



THE UNIVERSITY *of* EDINBURGH

## Edinburgh Research Explorer

# A numerical modelling and deep learning approach to the ballistic impact resistance of additive manufactured maraging steel

### Citation for published version:

Edwards-Mowforth, M, Thompson, S, Costas, M, Kristoffersen, M, Børvik, T & Teixeira-Dias, F 2022, 'A numerical modelling and deep learning approach to the ballistic impact resistance of additive manufactured maraging steel', Light-Weight Armour for Defense & Security, Freiburg, Germany, 15/09/22.

### Link:

[Link to publication record in Edinburgh Research Explorer](#)

### Document Version:

Publisher's PDF, also known as Version of record

### General rights

Copyright for the publications made accessible via the Edinburgh Research Explorer is retained by the author(s) and / or other copyright owners and it is a condition of accessing these publications that users recognise and abide by the legal requirements associated with these rights.

### Take down policy

The University of Edinburgh has made every reasonable effort to ensure that Edinburgh Research Explorer content complies with UK legislation. If you believe that the public display of this file breaches copyright please contact [openaccess@ed.ac.uk](mailto:openaccess@ed.ac.uk) providing details, and we will remove access to the work immediately and investigate your claim.



# A numerical modelling and deep learning approach to the ballistic impact resistance of additive manufactured maraging steel

Maisie Edwards-Mowforth<sup>a\*</sup>, Samuel Thompson<sup>a</sup>, Miguel Costas<sup>b</sup>, Martin Kristoffersen<sup>b</sup>, Tore Børvik<sup>b</sup>, Filipe Teixeira-Dias<sup>a</sup>

<sup>a</sup>*Institute of Infrastructure and Environment, School of Engineering, The University of Edinburgh, Edinburgh, UK*

<sup>b</sup>*Structural Impact Laboratory (SIMLab), Department of Structural Engineering, NTNU – Norwegian University of Science and Technology, Trondheim, Norway*

---

## Extended Abstract

Improved performance of protective structures is critical to keep pace with demand for lightweight and mobile fortification. In recent years, additive manufacturing (AM) has enabled the fabrication of parts with multi-scale geometrical optimisation in the aerospace and automotive sectors – technology which could accelerate development of lightweight armour systems. Powder-bed fusion (PBF) is an AM process whereby powder is selectively fused by an energy source to build up material layer upon layer according to a computer model. Maraging steel is a low carbon steel well suited to the PBF process, drawing extreme strength from intermetallic precipitates developed during AM cyclic heating and post-AM heat treatment. On the basis that a material's yield strength is strongly correlated with perforation resistance, AM maraging steel is a promising candidate for protection against ballistic impact.

The testing of high-strength AM materials, however, escalates the complexity and cost of experimental campaigns. As a result, optimisation tasks become increasingly dependent on numerical modelling and predictive technologies. Widely used numerical techniques for ballistic impact problems were implemented to model experimental tests on as-printed and heat treated maraging steel [1]. Perforation processes for as-printed AM maraging steel were reproduced with good accuracy, but the models fell short for the ultra high-strength heat treated material. The latter is attributed to an inability of the material model to capture both projectile fracture, the mechanism that gives superior ballistic performance to the material, and the extent of target fragmentation present in experimental tests. The numerical simulation results are a step toward a functional model of AM maraging behaviour during ballistic penetration and perforation, but nevertheless highlight the drawbacks of methods reliant on empirical data, lacking at present due to experimental limitations.

Deep learning methods are computational systems which employ artificial neural networks (ANNs). Generative adversarial networks (GANs) fall into the category of 'unsupervised' deep learning: algorithms designed to extract patterns from unstructured datasets. Recent advancements in GANs and transfer learning have found utility in high-dimensional problem spaces with limited training data. These methods could hold potential to accelerate developments in AM for ballistic protection – a design process governed by a large number of complex factors for which experimental data is limited.

A GAN model was constructed and trained solely on experimental ballistic test data [1], as depicted graphically in Figure 1. After training, the GAN generated accurate quantitative predictions of ballistic limit velocity for both heat treated and as-printed maraging steel datasets, surpassing that of the numerical models, as shown in Table 1. Potential avenues for further research include exposing the GAN to variations of material composition and geometry and combining the use of GANs and numerical modelling. These techniques could be important tools in drawing upon the geometrical freedom and customisation possibilities of AM, as well as diminishing cost and resource requirements in the development stage of AM maraging steel for future protective structures.

---

\* Corresponding author.

