Institution: University of Leicester		
Unit of Assessment: UoA12		
Title of case study: Economic Gain and Environmental Protection by Modelling-Enabled Arc Welding		
Period when the underpinning research was undertaken: 2009–2020		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s): Hongbiao Dong	**Role(s) (e.g. job title):** Professor of Materials Engineering	**Period(s) employed by submitting HEI:** 2014–Present
Period when the claimed impact occurred: 2014–2020		
Is this case study continued from a case study submitted in 2014? N		

1. Summary of the impact

Welding is the most economical and effective way to join metals permanently, thus it is a vital component of our manufacturing economy. MINTWELD, a European Commission Framework 7 programme, led by Professor Dong at the University of Leicester (UoL), developed a modelling framework that has led to welds that are more resilient, especially to corrosion, and have extended lifetimes. This has resulted in **novel methodology**, **economic and environmental impacts**, and **procedural changes** in the global welding industry. Economic impact results from significantly fewer expensive repairs across all sectors. Environmental impact results from reduced leakages, resulting in lower environmental pollution. Beneficiaries are energy companies in the first instance and, consequently, all energy users globally. The economic and environmental impacts are global, benefitting all societies.

2. Underpinning research

Prior to the MINTWELD project, a significant volume of research had been carried out on modelling welding phenomena, including modelling the melting, mixing, and solidification of the weld pool and the final microstructure. However, many models did not incorporate the real effects of alloy chemistry and process parameters on the properties of welded structures. Additionally, models were developed separately, and research activities were largely uncoordinated. The MINTWELD project [**G1**] made a number of novel technological advances in modelling thermal computational fluid dynamics, and solid mechanics of arc welding, and then integrated these into microstructural models, thereby providing comprehensive modelling of the welding process [**R1**].

MINTWELD established the capability to design and engineer welding processes with a multi-scale, multi-physics computational modelling approach [**R2**]. Attention was paid to all relevant length scales, including: the description of macro-scale mass flow and thermal profile in the weld pool; meso-scale solid/liquid interface movements during melting and solidification of weld joints; micro/nano-scale grain boundary and morphology evolution in the solidified joints. Also considered were mechanical integrity and service life of the welded products. Models were fully implemented and results were validated.

MINTWELD took advantage of the fluid flow, solidification, thermodynamic, and microstructure models to provide thermodynamic, kinetic, and phase transitions during the melting, mixing, and solidifying of melt pool and the solidified weld joints. Ab-initio and molecular dynamics studies provided the required data for surface and interface phenomena. The above electronic, atomistic, and continuum information was then combined within the framework of the Cocks-Suo variational principle to predict component life [**R3**, **R6**]. Validation of the predictions was ensured by novel experiments at each scale, including real-time synchrotron imaging to observe morphological evolution of the welding fronts [**R4**] and internal flow in the weld pool [**R6**], as well as electron probe micro-analysis and atom probe to characterize alloy chemistry near grain boundaries [**R5**]. Strategies for intelligent selection of new weld materials with improved properties in arc welding joints were developed and passed on to the welding industry. Controlling the structure and properties in this way offers the opportunity to significantly improve the performance of welds, opening new markets for the EU welding industry. A unique result of this project was weld quality prediction for realistic systems in high speed arc welding applications. For example, industrially important steel/steel welds for structural applications and similar welding, and steel/Ni-based alloys welds for pipeline applications and dissimilar welding.

MINTWELD has provided welding industries with an integrated tool to guide the selection of welding materials and to optimise process routes to manufacture weld components with improved properties and performance [**R6**]. The work enables environmentally sustainable development in Europe by intelligent selection of new materials and process routes leading to a reduction of cost and energy consumption in the welding industry and, more importantly, the manufacture of welds that are resilient to corrosion and have extended lifetimes. The application of the models has been demonstrated in Europe's most advanced welding technological industries and welding institutions, and by end users in the gas and oil industries.

3. References to the research

[**R1**] **Dong H.B.**, Modelling of Interface Evolution in Advanced Welding, MINTWELD final report, https://cordis.europa.eu/project/id/229108, November 2013.

