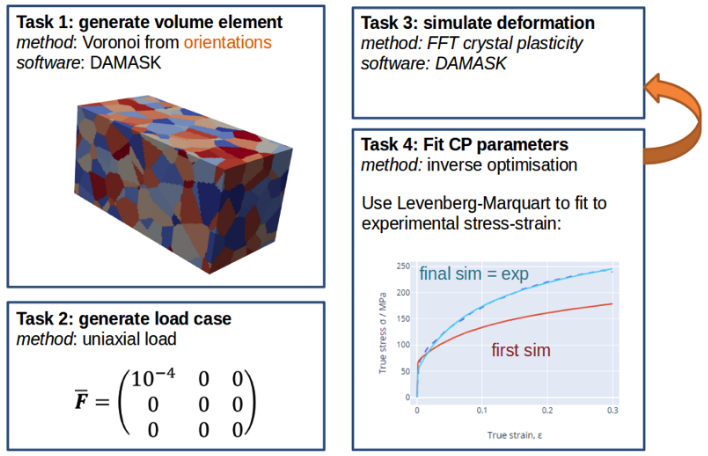
- To develop material sub-models that capture key aspects of the evolution of deformation structures
- Develop new models for sub-transus deformation of dual phase Ti alloys
- Couple microstructure evolution models with crystal plasticity codes to produce "virtual microstructure simulations" that can predict dynamic forming limits and yield surfaces
- Validate the models against rich data sets generated in Challenge 1, and inform and reduce experimental effort
- Develop accurate engineering process models for new flexible forming technologies (e.g. for property tailoring).
- Explore computationally efficient routes to integrate microstructurally informed simulations into engineering forming codes.

In year 2 the focus was on development of the modelling frameworks for virtual materials modelling, modelling the effects of deformation on precipitation and developing models for understanding the actual process conditions during simulations of thermomechanical processing in titanium alloys.

Research highlights

Computational Pipelines for Virtual Dynamic Materials Testing

One of the main aims of LightForm is to be able to run "virtual microstructure simulations" that can material behaviour and be used to predict forming limits. The aim is to reduce the time needed to test a new material and to help in the development of new alloys with good formability.
In year 2 we have developed the first version of "matflow", the computational framework that will make these simulations possible. In this first iteration, "matflow" has pipelines for efficient determination of crystal plasticity material parameters, yield surface generation, microstructure sensitivity studies and visualization. One key feature of "matflow" is the ability to iterate simulations using input from previous runs, making it possible to carry out large sensitivity studies in a self optimised way. In "matflow", all the simulation parameters and run results are stored in a database form so that it can be recalled at any time for visualization or post-processing, but also to ensure complete reproducibility.
The "matflow" framework aims to be agnostic to the modelling approach used. For example, yield surface determination can be made using a self-consistent, Taylor or full-field approach. Initial work has focused on using full-field crystal plasticity models which require high performance computing (HPC). HPC requires specific skills that limit it applicability by students and other researchers. To overcome this barrier, we have developed "hpcflow", a wrapper for interaction with HPC resources that is called directly from "matflow" when HPC resources are required. Both modelling frameworks are being developed as open source software and are available on the LightForm GitHub space.



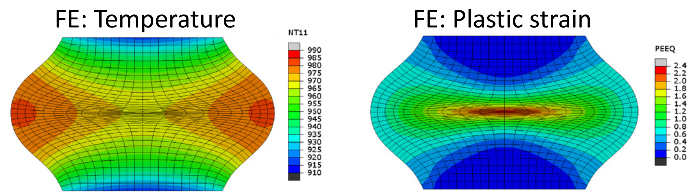
Example of a "matflow" pipeline for fitting single crystal hardening parameters using experimental determined orientations to create a virtual microstucture, testing it in uniaxial compression and refining hardening parameters using iteration. The methods and software used in the simulations and model creation are chosen by the user as inputs to "matflow".

Dynamic Precipitation Modelling

During warm forming of high strength aluminium alloys, the microstructure will evolve in ways that will affect the formability and the properties of the material after forming. To predict these effects, we have started developing a dynamic precipitation model, capable of accounting for the effects of deformation on the precipitation and dissolution of second phase particles. The model uses the established Kampmann-Wagner Numerical (KWN) framework to include deformation effects by implementing dislocation density evolution, and account for excess vacancies to simulate dynamic strain ageing. The model is now being calibrated using time-resolved synchrotron X-ray small angle scattering (SAXS) results and other lab-scale simulations. In year 3, the model will be implemented into a full field plasticity framework, for which a "matflow" pipeline will be developed so it can be used in virtual material simulations.

Process Models for Dynamic Materials Engineering

During the first year, research led by Cambridge University and supported by Manchester, focused on modelling lab-scale upsetting tests, containing thermal gradients and linking it to microstructure evolution", with initial models applied to the testing of zirconium alloys. In the second year, the models have now been applied to two Ti alloys and have been extended to model simulations carried out with different test machines. An extensive experimental matrix has been produced, comparing results from a deformation dilatometer, a Gleeble machine and a Servotest machine, all of which heat the material in different ways. This work has shown that although nominal stress-strain curves produced by the different machines are comparable, the temperature, and deformation gradients are very different. This knowledge of the actual process condition is essential to the interpretation of the microstructures and textures found in test specimens.



Finite element modelling simulation of a sample tested using a deformation dilatomer. Friction at the compression platens and the presence of a large temperature gradient leads to very non-homogeneous distribution of plastic strain in the sample, which must be accounted for when interpreting any microstructural changes observed.

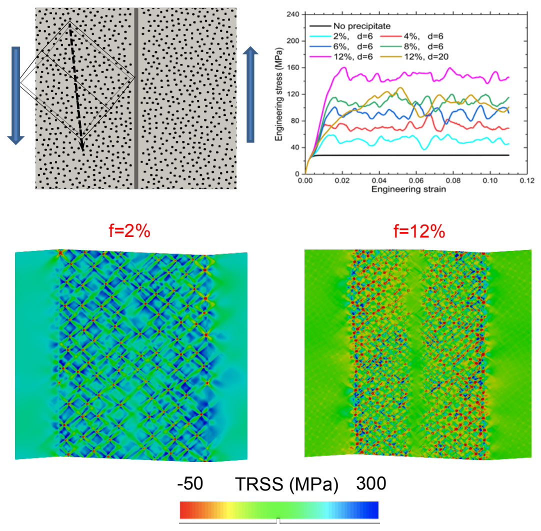
Modelling Twinning

Another highlight of year 2 was the collaboration between LightForm and the Max-Planck-Institut für Eisenforschung in Dusseldorf. In this work, the DASMASK framework was used to simulate the effect of precipitation on twin growth. Using crystal plasticity based phase-field model, the research demonstrated that precipitates cause an Orowan-like strengthening effect on twin growth. As is the case with slip, the strengthening effect was shown to depend on the distribution and shape of the particles. This new understanding enabled the proposal of new guidelines for the design of high strength magnesium alloys.

