Predictive Modelling for Incremental Cold Flow Forming:
An integrated framework for fundamental understanding and process optimisation

This project will establish a bespoke computational modelling framework to investigate, simulate and optimise incremental cold flow forming, thereby accelerating the adoption of this high-value metal-forming process. We will realise a fundamental, computationally-assisted understanding of this notoriously complex process and the influence of key process parameters, improving the reliability and repeatability of the technology and the quality of the product. The project will be shaped by input from several leading industrial partners and the high value manufacturing catapult. The computational model will be informed, and its veracity demonstrated, through extensive material characterisation and full-scale testing.

Part 1: Track Record

Research environment

The **Research Team** is comprised of academics from the Universities of Glasgow (UofG) and Strathclyde (UofS), and they are associated with the **Glasgow Computational Engineering Centre** (UofG) and the **Advanced Forming Research Centre** (UofS).

Glasgow Computational Engineering Centre (**GCEC)** at UofG is an EPSRC-supported research centre, with 10 dedicated academic staff - www.glasgow.ac.uk/gcec. GCEC provides a coherent focus and point of interaction for fundamental and applied research in computational engineering. GCEC pursues high-quality research in multi-physics modelling of complex materials to deliver new solutions for industrial challenges of strategic importance. GCEC embraces and develops open source scientific software and places significant importance on fostering expertise through training in computational engineering.

MoFEM (mofem.eng.gla.ac.uk) is an open source C++ library for the solution of partial differential equations using the Finite Element Method, tailored for multi-physics problems and optimised for high-performance computing. It is a key output and focus of the GCEC and central to this project. MoFEM provides the core functionality for managing the complexities of the finite element discretisation. Industry has supported a number of its key developments and it is currently being adopted by EDF Energy for reactor core structural integrity assessment of the UK's fleet of advanced gas-cooled reactors. Version control in MoFEM is professionally managed using Git. Numerous tests of the core library are run every day on a dedicated server and aggregated using CDash. Documentation and tutorials are on the website. An industry-ready version of MoFEM with a specific module for simulating incremental cold flow forming, and associated training and training material, will be key deliverables from this project.

The Advanced Forming Research Centre (AFRC) in Glasgow is part of the UK High Value Manufacturing Catapult. Established with support from government and Scottish Enterprise, the AFRC's key research focus is the manufacture of high integrity parts through metal deformation processes. The AFRC supports manufacturing in business and industry by raising the profile of innovation and supporting its delivery. The Centre helps companies to de-risk and accelerate the introduction of new technologies, new materials and processes. The AFRC has world-leading, research-oriented forming equipment and materials characterisation facilities. The AFRC facilities, including two incremental cold flow forming machines, and its industrial partners will play a key role in this project. The AFRC is owned and operated by the UofS - www.strath.ac.uk/research/advancedformingresearchcentre/.

Research Team

Chris Pearce is Professor of Computational Mechanics and founder and co-Director of the GCEC. He holds the RAEng/EDF Energy Research Chair in Computational Mechanics at the UofG. He specialises in the computational analysis of materials and structures, with particular focus on multi-scale mechanics and multi-physics. Supported by EPSRC, EU, Innovate UK and industry, his research is applied to problems ranging from safety critical structures to biomechanics. Given the strong industrial relevance of his research, Chris works closely with EDF Energy on new predictive modelling tools for structural integrity of the UK's fleet of civil nuclear reactors. The computational intensity of his work has driven the development of novel numerical techniques, bespoke solution strategies and code optimised for High Performance

Computing. Chris is a member of the EPSRC Engineering SAT, with responsibility for Computational Engineering. He is a member of the Advanced Manufacturing Thematic Leadership Group for the National manufacturing Institute for Scotland. He serves on the Executive Committee of the UK Association of Computational Mechanics, the General Assembly of ECCOMAS and the editorial board of Computers & Structures, and recently organised Europe's largest Computational Mechanics conference (ECCM-ECFD 2018) in Glasgow. Chris is Dean of Research for the College of Science & Engineering.

