

LIGHTWEIGHT BIMETALLIC GEARS FOR AEROSPACE TRANSMISSIONS ENABLED BY OPEN-AIR DIFFUSION BONDING

Zhuocheng Xu[1], Ernie Tang[1], Noe Teyssier[1], Micheal F Humphreys[1] & Jun Jiang*[1]

1 Department of Mechanical Engineering, Faculty of Engineering, Imperial College London, London, United Kingdom
*Corresponding author: jun.jiang@imperial.ac.uk

Abstract

Lightweight gears are attractive for aerospace and other high-value transmission systems because they can reduce both component mass and rotational inertia while improving power density. A steel-lightweight alloys bimetallic architecture is particularly promising: the steel ring preserves tooth contact, bending and wear performance, whereas the lightweight alloys core reduces the density of the central region. However, reliable lightweight alloys-Fe bonding such as (Al-Fe bonding) remains difficult because oxide formation, intermetallic formation and high joining temperatures can produce weak interfaces and compromise subsequent gear heat treatment. This paper showed our recent work on the development of a low-temperature solid-state bonding route for manufacturing bimetallic gears manufacturing. The process combines controlled surface preparation, an oxidation-resistant metallic coating, pressure-assisted bonding in open air and post-joining machining. Laboratory-scale gear prototypes with an Fe ring and Al core have been manufactured, and preliminary X-ray radiography and scanning electron microscopy indicate a continuous interface without obvious macroscopic voids at the inspected regions. The paper further describes the experimental workflow, preliminary prototype results and the planned transition from laboratory samples to industrially representative gears with dynamic fatigue, transmission efficiency, noise-vibration and corrosion validation.

Keywords: bimetallic gears; lightweighting; solid-state bonding; aluminium-steel; aerospace transmission

1. Introduction

Reducing the mass of transmission components is an important route toward higher efficiency in aerospace, automotive, energy and industrial systems. Gears are especially relevant because they combine high local contact stress, cyclic tooth bending loads and rotational inertia. In aircraft and wind-turbine applications, the cumulative mass of gears and associated transmission hardware can be substantial, so lightweighting has a direct effect on system-level efficiency and dynamic response.

Several lightweight gear concepts have been explored, including polymer gears, steel-composite hybrid gears and titanium or coated-metal solutions. These approaches can reduce mass, but industrial adoption remains limited where heavy cyclic loads, durability, dimensional accuracy and cost are simultaneously required [1]. A bimetallic steel-aluminium gear offers a more direct materials solution: steel is retained at the tooth ring where hardness, contact fatigue resistance and wear resistance are essential, while aluminium replaces steel in the core where the mechanical demand is lower.

Earlier work on aluminium-steel bimetallic gears demonstrated that large weight reductions are

possible, including hot forge welded Fe-Al gears with more than 40% mass saving compared with all-steel equivalents [2]. The main limitation was the high joining temperature. Aluminium and steel both form surface oxides, and the Al-Fe interface is susceptible to oxide entrapment and brittle interfacial reaction products. These issues can reduce bond strength, fatigue resistance and process reproducibility. High joining temperatures may also complicate case hardening or other tooth treatments required for long service life.

The objective of this paper is to present a low-temperature solid-state bonding strategy for Fe-Al bimetallic gears and to organise the work into a conventional conference-paper structure: experimental methodology, preliminary results and conclusions. The emphasis is on the manufacturing concept, interfacial design, prototype feasibility and the validation steps required to translate the process from laboratory-scale gears to industrially representative aerospace transmission components.

2. Experimental

2.1 Gear architecture and design basis

The investigated component architecture consists of an Fe-based outer gear ring joined to an Al-based core. The outer ring is intended to provide tooth strength, wear resistance and compatibility with conventional gear finishing routes. The Al core provides mass reduction and lower polar inertia. For a simplified axisymmetric gear disk with outer radius r_o, steel-ring inner radius r_i and thickness t, the hybrid-gear mass can be approximated by:

$$m = \pi t \left[\rho_{Fe}(r_o^2 - r_i^2) + \rho_{Al}\, r_i^2\right] \quad (1)$$

The corresponding polar inertia around the gear axis is:

$$I_p = (\pi t/2) \left[\rho_{Fe}(r_o^4 - r_i^4) + \rho_{Al}\, r_i^4\right] \quad (2)$$

These expressions were used as a first-order design tool to assess the effect of replacing the central steel region with aluminium. They also show why the radial position of material replacement is important: inertia saving depends more strongly on radius than mass saving.