Modelling Fast Ageing Following Pre-deformation

Work has has progressed on the development of material based models to predict the effects of pre-deformation on the ageing behaviour of 6xxx alloys after warm pre-deformation. These models will enable the prediction of the properties of aluminium alloy components after press quenching in the HFQ process, for example. New experimental work has shown that deformation can enhance the precipitation kinetics and these new material models are key to exploit these effects to speed up the ageing process after forming. See the HFQ highlight article for more details.

CHALLENGE UPDATES



Phase field modelling of the strengthening effect of precipitation on twin growth in magnesium. The strengthening mechanisms is Orowan-like and depends on the shape, volume fraction and size of precipitates.

Future plans

In the third year of LightForm, the plan is to increase the number of PhD students working with computational modelling by leveraging the "matflow" and "hpcflow" frameworks. The precipitation model will be fully integrated into the full-field DAMASK model and its predictions will be further validated, for a wider range of alloys and using results from Challenge 1. We will also develop a collaborative proposal for integrating these models into commercial codes using current project partners, In year three, we will also apply the full field modelling framework to model the deformation and microstructure evolution (including texture of Ti), as part of the new TIFUN consortium, more details of which are given in the titanium highlight article in page 14.
Two new PhD projects will also start in year 3: one on phase field modelling of grain boundary precipitation in Al alloys and one on coupled crystal plasticity- phase field modelling of Ti forgings.

Highlighted Publications

A. Plowman, hpcflow - An automated simulate, process, archive workflow on high performance computing (HPC) systems. https://github.com/LightForm-group/matflow

A. Plowman, matflow - Computational materials science workflow management in Python. https://github.com/LightForm-group/hpcflow

C. Liu, P. Shanthraj, J.D. Robson, M. Diehl, S. Dong, J. Dong, W. Ding, D. Raabe, On the interaction of precipitates and tensile twins in magnesium alloys, Acta Materialia. 178 (2019) 146–162. https://doi.org/10.1016/j.actamat.2019.07.046.

A. Orozco-Caballero, F. Li, D. Esqué-de los Ojos, M.D. Atkinson, J. Quinta da Fonseca, On the ductility of alpha titanium: The effect of temperature and deformation mode, Acta Materialia. 149 (2018) 1–10. https://doi.org/10.1016/j.actamat.2018.02.022.

D. Esqué-de los Ojos, C.-T. Nguyen, A. Orozco-Caballero, G. Timár, J.Q. da Fonseca, Back-stresses and geometrical hardening as competing mechanisms enhancing ductility in HCP metals, Materials Science and Engineering: A. 729 (2018) 37–47.

J.-H. Zheng, J. Lin, J. Lee, R. Pan, C. Li, C.M. Davies, A novel constitutive model for multi-step stress relaxation ageing of a pre-strained 7xxx series alloy, International Journal of Plasticity. 106 (2018) 31–47. https://doi.org/10.1016/j.ijplas.2018.02.008.

CHALLENGE 3:

PROCESS INNOVATION – MANUFACTURING WITH EMBEDDED MATERIALS ENGINEERING (MEME) IMPLEMENTATION

Challenge Theme 3 aims to exploit the fundamental materials engineering knowledge developed in Challenge 1 and the modelling and simulation tools developed in Challenge 2, to advance novel forming processes that will extend manufacturing technology and the ability to form more difficult materials.

Over the past year, the challenge 3 activity has continued to grow across all work-packages. The major research activities in Challenge 3 have been:

(i) Aluminium alloys: development of compressed HFQ routes, aiming to significantly reduce the processing time and increase productivity.

(ii) Magnesium alloys: determination of new, improved processing windows for the rolling of Mg, aiming to develop a rapid rolling technique at different temperatures ranging from liquid nitrogen temperature to 400 °C.

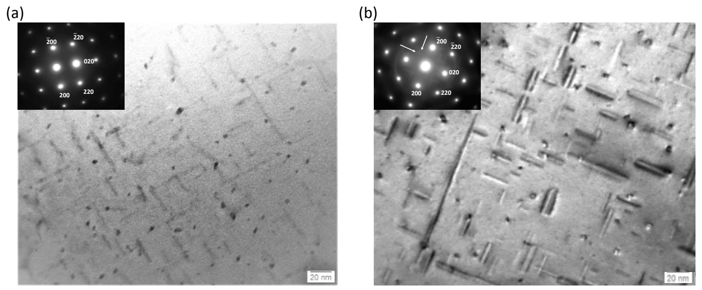
(iii) Titanium alloys: development of fast forming technique. Feasibility study of the optimized forming windows for the fast forming technique.

(iv) Method for generating accurate forming limit diagram: a new method was established to achieve forming limit diagram for hot stamping conditions. Originally applied to boron steel, this has now been used to test aluminium alloys and can be extended to other light alloys like magnesium, and titanium alloys.

Highlights

Rapid Post Forming Ageing

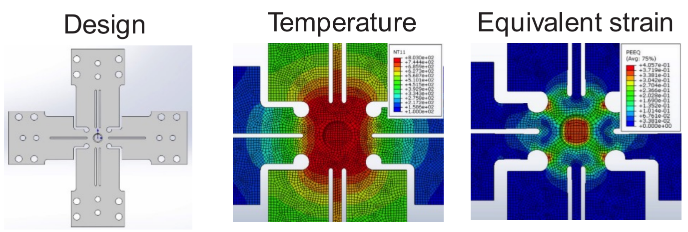
The aim of this project, led by Imperial College in close collaboration with Manchester and Cambridge, was to investigate the viability of reducing the artificial ageing cycle traditionally used after quench forming to achieve T6/8 peak strength in heat treatable aluminium alloys. Conventionally, ageing requires 9 to 12-hour ageing treatments, which is too long for large scale automotive production. Results to date are very encouraging and have demonstrated that, by control of the thermal cycle in standard automotive materials like AA6082, it is possible to reduce the time to less than 20 minutes and still achieve a yield strength that is 95% of that of the standard T6 temper. In-depth microstructural analysis was used to show that there is no clear evidence of heterogeneous precipitation, and no measurable change in the corrosion performance. As well as developing the rapid ageing method, this project has also provided an in-depth understanding of the microstructure evolution during the quench pressing and ageing process. The work involved close collaboration between Imperial College, Manchester and Cambridge.