Paul Blackwell is Professor and Director of Knowledge Exchange in the Department of Design, Manufacture and Engineering Management at the UofS. He is a specialist in materials characterisation, metallurgy and manufacturing and his research focuses on the interaction of materials processing conditions, microstructure and final properties. He has significant experience in academic, industrial and commercial research. He is Chair of the Technical Board of the AFRC and responsible for the delivery of the £2M p.a. core research programme. Paul will lead all aspects of the experimental work and will provide an invaluable interface with AFRC.

Paul Steinmann is Professor of Computational Engineering Science at UofG and co-Director of the GCEC. He is also Full Professor at Friedrich-Alexander University, Germany, where he leads the Chair of Applied Mechanics. He is recognised internationally for his contributions in the fields of geometrically non-linear Continuum Mechanics and Continuum Physics, and for his significant expertise in Computational Mechanics and Dynamics, including material modelling, multiscale methods, configurational failure / fracture mechanics, nonstandard continua, multi-physics, and developments in finite element technology and discretisation methods. Related research includes seminal contributions to models of large deformation plasticity and configurational mechanics. He is also part of the Collaborative Research Center 814 - Additive Manufacturing. He will lead on the constitutive modelling and the development of algorithms for the large deformation plastic that characterises ICFF.

Andrew McBride is Senior Lecturer in Computational Engineering at UofG and deputy director of the GCEC. He also leads the Materials and Manufacturing Research Group www.materials-glasgow.org. His research is in nonlinear solid mechanics with a particular focus on computational materials science and, more specifically, extended models of single-crystal and polycrystalline plasticity that account for scale effects. In collaboration with Rolls-Royce his research has focussed on modelling and experimentally measuring the extreme plastic deformations and thermal gradients during inertia friction welding, and microstructure evolution in nickel superalloys and titanium alloys. Andrew is a strong advocate of open source computational engineering tools and has made many contributions to the deal.II finite element library. He will lead on most of the new computational modelling innovations.

Lukasz Kaczmarczyk is a Senior Lecturer in Computational Mechanics at the UofG and a member of the GCEC. A particular focus of his research is the numerical analysis of materials using high performance computing. The continued high quality of his work was acknowledged through the award of the UK Association of Computational Mechanics' Crisfield Prize for an unprecedented two years in succession. He works closely with the PI Chris Pearce and their group has developed the open source development platform MoFEM. Lukasz is the principal developer and architect of MoFEM and leads a team of 7 core developers comprised of RAs and PGRs. His expertise in developing efficient numerical procedures is a key aspect of this project and he will lead all aspects of software development.

Some Key Publications

[a] Kaczmarczyk, L., Ullah, Z. and Pearce, C. (2017). Energy consistent framework for continuously evolving 3D crack propagation. *Comput. Methods in Appl. Mech. Eng*. **324**, 51-73.

[b] Bylya, O.I., Khismatullin, T., Blackwell, P., Vasin, R.A. (2018). The effect of elasto-plastic properties of materials on their formability by flow forming. *Journal of Materials Processing Technology*. **252**, 34-44.

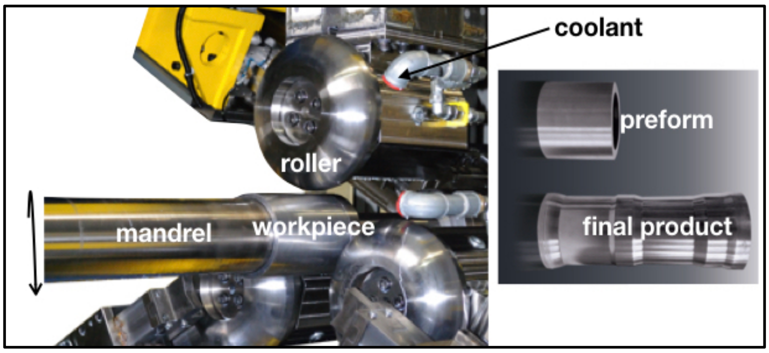
[c] Steinmann, P. and Maugin, A. (2005). Mechanics of Material Forces. Advances in Mechanics and Mathematics, Springer.