2.2 Surface preparation and interfacial coating

The low-temperature joining route was designed to suppress oxide formation and promote intimate metal-metal contact before bonding. The generic surface preparation sequence consisted of mechanical grinding to remove surface contamination and control roughness, sandblasting where appropriate to increase surface activation, ultrasonic cleaning in organic solvents, chemical pickling, electroplating of an oxidation-resistant metallic coating and pressure-assisted bonding. The coating layer acts as an interfacial mediator, limiting re-oxidation after surface activation and enabling joining under open-air conditions.

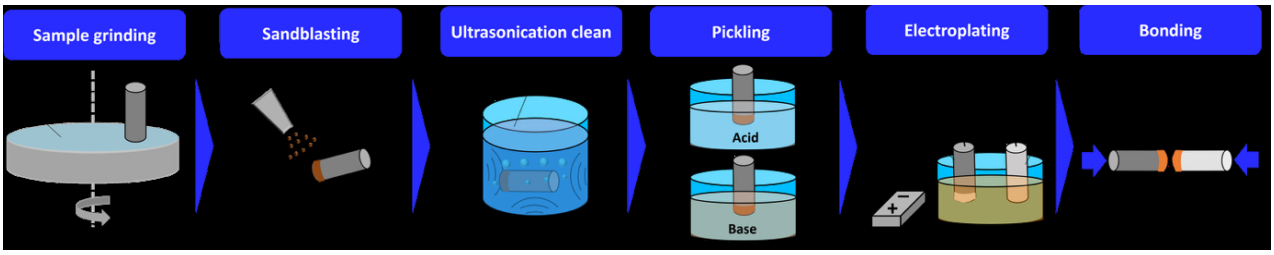


Figure 1 - Surface preparation and low-temperature solid-state Al-Fe joining sequence.

2.3 Low-temperature bonding and gear manufacture

The sample-level bonding sequence was adapted to an annular gear geometry. The Fe ring and Al core were machined to controlled dimensions before surface treatment. The Fe ring can be processed for tooth performance, including heat treatment and case hardening where required, before joining. After coating, the Al core and Fe ring were assembled and bonded by locally applying pressure and heat at a temperature far below conventional hot forge welding. The low bonding temperature is intended to minimise oxide growth, reduce brittle Al-Fe intermetallic formation and

preserve the condition of the steel gear ring.

For gear manufacture, the coated Al core was inserted into the Fe ring and compressed using an expanding mandrel/die arrangement. This geometry promotes radial pressure at the interface. Digital-twin and finite-element analysis were included in the process design to improve pressure alignment and temperature uniformity during scale-up. After bonding, end-surface machining was used to remove excess material and prepare the component for inspection and testing.

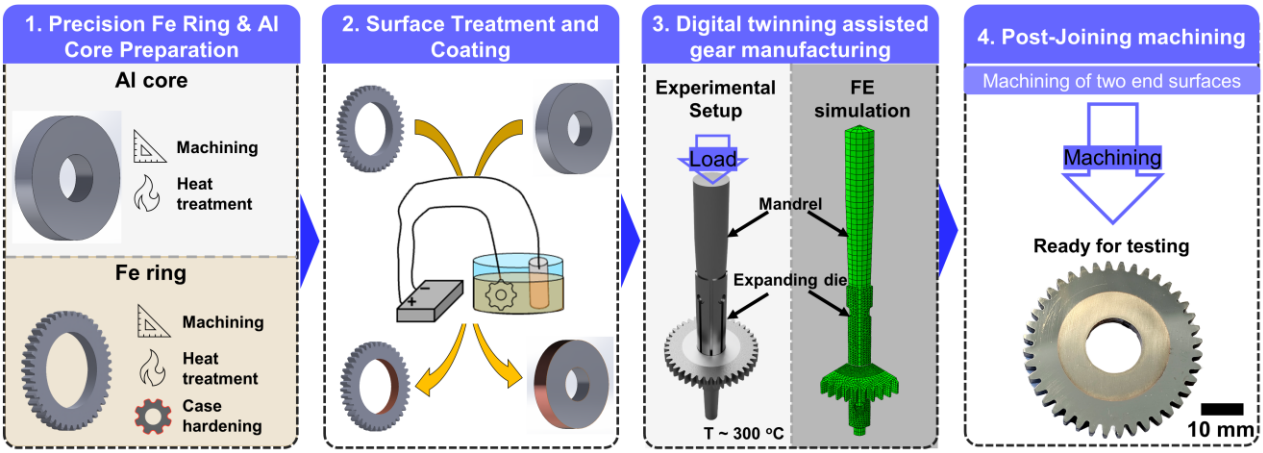


Figure 2 - Low-temperature solid-state manufacturing route for bimetallic gears.