E-mail address: Maisie.Edwards-Mowforth@ed.ac.uk

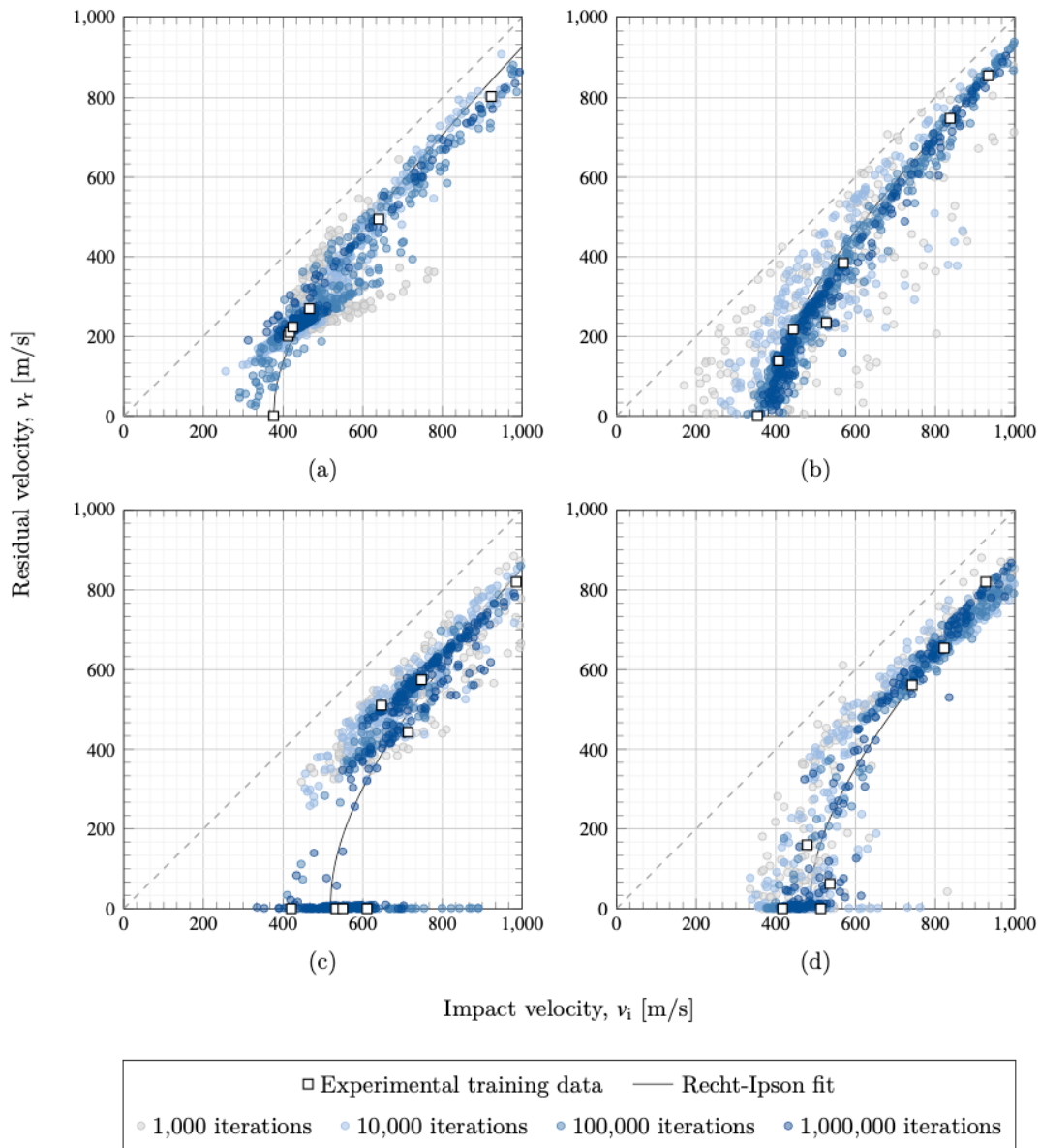


Figure 1. Iterative GAN predictions of ballistic curves for experimental tests on maraging steel plates [1]: (a) as-printed; core only, (b) as-printed; full APM2 bullets, (c) heat treated; core only, (d) heat treated full APM2 bullet.

Table 1. Error in ballistic limit velocity prediction for numerical models and GAN for various ballistic tests.

	Percentage error [%]			
	(a) As-printed; core only	(b) As-printed; full bullet	(c) Heat treated; core only	(d) Heat treated; full bullet
GAN	9.53	1.19	5.24	2.25
Numerical models	7.37	3.36	35.92	42.84

- [1] Costas M, Edwards-Mowforth M, Kristoffersen M, Teixeira-Dias F, Brøtan V, Paulsen CO, Børvik T. Ballistic impact resistance of additive manufactured high-strength maraging steel: An experimental study. *International Journal of Protective Structures* 2021; 12:577-603.

**Acknowledgements:** For the purpose of open access, authors Edwards-Mowforth and Teixeira-Dias have applied a Creative Commons Attribution (CC BY) licence to any Author Accepted Manuscript version arising from this submission.