[d] Kuhl, E. and Steinmann, P. (2005). A hyperelastodynamic ALE formulation based on referential, spatial and material settings of continuum mechanics. *Acta Mech.* **174**(3), 201-222.

[e] McBride, A., Reddy, B.D. and Steinmann, P. (2018). Dissipation-consistent modelling and classification of extended plasticity formulations. *J. Mech. Phys. Solids*. **119**, 118-139.

Part 2: Description of Proposed Research
1. Introduction

Background: Incremental metal forming processes, including flow forming, shear forming, metal spinning and sheet forming, can result in considerable cost savings via improved yields, reduced production times and improved material properties, as compared to standard manufacturing routes [1]. To take full advantage of such processes it is necessary to understand the underpinning physics. This fundamental understanding is crucially supported by efficient, robust and reliable predictive modelling and simulation tools, that will eventually enable process optimisation - supporting an industry-wide move towards the virtualisation of product development. These modelling tools connect the process, structure and property relationships, enabling rapid virtual prototyping, evaluation of material formability, identification of optimised preform geometries, and assist operators to identify key process parameters.



The focus of this proposal is **incremental cold flow forming** (ICFF) for the manufacture of tubular and complex, rotationally-symmetric products for high-value sectors including Aerospace, Automotive and Oil & Gas. A cylindrical preform is attached to a rotating mandrel and rollers apply compression to the outside surface, leading to extrusion of the workpiece material through significant accumulated plastic flow. As a result of the incremental process, where the rollers are only in contact with a small area of the workpiece at any one time, the extrusion of the material occurs with much lower force than required for other processes, such as stamping. This makes ICFF very attractive when forming high strength materials.

ICFF achieves ready-to-install geometries (net-shape forming) with high precision. Compared to conventional processes such as hot forming, the advantages are shorter process times, higher surface quality, improved mechanical properties and reduced thermal load. The increased material exploitation is imperative for high-value manufacturing sectors (e.g. aerospace), due to their use of expensive materials such as superalloys. The efficient use of resources also reduces the environmental impact of manufacturing.

A coolant is applied throughout the forming process and the deformation occurs significantly below the material's recrystallisation temperature, with the initial workpiece at room temperature. Through cold work hardening, the mechanical properties evolve, leading to increased strength, stiffness and hardness. Materials such as aluminium, nickel and steel alloys are all flow formable, with the full range of materials the subject of ongoing research. Understanding the magnitude and distribution of the significant residual stresses, introduced through ICFF, is critical to tailor the process to achieve products within dimensional tolerance and with desired mechanical properties [1]. Heat treatment is often applied post forming to relieve residual stress.

ICFF is gaining popularity and has enormous potential – as indicated by the letters of support. The AFRC has invested in two ICFF machines, supplied by WF Maschinenbau (a Tier 2 member of the AFRC). The first is the largest such machine in a research establishment worldwide, with three independently controllable rollers that can form products up to 600 mm in diameter and 3,900 mm in length. The second is primarily for R&D purposes, highly instrumented and with 4 rollers that can form products up to 600 mm in length.

Initial work carried out by the AFRC shows that, because of the complexity of the process, it can be challenging to achieve repeatable and reliable results. The process can be unstable and material failure does occur. Furthermore, the number and range of process parameters are large – these include magnitude of compressive loads, slewing angle of the rollers, forward or reverse forming, angular speed, feed rates, tool design, number of process steps required, etc. Deformation induced changes in material properties also have a major influence on how a particular component is formed.

Therefore, predictive modelling of ICFF is critical to inform, and ultimately optimise, the production process. To this end, the AFRC and their industrial partners have invested substantial resources into computational modelling tools, including dedicated, commercial metal forming finite element (FE) packages. However, these tools were not able to provide them with viable solutions that delivered a fundamental understanding of the ICFF process. This is unsurprising as commercial software, by necessity, is slow to adopt latest developments, favouring traditional technology to ensure solution robustness and stability. In addition, these commercial tools cannot in general be tailored easily to the application of ICFF and are hence prohibitively computationally expensive to use.