Bright field TEM images of optimum fast-aged specimens with fast heating pre-aged at (a) 210 °C for 15 min and (b) 210 °C for 40 min

Generating Forming Limit Data Under Hot Stamping Conditions

Predicting the formability of metal sheets under hot stamping conditions requires the determination of the material's unified constitutive equations. We have developed a novel experimental method to quickly characterise material behaviour under biaxial deformation. A this stage of the project, we have developed a standard cruciform specimen and tested for formability determination in in-plane biaxial tensile tests in various forming conditions, such as metal forming at room temperature and under hot stamping condition. We designed and developed a novel gear-driven rig for in-plane biaxial tensile tests, now A patented, which has been optimised to stretch cruciform specimens using linear strain paths under various strain states, such as uniaxial tensile, plane-strain tension and equi-biaxial tension.

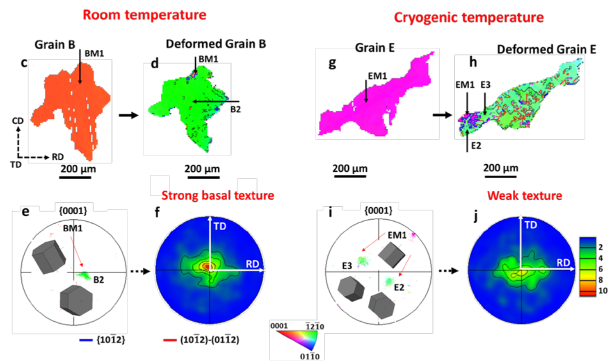


Optimised biaxial specimen for uniform temperature control in gauge area

Development of Low-cost Rolling Process of Mg Alloys using Cryogenic Deformation Technique

This project aims to use the cryogenic deformation technique to improve production efficiency and develop a low-cost rolling process for Mg alloys. Over the first part of the project, we have conducted on a feasibility study using cryo-deformation and investigated the operative deformation mechanisms. This understanding will be used for future technique development.

The deformation mechanisms were investigated of magnesium alloys uniaxial compressed at cryogenic temperature. It has been found that desirable weakening of texture was developed during cryogenic deformation. In future work, we aim to exploit this phenomenon at the industrial scale.



Deformation bands, twins and texture comparison between room and cryogenic temperature deformation.

Hot Stamping of Ti64 Sheet

The aim of this work is to develop a novel cost-effective hot stamping process for forming complex-shaped titanium alloy panel components with low energy consumption. Microstructures and hot deformation viscoplastic behaviour have been determined for achieving optimized forming windows. Challenges of this work involved (i) find ways to reduce the strain-softening phenomenon during forming, such that complex geometry Ti alloy panels could be achieved. (ii) retain the required microstructures with required mechanical properties. An optimum balance in strain rate during forming is required to avoid excessive adiabatic heating (at high rates) whilst minimizing undesirable microstructural coarsening at low rates.

Control of Abnormal Grain Structures in Ti Forgings

Large Ti structural forgings, used in aero structures, are usually beta heat treated to produce an optimized microstructure with high toughness. On occasion, unwanted abnormal grain structures can develop during heat treatment, which can affect the properties of the material. This project aimed to understand the origins of these abnormal microstructures. Using electron backscatter diffraction (EBSD) analysis, it was found that these defects originate in regions of very strong texture that develop during hot working. This new understanding can be used to modify the processing route during forging, and avoid the development of abnormal grains. More details are given in the titanium highlight article.

Future Plans

In the coming years, Challenge 3 will focus on applying the fundamental knowledge from challenges 1 & 2 to the development of new light-alloy forming techniques advancing the more established techniques. We will further validate the fast-ageing method and test it in an industrial setting, where it is expected to significantly reduce the processing cycle time, especially for HFQ applications. We are also currently developing a novel extrusion technique for producing curved extruded profiles. Research will be focus on validating the effectiveness of new extrusion technique, in terms of microstructure and grain refinement control and investigation and viscoplastic behaviour and material modelling. For magnesium alloys, we will focus on transferring the mechanistic understanding obtained this year, to increase the rolling speed of Mg and improve productivity. A new project will start on creep age forming of aluminium, making use of the new precipitation models developed in challenge 2. Another project will concentrate on developing digital microstructure descriptors for the classification of Ti alloy microstructures and the creation of efficient virtual materials models.

Highlighted Publications

[1]. Zheng, J.-H., Dong, Y., Zheng, K., Dong, H., Lin, J., Jiang, J., Dean, T.A., 2019a. Experimental investigation of novel fast–ageing treatments for AA6082 in supersaturated solid solution state. Journal of Alloys and Compounds 810, 151934. https://doi.org/10.1016/j.jallcom.2019.151934

[2]. Zheng, K., Dong, Y., Zheng, J.-H., Foster, A., Lin, J., Dong, H., Dean, T.A., 2019b. The effect of hot form quench (HFQ®®) conditions on precipitation and mechanical properties of aluminium alloys. Materials Science and Engineering: A 761, 138017. https://doi.org/10.1016/j.msea.2019.06.027

[3]. K. Zhang, J.-H. Zheng, Z. Shao, C. Pruncu, M. Turski, C. Guerini, J. Jiang, Experimental investigation of the viscoplastic behaviours and microstructure evolutions of AZ31B and Elektron 717 Mg-alloys, Materials & Design 184 (2019) 108160. https://doi.org/10.1016/j.matdes.2019.108160