[**R2**] M. Tong, G. Duggan, J. Liu, Y. Xie, M. Dodge, L. Aucott, **H. Dong**, R. L. Davidchack, J. Dantzig, O. Barrera, A. C.F. Cocks, H. Kitaguchi, S. Lozano-Perez, C. Zhao, I. Richardson, A.Kidess, C. R. Kleijn, S. Wen, R. Barnett & D. J. Browne, Multiscale, Multiphysics Numerical Modeling of Fusion Welding with Experimental Characterization and Validation. JOM, 2013. **65**(1): p. 99-106.

[**R3**] L. Aucott, D. Huang, **H. B. Dong**, S. W. Wen, J. A. Marsden, A. Rack & A. C. F. Cocks , Initiation and growth kinetics of solidification cracking during welding of steel. Scientific Reports, 2017. 7(1): p. 40255.

[**R4**] Mirihanage, W. U., Di Michiel, M., Reiten, A., Arnberg, L., **Dong, H. B**., Mathiesen, R. H. (2014). Time-resolved X-ray diffraction studies of solidification microstructure evolution in welding. Acta Materialia, 68, 159-168.

[**R5**] Dodge, M. F., Gittos, M. F., **Dong, H.**, Zhang, S. Y., Kabra, S., & Kelleher, J. F., In-situ neutron diffraction measurement of stress redistribution in a dissimilar joint during heat treatment. Materials Science and Engineering: A, 2015. **627**: p. 161-170.

[**R6**] L. Aucott, **H. Dong**, W. Mirihanage, R. Atwood, A. Kidess, S. Gao, S. Wen, J. Marsden, S. Feng, M. Tong, T. Connolley, M. Drakopoulos, C. R. Kleijn, I. M. Richardson, D. J. Browne, R. H. Mathiesen & H. V. Atkinson., Revealing internal flow behaviour in arc welding and additive manufacturing of metals. Nature Communications, 2018. **9**(1): p. 5414.

Grants:
[**G1**] **MINTWELD** (Modelling of Interface Evolution in Advanced Welding) EU FP7 GBP4.3M GR229108, 01/09/2009 to 31/08/2013.

4. Details of the impact

Dissimilar metal welds are often used in subsea production systems to join clad hubs to clad pipelines or corrosion resistant alloys. MINTWELD has shown that microstructures can form at the fusion line of these joints, making these components sensitive to hydrogen embrittlement. This is a real issue in the context of oil and gas pipelines in subsea environments. Examples of failures in the previous generation of dissimilar metal weld combinations and configurations are provided in [**E1**, **E2**]. Such failures result in lost production, costing tens of millions of GBP, in addition to severe environmental consequences.

The EU FP7-funded MINTWELD project was a collaboration between UoL, Liberty Steel, and British Steel (formally Tata Steel) and The Welding Institute (TWI), as well as academic partners from Ireland, Norway, Sweden, Netherlands, Poland, and Switzerland. Beneficiaries include the Materials Processing Institute (MPI) and its members. The economic, environmental and training impact of MINTWELD to the European welding industry and the end users of arc weld structures was realised between 2013 and 2020, and is continuing.

Economic and environmental impacts
The MINTWELD project has provided materials that are better at avoiding hydrogen ingress and embrittlement, thus are more resilient to corrosion and better able to withstand fatigue due to external forces. Lower hardenability forgings have been used to create such joints, which have a lower propensity to form hard interfacial microstructures, and hence minimize the likelihood of hydrogen crack initiation. The use of MINTWELD approaches in subsea applications since 2013 has contributed to reducing the risk of pipeline failures. The Welding Institute — the leading professional engineering institution for the professional registration of welding and joining personnel — describe the devastating environmental impact of failure of a single weld of subsea pipes, in addition to the significant costs to the oil and gas industry from shutdown, subsequent lost production and replacement costs:

“It is very difficult to quantify the potential harmful effects that subsea failures have on the environment, including loss of habitat and wildlife and costs of cleaning up spillage; however, the average cost of retrieval and repair alone is expected to be in the [GBP]10s of millions. Hence MINTWELD has significantly contributed to reduce environmental impact and substantial economic savings by reducing the risk of pipeline failures” [**E3**].