Thus, the complexity of ICFF, the absence of a full understanding of the process and the inherent limitation of existing modelling tools, means that the potential of ICFF is not being realised. The primary Challenges and our approach to overcoming them include:

- **Material properties evolve due to the deformation process**. An experimental programme will characterise the material behaviour and this will inform the features of the constitutive model.
- **The workpiece is rotating** (up to 500 rpm), **axially fed** (~6 mm/s) **and extruded. The material accumulates very large elasto-plastic deformations** (circumferential and axial). We will deliver a series of modelling innovations that will ensure accuracy and computational efficiency.
- **There are multiple contact zones between workpiece and the rollers / mandrel.** A contact formulation for rotating bodies will be developed.
- **Heating at the contact zones (plasticity and friction), as well as heat removal through cooling**. Experimental characterisation of the ICFF process will improve understanding of the thermal processes and inform both the constitutive and thermo-mechanical modelling (including contact).

Aim: We will realise a fundamental, computationally-assisted, understanding of ICFF and the influence of key process parameters, to improve the reliability and repeatability of the technology and the quality of products. We will create a comprehensive analysis framework for simulating flow forming based on predictive modelling that captures all the key features of the process, including large elasto-plastic deformations, contact, thermal effects and residual stresses. This will be achieved through the tight integration of novel developments in mechanics, numerical methods, FE technology and scientific computing. These advances will be underpinned by extensive materials characterisation and model validation. Through modelling and simulation, we will deliver a step-change in the use of ICFF for the manufacture and optimisation of high-quality, high-precision metallic components in multiple industries.

Objectives: To deliver our aim, we must achieve five key objectives:

O1. Comprehensively characterise the ICFF process in order to instantiate, calibrate and validate the computational model. This will require extensive materials testing and analysis of data obtained from the ICFF equipment. In addition, a materials characterisation procedure for ICFF will be developed.

O2. Develop a finite-element-based model to capture the mechanics of the rotating workpiece and the forces applied to it by the rollers. An Arbitrary Lagrangian Eulerian (ALE) method will ensure the computational mesh maintains sufficient quality.

O3. Develop a thermodynamically consistent procedure for updating the variables that track the evolution of the inelastic deformation by exploiting the framework of Configurational Mechanics.

O4. Implement the FE model of ICFF into the existing, state-of-the-art, open-source library MoFEM.

O5. Demonstrate the veracity of the model through component-scale testing for a range of process control parameters and realistic operating conditions. The final task is to demonstrate the ability of the software to inform process optimisation to support virtual product design.

2. Programme of Work (Led by Pearce)

WP1: Characterisation of bulk material and cold flow forming process (Led by Blackwell)

1.1 Bulk material characterisation: To focus the research on the development of a robust numerical model, we will consider stainless steel preforms as opposed to more complex alloys. Microscale uniaxial tensile testing will provide the material properties of the as-received and as-formed material. Samples from the near-surface and bulk of the as-formed component will be tested to determine through-thickness variability induced by localised contact. Torsion tests will allow for the determination of hardening parameters at large strains.

Electron backscatter diffraction (EBSD) will be used to quantify evolution of crystallographic structure through thickness and hence determine the depth of the plastic and heat-affected zones. The smoothness of the as-formed surface will be assessed using a profilometer to determine banding and depth of surface deformation. Residual stress at the surface, near surface and in-bulk will be measured using X-ray diffraction (XRD) and Electronic Speckle Pattern Interferometry (ESPI) based hole drilling. This is critical, as the residual stress state plays a major role in the outcome of the process.

1.2 Cold flow forming process: The ICFF research machine is instrumented, and we will measure the forces on the rollers, the movement of the rollers, coolant flow rate, and system losses. Measurement of the frictional properties of the contact and the thermal properties of the lubricant will be performed using a variety of techniques e.g. a modified Male & Cockroft ring test, and the laser flash method. In addition, we will use embedded thermocouples to track the evolution of temperature in-situ at various depths through the wall thickness. These tests are challenging due to the complex nature of the ICFF process. A new test methodology will be designed to generate material data specifically for ICFF. This should approximate the discrete load cycles, strains and temperature that the workpiece experiences and will be informed by both measured and simulated data. The procedures and data in WP1.1 and WP1.2 will guide the development of the constitutive models and will form the basis for the validation of the FE model.