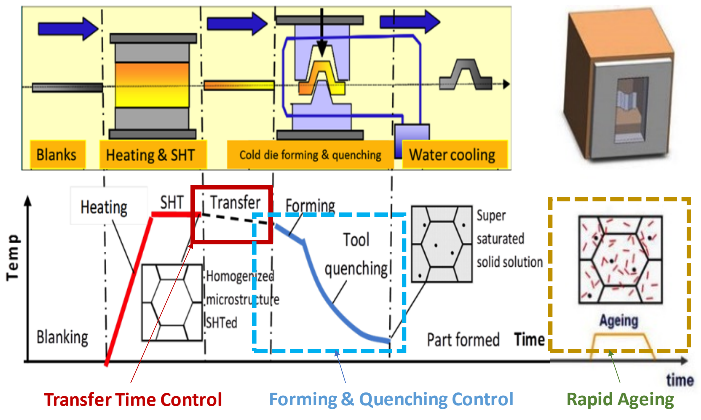
[4]. Zheng, K., Zhu, L., Lin, J., Dean, T.A., Li, N., 2019. An experimental investigation of the drawability of AA6082 sheet under different elevated temperature forming processes. Journal of Materials Processing Technology 273, 116225. https://doi.org/10.1016/j.jmatprotec.2019.05.006

[5]. Analysis of the development of abnormal grains structures during beta annealing of Ti-64 wrought products [Preprint]. Byres, Nicholas Edward, Quinta da Fonseca, João, Dod, Benjamin, & Prangnell, Phillip B. (2019, September 26). Zenodo. http://doi.org/10.5281/zenodo.3462337

Researchers:

Prof. Jianguo. Lin, Prof. Joe Robson, Dr. Hugh Shercliff, Dr. Jun Jiang, Dr. Nan Li, Dr. Paloma Hidalgo-Manrique, Dr. Alex Cassell, Dr. Jing-Hua Zheng

Hot Form and Quench (HFQ®) is a cutting-edge sheet metal forming technique for producing aluminium panel structures with complex geometries. This method has been successfully applied to form high-strength automobile body panels. The essential features of the HFQ process are shown adjacent.



This research concentrates on a wide range of property control of HFQ formed panels, including: (i) the effect of the blank transfer and forming times on premature precipitation, providing indications of the tolerance to process speed in industry; (ii) quantifying the dislocation densities after forming, giving comprehensive microstructural data for understanding and modelling of the hot deformation behaviour; (iii) developing a rapid ageing treatment, significantly reducing the ageing time from 9 h to 20 min. Complementary to the development of novel process routes led by Imperial are microstructural analysis, tensile testing, and corrosion characterisation performed at Manchester and Cambridge.

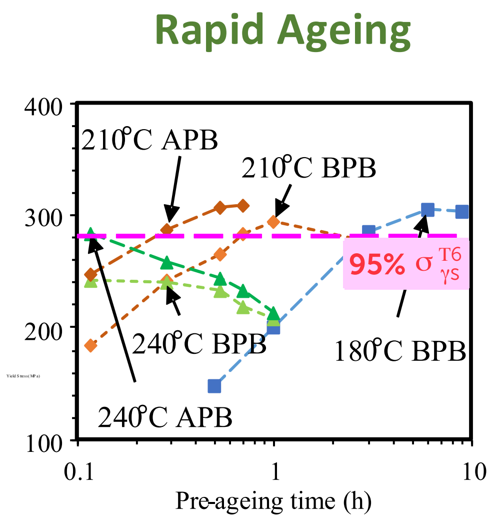
From the industrial perspective, the studies provide important knowledge for better design of HFQ parts and process parameters, especially for property control. Additionally, the novel accelerated ageing treatment leads to a significant reduction in the processing time and increased productivity, leading to economic savings. The scientific focus has been to understand the evolution of microstructure during the HFQ process, and to compare this with that obtained without hot forming. Previous studies have focussed primarily on demonstrating that the HFQ process can obtain strength levels in the final product that are comparable to standard T6 temper sheet, but the present work has extended this to properties such as ductility and corrosion response. This study has included both real HFQ parts formed using the commercial process, and controlled laboratory simulations enabling particular aspects of the process to be targeted. Selected results are highlighted below, from different stages in HFQ.

Key outputs:

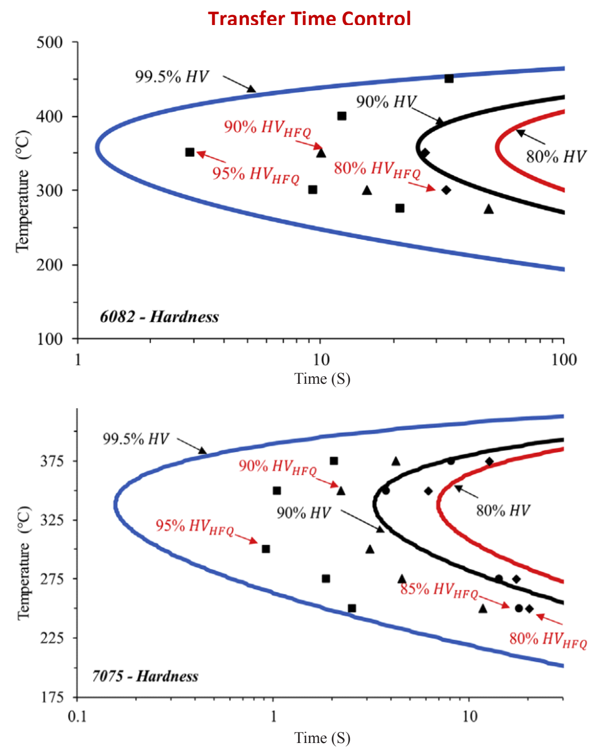
Blank Transfer Effects:

The cooling during the blank transfer operation in HFQ® may reduce the post-treatment mechanical properties – this has been shown to be negligible in alloy 6082, but may be significant for highly quench sensitive alloy 7075.

A substantial loss of post-ageing was found for the sensitive temperature range, from 250 °C to 400 °C for 7075 sheet. The strength loss increases with increasing delay in the holding time.



Strength after different age ing treatments, before and after paint-bake (PB) treatment.



TTT diagram showing precipitation kinetics during cooling.

Dislocation Density Quantification for HFQ®

This work visualised and quantified the dislocation distributions after hot deformation, and clarifies the key mechanisms, providing valuable data for calibrating physically-based material models.

The overall dislocation density increased with applied plastic strain. High temperatures and low strain-rates reduced the accumulation of geometrically-necessary dislocations.

Quench induced Precipitation

Some precipitation occurs on grain boundaries during the quench in HFQ, particularly in regions of the part that experience the slowest cooling rate in the critical temperature range for quench sensitivity.

The size of quench induced precipitates remains small and their volume fraction is low. Grain boundary precipitates have no effect on the subsequent age hardening response.

Rapid Ageing for HFQ®

A rapid ageing treatment was developed to reduce the ageing time from 9 h to 20 min for AA6082. The strength achieved was 90% of the nominal T6 value.