MINTWELD has been used across Liberty Steel’s Business Units, including what is now British Steel, since 2013. Numerical modelling was used to predict the residual stress distribution and concentration at a fillet weld joint of the downcomer structure of a blast furnace. The modelling identified how to reduce cracking and improve the integrity of the welds, and hence the furnace. Liberty Steel outline that the better controlled welding processes afforded by MINTWELD have led to “reduced scrappage, shorter lead times and more economic in-situ welding repair processes (for life extension of blast furnace and rail track). This is key for our customers” [**E4**].

Another example of the industry application of MINTWELD that is key to British Steel’s business is in the rail business sector. British Steel assert that “modelling results successfully showed that the repair welding processes specifically developed and designed by Tata Steel ‘Rail Technology’ Group at Swindon Technology Centre (now part of British Steel) were viable and can be used for the aimed in-situ operations for the rectification of the defective rail tracks” [**E5**]. The successful application of MINTWELD across the sector led the Materials Processing Institute (MPI) to acknowledge on behalf of their members that “The philosophy of the project (combining modelling with actual observation) was excellent and has led to significant economic benefits to the project participants; measured in [GBP]millions in the prevention of premature failure alone” [**E6**].

Novel Methodology

The primary impact of MINTWELD has been to understand the failure mechanisms and essential parameters leading to hydrogen assisted cracking (HAC) of dissimilar metal welds (DMWs). MINTWELD allows the prediction of interface evolution in industrially-relevant systems, such as steel/steel and steel/Ni-based alloys. MINTWELD novel environment testing enabled the identification of features that cause hydrogen cracks in joints whilst in service. According to the TWI, this led to “the development of materials, welding processes and heat treatment procedures which are superior in that they result in the formation of fewer hydrogen-susceptible micro-structures and are consequently better at resisting the effects of hydrogen embrittlement. This materials screening procedure has been adopted across the Energy sector” [**E3**].

Another example of the application of the MINTWELD methodology is the implementation of computational techniques for assessing and insuring weld integrity at Liberty Steel. Used particularly in the rail industry, “numerical modelling of (the repair) welding has led to a greater understanding of the physical processes and has identified the residual stress profiles in key areas of the steel downcomer structure and cooling rates in the repair welds of defective rail heads” [**E4**].

MINTWELD has made these processes more guided and accessible to TWI’s industrial members and the wider engineering world. Through numerical modelling and experimental testing, a procedure for better materials selection for welding has been developed and used in related welding training materials. The MPI assert that MINTWELD “pioneered the use of synchrotron X-rays to characterize the internal flow path and velocity of molten steel. This information was not available before and has led directly to enhancing the understanding of fluid flow in molten metal and increase the accuracy of solidification modelling” [**E5**]. The combined approach using MINTWELD modelling and key experiments has been used in the design of new filler materials for welding new pipeline steels (X65, 8630M, 9wt.%Ni steel), enabling the steels to enter new markets.

The superior materials developed from the MINTWELD processes are better at resisting the effects of hydrogen embrittlement. The MINTWELD materials screening process has been adopted across the sector [**E3**], e.g., end users include EQUINOR, the Norwegian state oil company.

MINTWELD has delivered improved technology in the continuous welding of pipeline and improved understanding of materials selection in welding of dissimilar metals to avoid corrosion. This has prevented both economic and environmental damage resulting from pipeline failures across the sector.

5. Sources to corroborate the impact

[**E1**]. Proceedings of the ASME 2017 36th International Conference on Ocean, Offshore and Arctic Engineering OMAE2017, June 25-30, 2017, Trondheim, Norway.
[**E2**]. NACE International Corrosion Conference 2015. Paper: C2015-5500.
[**E3**]. Letter of Support from The Welding Institute (TWI).
[**E4**]. Letter of Support from Liberty Steel.
[**E5**]. Letter of Support from British Steel.
[**E6**]. Letter of Support from the Materials Processing Institute (MPI).