Risk (low/medium): Generally well understood experiments, existing ICFF rig for R&D and expertise of the AFRC. The thermocouple experiments and new test methodology are challenging but do not impact critically on the model development and validation.

WP2: Rotating Arbitrary Lagrangian Eulerian (ALE) formulation (Led by McBride)
Modelling problems such as ICFF with large deformations can lead to significant numerical difficulties due to distortion of the FE mesh. Whilst remeshing can overcome this, it is computationally expensive and can lead to the accumulation of numerical errors. We will adopt an ALE formulation (now best practice for simulating forming processes, including ICFF [2][3]), whereby the FE mesh within the body of the workpiece will continuously adapt *independently* of the material [d]. This will optimise the shape of elements to maintain mesh quality. Meanwhile, the mesh on the boundary will move with the material to accurately represent the changing workpiece geometry. Nevertheless, there remain challenges in the successful application of ALE in solid mechanics that we will overcome - specifically for large deformation history-dependent elasto-plasticity, further complicated by rotation of the body.

2.1 ALE Formulation: The relative motion between the mesh and the material must be accounted for in the treatment of the constitutive relations. This requires convection of the plastic history (internal) variables that are associated with the numerical integration points (not the nodes). Although various approaches have been proposed [4][5] and implemented in commercial FE packages, they are generally applied to problems that are comparatively less complex than ICFF. WP3 describes our proposed methodology for convecting the history variables in a consistent manner; we will incorporate this with the ALE formulation to solve a significant and enduring challenge that will have impact beyond ICFF.

2.2 Mesh Smoothing: In order to maintain mesh quality, smoothing of the mesh will be undertaken as a continuous process, driven by the imposition of a global mesh quality control procedure. Simultaneously, the mesh will be constrained to preserve the domain topology. We have shown how this can be achieved and combined with other local mesh improvement techniques for similarly challenging problems [a].

2.3 Rotating ALE: Despite the work proposed above, the continuous rotation of the workpiece and contact with the rollers bring additional complexities to the modelling of the workpiece's movement and deformation. We will develop a novel solution by exploiting the kinematics of the rotating body and expressing the ALE formulation in a continuously rotating frame of reference. The modelling of steady-state rolling was initially proposed for elastic and viscoelastic processes [6]. However, this will be the first development and application of a rotating ALE formulation to model such a complex process involving rotation, extrusion, plasticity and finite deformation for realistic components.

2.4 Mortar Contact: The state-of-the-art Mortar contact formulation [7] will be adopted and tailored for this problem. The Rotating ALE formulation will be exploited to simplify the modelling of contact and considerably reduce the need for continuous updating of the contact surfaces (compared to a rotating mesh). This will dramatically decrease complexity and improve computational efficiency and robustness.

The resulting nonlinear system of equations developed in WP2 will be solved monolithically within a

Newton-Raphson formulation, with automatic differentiation [8] aiding the linearization of the governing equations and the rapid development of constitutive relations within MoFEM.

Risk (medium/high): WP2 will extend the state-of-the art with several new innovations. Strong dependence on WP3 is the key risk. Existing methods [4][5] could be adopted in mitigation. This would be a viable approach, although important efficiency gains would not be realised.

WP3: Finite deformation elasto-plasticity (Led by Steinmann)

Finite deformation elasto-plasticity is well understood and the associated constitutive models widely adopted [9]. However, the description of plastic deformation via internal variables and the requirement to convect them in the ALE formulation is problematic and restrictive (see WP2). The root of the problem is the absence of a conservation principle for plastic deformation in the classical theory [10]. We will tackle this persistent challenge by employing Configurational Mechanics (CM) [c] to provide a new, thermodynamically consistent and theoretically sound structure.

CM is a significant innovation in continuum mechanics, providing a general and effective framework to analyse different kinds of material rearrangements [c]. Configurational forces perform work within the material configuration, leading to changes irrespective of deformation. The ALE approach in WP2 possess this dual character of material and spatial motion and thus complements the application of CM [d].