Rapid ageing produces a somewhat different precipitate size distribution compared to standard ageing, but the differences only have a small effect on properties.

Corrosion and Fracture Behaviour

The corrosion behaviour of 6082 HFQ sheet in both standard and rapid aged conditions is comparable to unformed T6 temper material using standard corrosion tests.

Regardless of position in the part or the amount of grain boundary precipitation, the fracture mode for 6082 after HFQ and ageing remains transgranular and ductile.

Summary

HFQ combined with rapid ageing can be successfully used to form parts from medium strength aluminium alloys, with greatly reduced cycle times compared to conventional sheet forming. The HFQ process leads to some differences in microstructure in formed parts, compared to standard T6 aged sheet, but these differences have only a small effect on the properties, at least for AA6082. Work is ongoing to understand the effect of the HFQ process on more complex properties of importance in the more quench-sensitive 7xxx alloys (7075), including the resistance to stress corrosion cracking.

Researchers that Contribute to this Topic:

Prof. Jianguo. Lin, Prof. Joe Robson, Dr. Hugh Shercliff, Dr. Jun Jiang, Dr. Nan Li, Dr. Paloma Hidalgo-Manrique, Dr. Alex Cassell, Dr. Jing-Hua Zheng

Highlighted Publications

[1]. Zheng, J.-H., Dong, Y., Zheng, K., Dong, H., Lin, J., Jiang, J., Dean, T.A., 2019a. Experimental investigation of novel fast–ageing treatments for AA6082 in supersaturated solid solution state. Journal of Alloys and Compounds 810, 151934. https://doi.org/10.1016/j.jallcom.2019.151934

[2]. Zheng, K., Dong, Y., Zheng, J.-H., Foster, A., Lin, J., Dong, H., Dean, T.A., 2019b. The effect of hot form quench (HFQ®®) conditions on precipitation and mechanical properties of aluminium alloys. Materials Science and Engineering: A 761, 138017. https://doi.org/10.1016/j.msea.2019.06.027

[3]. Zheng, K., Zhu, L., Lin, J., Dean, T.A., Li, N., An experimental investigation of the drawability of AA6082 sheet under different elevated temperature forming processes. Journal of Materials Processing Technology 273, 116225. https://doi.org/10.1016/j.jmatprotec.2019.05.006

Research highlight: Titanium alloys

Titanium alloys are essential to the aerospace sector, where they are used extensively in both power plants and structures. Their attractiveness stems from both their unique combination of strength, stiffness and low density and their versatility, which is in great part due to a microstructure that can be tailored by thermomechanical processing. The most popular alloy in aerospace is Ti6Al4V, which is used to make the fan blades of jet engines and as structural elements in wings, particularly in aircraft with a carbon-fibre composite bodies. Although the same chemical composition is used in both applications, the microstructure used is quite different: engineers prefer a duplex microstructure for the blades, which is stronger and more fatigue-resistant, and a beta heat-treated microstructure for the wings and pylons, which is more resistant to crack propagation.

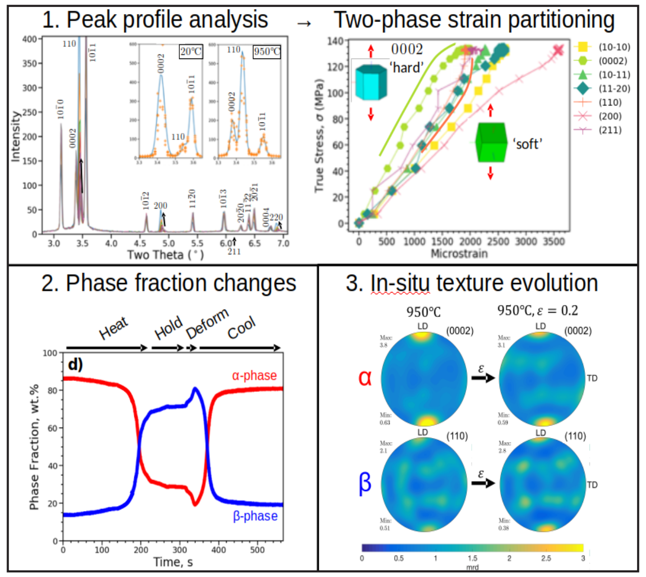
Although the metallurgical routes needed to produce these micro-structures are well-established industrially, it is very difficult to predict the microstructure evolution during processing of these alloys when the processing conditions or alloy chemistry vary from those currently established empirically. As a consequence, the processing of these alloys is resource intensive and it is difficult to innovate in either alloy composition or process route. One of the aims of LightForm is to develop new computational models that are able to better predict microstructure evolution in titanium alloys, with a particular focus on texture, and how it is affected by changes in material chemistry. These models will help overcome the current limitations imposed by empiricism and enable innovation.

The challenge lies in the complex nature of the microstructure evolution in these alloys. Alloys like Ti6Al4V are processed at very high temperatures, during which deformation, annealing and phase transformation all take place simultaneously. As a consequence, the deformed microstructure is usually unavailable for studying after processing because it changes dramatically on cooling. Furthermore, processing is carried out in multiple incremental steps, during which the temperature fluctuates and the microstructure is modified, obscuring any changes that developed in previous steps.

The approach in LightForm is to use new developments in materials testing and characterisation, to generate much richer datasets that can be used to develop and refine computational models. In-situ characterisation, for example, produces time-resolve data that can follow the microstructure evolution during deformation and between deformation steps, revealing information that was once unavailable.

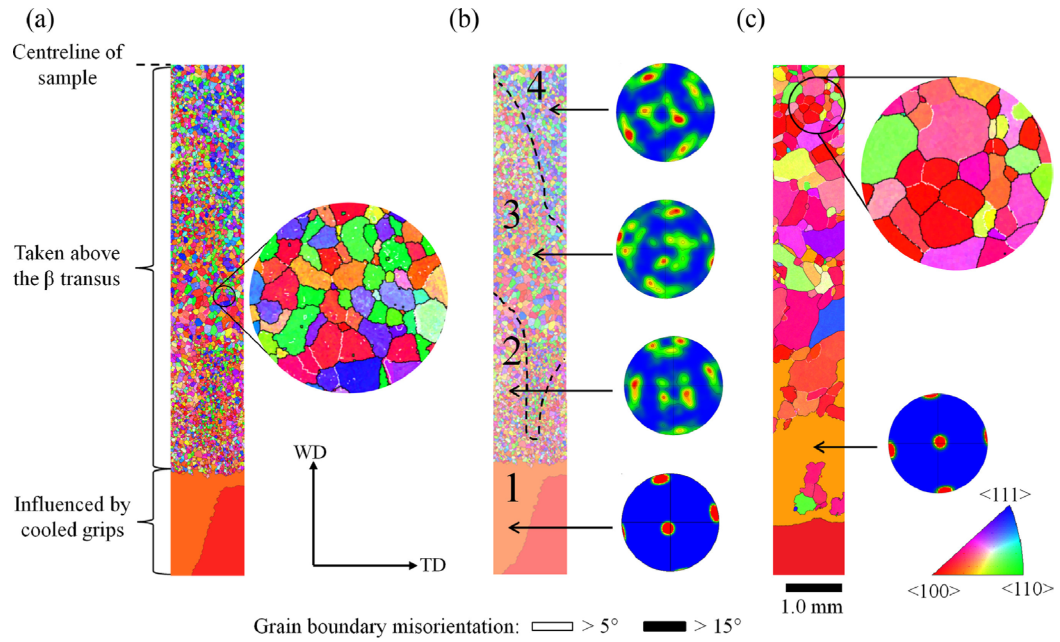
One of the techniques being exploited in LightForm to obtain this precious in-situ data is synchrotron diffraction. The powerful X-rays produced at facilities like Diamond Light Source, in the UK, are capable of making diffraction measurements in fractions of a second. Diffraction can be used to measure texture, internal strains and phase volume fraction during hot deformation. These fast acquisition times lead to large data sets that are difficult to analyse. In LightForm we have developed new tools for the data analysis of in-situ diffraction datasets. These tools, which are openly available to the community via GitHub and Zenodo, were built to analyse the changing, shifting diffraction peaks during heating, hot deformation and cooling.

Preliminary results presented at the 2019 Titanium World Congress have confirmed the potential of this approach to study the deformation of Ti6Al4V. Working on beamline ID-11 at Diamond, an electro-thermal-mechanical tester (ETMT) was used to heat up and deform samples in tension at strain rates of 0.1 s^{-1}, whilst diffraction patterns were acquired at a frequency of 10Hz. These experiments revealed that the β phase fraction increases noticeably during deformation at constant temperature, suggesting the operation of dynamic phase transformation. Alongside this phase transformation, there was a measurable change in the texture of the α-phase which implies that dynamic phase transformation is a potential new mechanism for texture evolution during hot deformation. This data can be used to refine crystal plasticity finite element models for texture prediction, that can be extended to include phase transformation and chemistry effects by using a phase field formulation.



Analysis of the synchrotron data provides a wealth of invaluable data, including the load partitioning between the alpha and beta phase, changes in the phase volume fractions and changes of texture during deformation.

The same synchrotron diffraction approach was used to study the texture evolution during the annealing of wire-arc additive manufacturing (WAAM) with inter-pass deformation. Microstructure analysis of the WAAMed material had revealed a very characteristic texture, which appeared to be related to the original β-phase orientation by twinning. However, it was not possible to determine when in the process this new texture developed. The AM process is characterised by very high heating and cooling rates, nevertheless we were able to capture the texture change during heating and show that is only happens later in the transformation. The initial texture is very similar to the cold beta orientation, but towards the end of the heating cycle and as the material approaches the beta transus, it is replaced by the new orientations, which are (double) twin related to the starting orientations. These results were consistent with the observation of twins during in-situ heating experiments in the SEM, which have also been pioneered at Manchester.



By simulating the annealing of deformed additive layer manufactured material, we discovered a new, twinning-related mechanism of beta grain refinement.

The abnormal beta grain structure found at the centre of Ti6Al4V forgings is related to the strong cube texture characteristic of this region.

In-situ heating experiments in the SEM are another important part of our effort to try to understand the growth of abnormal grain structures during the β-heat treatment of titanium aero-frame components. The presence of abnormal grain structures make it difficult to predict the performance of the component and therefore they are avoided altogether. Nevertheless, they are produced through certain process routes, often unexpectedly. Work in LightForm has established that these abnormal structures originate in highly textured regions of hot forged and rolled material. Using a newly developed in-situ heating stage in the SEM, we are able to show that although different beta orientations are originally present in the material, they are in most cases consumed by a prevalent cube (or rotated cube for rolled material) oriented sub-grain matrix. These experiments also revealed that recrystallization of the β phase starts before the alpha phase is fully dissolved. These results suggest that abnormal structures arise from unlikely combinations of local grain misorientations and/or local dissolution behaviour which then recrystallize in the strongly textured sub-grain matrix.

The next step in in-situ testing is to move from simple annealing and tensile testing to in-situ compression, or upsetting, which is more representative of forging or rolling. Compression testing is more difficult, however, due to friction and temperature gradients that cannot be avoided in the test machines that can be used in a synchrotron. Because these effects cannot be avoided, we have developed finite element based process models for the tests using the deformation dilatometer and Gleeble machines. Once calibrated using a good number of instrumented tests, the model can be used calculate the actual deformation conditions throughout the specimen during a test performed at any nominal test conditions (temperature and strain rate). This information will be essential to the interpretation of both in-situ tests and microstructure observations of other lab-scale test thermomechanical tests.

Highlighted Publications

1. LightForm-group/xrdfit: Initial Release (Version v0.1.0). Crowther, Peter & Daniel, Christopher. (2020, January 22). Zenodo. http://doi.org/10.5281/zenodo.3621299
2. Direct Evidence for a Dynamic Phase Transformation during High Temperature Deformation in Ti-64 [Preprint]. Daniel, Christopher Stuart, Nguyen, Chi-Toan, Atkinson, Michael D., & Quinta da Fonseca, João. (2019, August 20). Zenodo. http://doi.org/10.5281/zenodo.3381183
3. On the observation of annealing twins during simulating β-grain refinement in Ti–6Al–4V high deposition rate AM with in-process deformation, Donoghue Jack, Davis Alec E., Daniel, Christopher S. , Garner, Alistair, Martina Filomeno, Quinta da Fonseca, João, & Prangnell Philip B., Acta Materialia. 186 (2020) 229–241. https://doi.org/10.1016/j.actamat.2020.01.009.
4. Understanding the β-phase texture development in Ti-6Al-4V during compression in the α+β regimes [Preprint]. Nguyen, Chi-Toan, Balzer, Mario, Witulski, Thomas, Böhm, Markus, Dod, Benjamin, Preuss, Michael, & Quinta da Fonseca, João. (2019, August 20). Zenodo. http://doi.org/10.5281/zenodo.3381205
5. Analysis of the development of abnormal grains structures during beta annealing of Ti-64 wrought products [Preprint]. Byres, Nicholas Edward, Quinta da Fonseca, João, Dod, Benjamin, & Prangnell, Phillip B. (2019, September 26). Zenodo. http://doi.org/10.5281/zenodo.3462337
6. Quantifying Processing Map Uncertainties by Modelling the Hot-Compression Behaviour of a Zr-2.5Nb Alloy [Preprint]. Daniel, Christopher Stuart, Jedrasiak, Patryk, Peyton, Christian J., Quinta da Fonseca, João, Shercliff, Hugh R., Bradley, Luke, & Honniball, Peter D. (2019, December 13). . Zenodo. http://doi.org/10.5281/zenodo.3604101