3.1 Plastic strain update: Inspired by the framework of CM, we will develop a mixed variational approach. Conceptually, plastic flow will be considered an evolution of the material configuration, with the classical Eshelby stress the driver for plastic deformation. Thus, we will derive the material momentum conservation equation (as a counterpart to spatial linear momentum), and this will enable us to evolve plastic strains in the ALE framework without requiring internal variables. This will also enable us to use CM to predict the onset of failure (crucial to inform process optimisation) [a].

3.2 Solution schemes: A challenge will be the discretisation and solution of the coupled system of equations (deformation, heat conduction, finite plasticity, and contact) – such problems are particularly prone to solution instability, resulting in non-physical and spurious results. To address this, the monolithic, implicit approach developed in WP4 will also ensure that the mathematical setting of the model (i.e. the functional space wherein the field variables exist) is replicated and respected in the numerical model.

Risk (medium): The risk associated with WP3 is the same as WP2 (updating of plastic variables). The same mitigation strategy would be employed should the CM approach proposed here not perform as expected. However, Co-I (Steinmann) is a world-leader in CM and this gives a unique advantage.

WP4: Open source Finite Element modelling framework (MoFEM) (Led by Kaczmarczyk)

4.1 MoFEM development: The models developed in WP2 & WP3 will be continuously implemented into the FE analysis library MoFEM throughout this project. By developing a bespoke FE analysis tool based upon a mature open source library, we will achieve an efficient, accurate and robust flow forming simulation.

4.2 Algorithm efficiency & code refactoring: The accuracy of FEM relies on the quality of the mesh and the choice of the approximation space. We will exploit the hierarchical and heterogeneous approximation bases [a] available in MoFEM: automatically increasing the order of approximation in critical regions (e.g. contact area) to minimise the number of degrees of freedom without compromising accuracy; hierarchical approximation bases will be exploited to create a bespoke and efficient solver (i.e. a multi-grid block solver). Code refactoring (restructuring to improve efficiency and readability) is a necessary practice in the development of quality and efficient code.

Risk (low): MoFEM is under continuous development, with many of the foundations necessary for this WP, and is tightly-integrated into the GCEC's research activities.

WP5: Verification & validation of modelling framework and process optimisation (Led by Pearce)

The experimental results from WP1 will be used to validate the modelling framework developed in WP2-4. This will be done in addition to the verification tests to ensure the correctness of the numerical formulation. The benchmark validation case will be the flow forming of a stainless steel component. The validity of the simulation will be assessed by comparing with the profile and thickness of the formed component, as well as the thermocouple data. The extent of the plastic and heat affected zones will provide a quantitative measure of the accuracy of the contact and plasticity models. Critically, the predicted residual stress state will be compared with the experimental one - allowing the process to be optimised to achieve the required dimensional tolerance.

Furthermore, the capability of the model will be demonstrated by simulating an ICFF process that led to component failure. We will use the simulation to identify the cause of failure and, via an iterative process, estimate the optimal process parameters to be adjusted to avoid failure and produce the desired shape.

Risk (low): The AFRC are experts in materials characterisation and residual stress measurement and have access to the required state-of-the-art facilities.

WP6: Management (Led by Pearce)
Project management will be led by Pearce, structured around quarterly meetings of the entire project team. Progress will be monitored against the workplan, which also defines the key milestones. In addition, Pearce will maintain and manage a risk register that will be discussed and updated at each project team meeting. Risks have already been identified for each of the WPs, with clear mitigating actions to ensure the project can still deliver the main aims. Following practice in our other projects, our industrial partners (Boeing, Spincraft, BHGE) will form a Steering Group (SG) led by Blackwell, with meetings preceding project team meetings every 6 months. SG will inform management, research and impact directions. Identifying and managing IP will be a shared responsibility. The co-location of the entire research team in Glasgow will allow for frequent face-to-face meetings to support the project outwith the formal quarterly team meetings. The impact plan will be led by Blackwell in cooperation with our partners. Careful management of our researcher mobility programme, which involves frequent visits and placements to partners, is vital, to best fit with the programme milestones and integrate the whole team optimally to progress towards impact.