LIGHTFORM STRUCTURE

Professor Phil Prangnell
Principal Investigator

UNIVERSITY OF CAMBRIDGE	MANCHESTER 1824 The University of Manchester	Imperial College London
Dr Hugh Shercliff *Co-Investigator*	Professor João Quinta da Fonseca *Co-Investigator* Professor Joseph Robson *Co-Investigator* Dr Michele Curioni *Co-Investigator* Professor Xiaorong Zhou *Co-Investigator*	Professor Jianguo Lin *Co-Investigator* Dr Nan Li *Co-Investigator* Dr Jun Jian *Co-Investigator*

Operations Team Members

Natalie Shannon, Project Manager	Professor Phil Prangnell	Professor João Quinta da Fonseca
Professor Joseph Robson	Dr Michele Curion	Professor Xiaorong Zhou

Challenge Theme Leaders

THEME 1	THEME 2	THEME 3
Professor Joseph Robson	Professor João Quinta da Fonseca	Professor Jianguo Lin/Dr Jun Jiang

Management Team Members

Professor. Phil Prangnel	Professor João Quinta da Fonseca	Professor Joseph Robson
Professor Xiaorong Zhou	Dr Michele Curioni	Dr Sarah Haigh
Professor Jianguo Lin	Dr Nan Li	Dr Jun Jiang
Dr Hugh Shercliff	Dr Christopher Race	Dr Pratheek Shanthraj
Natalie Shannon		

LightForm International Advisory Board – Steering Committee Members

Dr Michael Clinch (Chair)	Innoval Technology	Dr Cyrille Bezencon	Novelis
Dr Richard Hunt	Impression- Technologies	Professor Paul Blackwell	University of Strathclyde
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Professor Bjorn Holmedal	Norwegian University of Science and Technology	Professor Trond Furu	Nord Hydro
Dr Rebecca Higginson	Loughborough University	Prof Claire Davis	The University of Warwick
Dr Matthew Murphy	Luxfer		

Engineering and Physical Sciences Research Council

Lucy Hackett, Senior Portfolio Manager

LIGHTFORM PEOPLE

Principal Investigator
Prof. Phil Prangnell

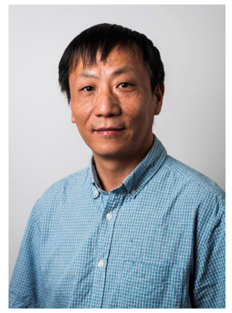
THE UNIVERSITY OF MANCHESTER
Co-Investigators

Prof. João Quinta da Fonseca

Prof. Joseph Robson

Dr Michele Curioni

Prof. Xiaorong Zhou



Prof. Sarah Haigh

Dr Christopher Race

Dr Pratheek Shanthraj

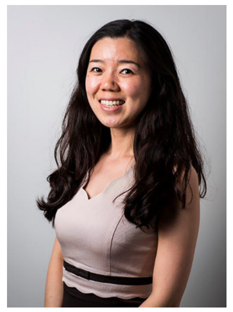
CAMBRIDGE UNIVERSITY
Co-Investigator

Dr Hugh Shercliff

IMPERIAL COLLEGE LONDON
Co-Investigators

Prof. Jianguo Lin

Dr Nan Li

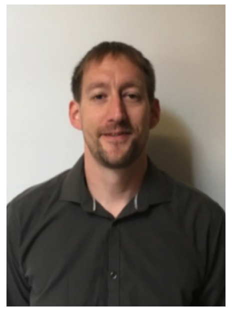


Dr Jun Jian

RESEARCH TEAM

THE UNIVERSITY OF MANCHESTER

Dr Alex Cassell



Dr Christopher Stuart Daniel

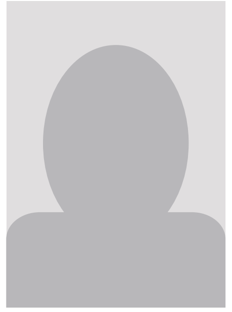
Dr Adam Plowman

Dr Sumeet Mishra

Dr. Peter Crowther

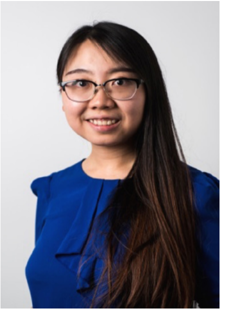
CAMBRIDGE UNIVERSITY

Dr Patryk Jedrasiak



IMPERIAL COLLEGE LONDON

Dr Jinghua Zheng



OUTREACH

The past year has seen the LightForm team delivering high impact outreach activities to our stakeholder groups including the research community, industry, the general public, and schools. Highlights include two major new activities; organizing and hosting the LightMAT 2019 international conference in Manchester and developing a new partnership with a local school that will act as a pilot for future schools' activity. In addition, the LightForm team have made major contributions to the outreach activities of our partner organizations, in particular the Centre for Doctoral Training in Advanced Metallic Systems and Cambridge University's School Outreach Project.

LightMAT 2019 (The 3rd International Conference on Light Materials – Science and Technology) took place in Manchester from 3rd to 5th November 2019, providing a comprehensive overview and new insight into the three most important light metals Aluminium, Magnesium and Titanium and their combinations.

A total of 170 delegates attended, with plenary speakers from both academia and industry including Nick Birbilis from ANU Australia, Blanka Lenczowski from Airbus Germany, Teresa Pérez-Prado from IMDEA Spain, and David Rugg from Rolls Royce. Presentations covered a wide range of current priority areas in light alloys including new applications, novel manufacturing methods, recycling and sustainability, and simulation.

Over 20 countries were represented including The United Kingdom, Germany, Austria, France, Norway, Belgium, Canada, United States of America, Japan, Spain, Czech Republic, Australia, Switzerland, China, Italy, Latvia, Poland, Sweden, Slovakia and Turkey. This represents the most diverse and international participation in any LightMAT event.

LightForm contributed significantly to the conference with a total of 13 papers, 8 of which were invited. 4 papers were also from members of LightForm International Advisory Board. The conference was well received by delegates with extremely positive feedback. Discussions held at the conference have led to new collaborations, including in the area of understanding dynamic effects in aluminium alloys.

In 2019 the LightForm team have developed and delivered outreach activities for Year 2 – KS1 pupils, which have been piloted through a partnership with Medlock Primary School in Manchester. This primary school has a high percentage of pupils from backgrounds that are under-represented in STEM. Research has shown that it is important to engage with pupils at an early stage in their education if they are to choose a career in STEM, and hence we have focussed on KS1 pupils. A number of hands-on activities were developed by LightForm researchers around the topic of materials forming and testing. This includes using play dough to mimic industrial forming processes, Charpy impact testing of fracture toughness, and an experiment where plastic cups are recycled into badges. To accompany the hands-on experiments, the LightForm researchers engaged with pupils using simple presentations to explain what a scientist does, and to discuss materials found in everyday objects. All the activities were designed to be as engaging and interactive as possible, with plenty of questions and answers.

The pilot was a great success, with pupils strongly engaged in the activities and there was a very positive response from the class teacher. The pupils commented particularly favourably on the opportunity to meet and talk to "real scientists", and this personal engagement is critical to encourage wider participation in STEM. This has resulted in an invitation to run the activity again for the new year 2 pupils as part of our ongoing partnership.

Following the success of this pilot, we plan to roll out the activities through partnerships with other local schools in the Manchester area. The activities developed are also available for use by other outreach groups and we would be delighted to share our resources and experiences; please contact us at lightform@manchester.ac.uk

Further details of our schools' activities and other LightForm outreach can be found at: https://lightform.org.uk/outreach

Going forward, we plan to host another major conference event in 2020 on light metal forming, in association with the Institute of Materials, Minerals, and Mining. This will be held in collaboration with the new Sir Henry Royce Institute (SHRI) and will give delegates an opportunity to visit the new SHRI facilities. We will also broaden our engagement with local schools and continue to develop partnerships with other outreach activities within and beyond the LightForm consortium.

LIGHTFORM PROJECTS

ALUMINIUM

1 EAC of new generation 7xxx aluminium aerospace alloys - 4D imaging of initiation processes

2 Formability and performance of circular 75R aluminium alloys

3 Generating forming limit curves at hot sheet forming conditions - formability assessment for metallic sheet materials under hot stamping conditions

4 Development of novel corrosion testing methods for anticorrosion performance evaluation of treated light alloys

5 EAC initiation in wrought aerospace plate

6 Age forming of AA2139 with prior deformation

7 Localized corrosion in Al-Cu-Li alloy thick plate

8 Microstructure evolution in sideway extrusion of aluminium alloys

9 Novel aluminium alloys for defence applications

10 Novel pre-age deform and re-age processing route for tailoring

11 Properties in aluminium alloys

12 SCC in AA7050 aluminium alloy

13 Slip localisation in forming high strength aluminium warm forming of 7xxx alloys

14 Surface corrosion of wrought alloys

15 Tailored properties in aluminium automotive body sheet with taper-rolled geometry

16 The effect of accelerated ageing of hybrid-hot formed aluminium automotive panels on corrosion resistance

17 Through process modelling for sustainable aluminium

18 Understanding EAC in wrought aerospace plate

19 Creep age forming of aircraft panels

20 HFQ - compressed process route

21 Corrosion control of 3xxx heat exchanger material

22 Designing SCC resistant forging alloys

23 Atomistic simulation of hydrogen embrittlement mechanisms in 7xxx series aluminium alloys

24 Chemo-mechanical modelling of hydrogen diffusion and fracture in wrought 7xxx series aluminium alloys

25 LightForm simulation of metal forming

TITANIUM

26 Developing a microstructural fingerprint of titanium alloys metallurgy in the information age

27 Superplastic forming and diffusion bonding of titanium alloys

28 The effect of microstructure on the ductility of titanium alloys

29 The texture of hot formed titanium alloys

30 Modelling the microstructure evolution during hot working of titanium alloys

31 Novel hot stamping of titanium alloy panel components development of novel hot stamping process of titanium alloy

32 Microstructure evolution during forging high performance titanium aerospace alloys

33 Control of abnormal grain structures in titanium forgings

34 LightForm Micromechanics of Ti Deformation (In-situ)

OTHER PROJECTS

35 Deformation behaviour of magnesium alloys studied using digital image correlation

36 Dynamic strengthening of magnesium alloys

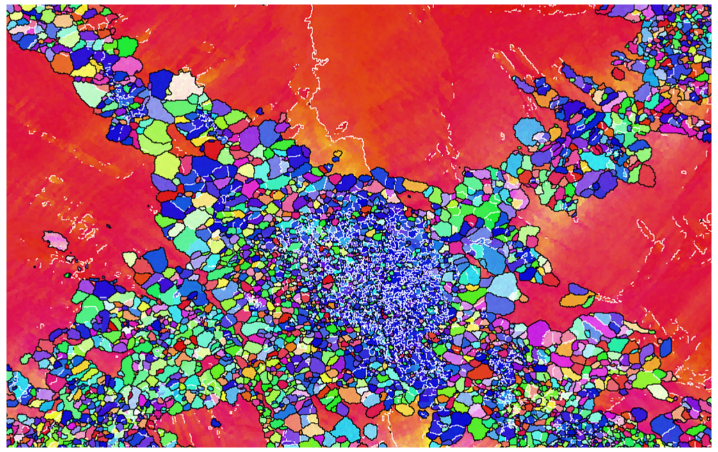
37 Low cost rolling of magnesium alloy sheets - a novel and cost effective method to manufacture magnesium alloy sheets

38 Reproducibility and data management

39 LightForm computational modelling of formability

40 OAAM programme plans to develop directed energy deposition additive manufacturing technologies that can build multi-metre scale components with in-process deformation.

41 Influence of process variables upon microstructure and texture of dual phase zirconium alloys



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INDUSTRY PARTNERS & COLLABORATORS