3. Importance and Impact

National importance: The UK is the 11th largest manufacturing nation worldwide. Manufacturing makes up 11% of the UK GVA and 54% of UK exports, directly employing 2.6 million people and accounting for over 70% of investment in R&D [10]. However, the High Value Manufacturing (HVM) strategy [10] recognises that the UK remains vulnerable to eroding investment and capability. Moreover, manufacturing productivity has flatlined since 2008 [11]. This has led the UK Government to increase the role that manufacturing plays in the growth of the economy, with innovation in HVM fundamental to these growth ambitions. Improving productivity is a cornerstone of the UK's Industrial Strategy. This research supports cost savings via improved yields, reduced production times and improved material properties.

Metal products are a key aspect of a sustainable manufacturing economy because they can be readily recycled and remanufactured. The UK has ambitious plans to develop new generations of cars, aircraft and other products, and to upgrade its energy and transport infrastructure, creating extra demand for high-value metal manufacturing. However, metal forming is energy intensive. This research enables a transformative technology that reduces demand on energy and material resources.

The UK Government [12] has recognised modelling and simulation as a pervasive and underpinning technology for manufacturing, requiring a growth in technical skills. Modelling and simulation are key aspects of the digitisation of manufacturing processes that dominate the 2017 Made Smarter review. This proposal is also strongly aligned with the **EPSRC** Productive Nation *Prosperity Outcome* and in particular "Design, modelling, computation and simulation to develop new tools and methods":

P1: Introduce the next generation of innovative and disruptive technologies.	*We will deliver innovative predictive modelling tools and skills that will accelerate R&D in HVM and consequently accelerate the uptake of new manufacturing techniques that can significantly enhance productivity.*
P2: Ensure affordable solutions for National needs.	*This research will enhance understanding and improve reliability of new HVM techniques, increasing uptake and driving down costs. It will also reduce demand on resource, both in terms of energy efficiency and cost.*

Impact: Manufacturing machines are a major capital expenditure and lack of investment in such facilities is a key reason for low productivity [11]. This project will establish a bespoke computational modelling framework for ICFF. Together with experimental validation, this framework will provide a practical tool to de-risk and accelerate the adoption of this and other high-value metal-forming processes. Our modelling tools will connect the process, structure and property relationships, enabling rapid virtual prototyping, evaluation of material formability, identification of optimised preform geometries, and will assist operators to determine key processing parameters. A transformation of the metal forming industries, through advanced modelling, will be accelerated by this programme of research, giving the UK a significant and important international lead. This project will also deliver world-leading research, including new modelling and simulation technology, and skilled researchers and engineers with knowledge of modelling and simulation, that will support a more competitive and less resource intensive manufacturing sector.

Academic impact: We will deliver new research in the modelling of processes involving large plastic deformation, rapidly rotating workpieces, contact and high thermal gradients. Such processes are characteristic of many industrial forming, forging and joining operations. Thus, the open source computational tools developed will be of considerable value to academics working in these fields. The novel method proposed to update internal variables has application beyond plasticity and can be applied to any inelastic process. The experimental data used to develop the constitutive model and validate the computational model will have significant impact. It will allow modellers to develop their own constitutive relations and to explore the influence of mechanical environment on the development of microstructure.

Establishing the partnership between GCEC and the AFRC will form the basis for significant future collaboration based on our individual strengths and mutual scientific objectives.

Timeliness: The research supports the UK's Industrial Strategy to boost productivity by supporting the manufacturing sector with advanced numerical tools. The need to develop bespoke tools for modelling ICFF was identified by the manufacturing experts at the AFRC; they could not realise this using commercial codes. This is due in part to the inflexibility of such codes to react swiftly to new developments in computational mechanics. Within the Scotland context, the new National Manufacturing Institute for Scotland (NMIS) is currently under development, with a strong focus on virtualisation of advanced manufacturing processes. The advent of low-cost computing power and state-of-the-art open source numerical libraries (such as those that underpin MoFEM), and modern software tools allow research codes to develop robust and scalable solutions for engineering problems. Furthermore, new developments in continuum and computational mechanics are readily explored and exploited. The investigators have already demonstrated their application to industrial problems in the nuclear and aerospace industries.

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