2.4 Characterisation and performance-validation approach

The preliminary prototype was examined using X-ray radiography to assess component-scale defects and scanning electron microscopy in backscattered-electron mode to inspect the interface. These methods were selected because a gear joint must be evaluated at both the component scale and the metallurgical-interface scale. Radiography provides a non-destructive indication of internal discontinuities, while microscopy resolves the Al-coating-Fe interfacial region.

Functional performance validation is being developed around dynamic gear testing. The planned testing sequence includes static bond assessment, dimensional inspection, dynamic fatigue under representative torque, transmission-efficiency measurement, noise and vibration monitoring, and environmental durability tests such as corrosion exposure. This staged approach is required because static bond strength alone is not sufficient to qualify a gear for cyclic transmission service.

3. Results

3.1 Prototype manufacture

Laboratory-scale bimetallic gear prototypes with a diameter of approximately 40 mm were manufactured using the low-temperature route. The resulting components consisted of a continuous Fe outer ring bonded to an Al core. The process demonstrated that an annular Al-Fe interface can be formed without using the high temperatures associated with earlier hot forge welding approaches. This is significant because it provides a pathway to retain steel-tooth performance while introducing a lightweight core.

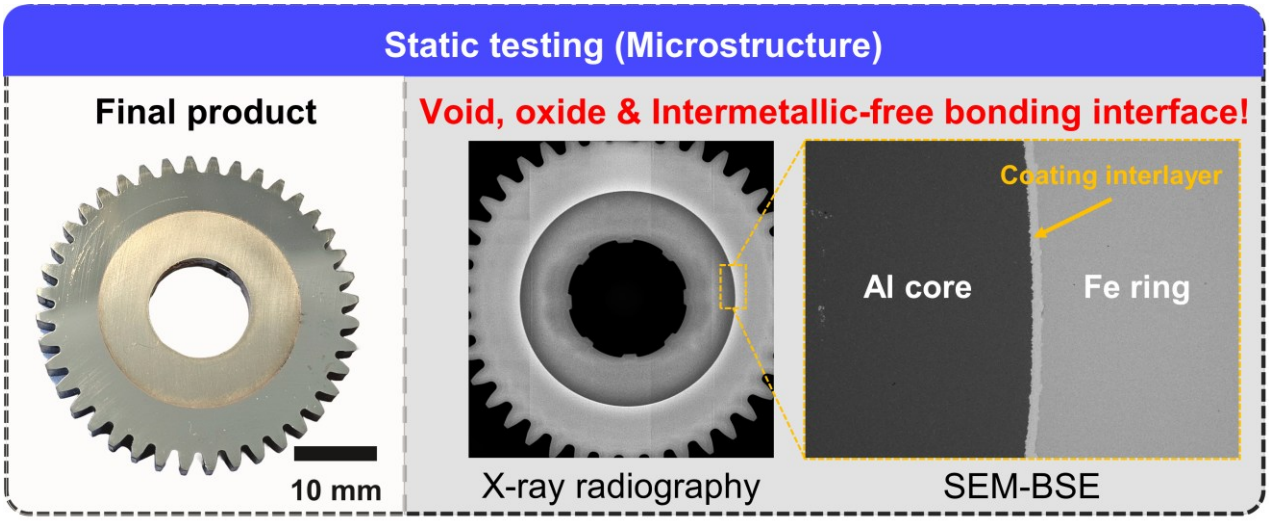


Figure 3 - Laboratory-scale bimetallic gear prototype, X-ray radiography and SEM-BSE inspection of the Al-Fe interface.

3.2 Preliminary interface quality

The preliminary radiographic and SEM observations suggest that the inspected regions of the Al-Fe interface are continuous and free from obvious macroscopic voids. In the SEM-BSE image, the Al core, coating interlayer and Fe ring can be distinguished by contrast. The absence of an obvious discontinuous weld line at the component scale is an encouraging indication that the pressure-assisted route produced intimate contact around the annular interface. Further quantitative assessment is still required, including interface-thickness measurement, higher-resolution microstructural analysis, local chemistry and statistically repeated inspection across multiple gear positions.

3.3 Bonding performance and cost-down pathway

A key translational requirement is to replace expensive precious-metal coatings with a lower-cost interfacial system. Preliminary joining trials also indicated an increase in joint strength from approximately 170 MPa to approximately 240 MPa, together with a shorter joining cycle. These results suggest that the cost-down route is not merely an economic substitution, but can also improve bonding performance. The mechanism is expected to involve improved interfacial continuity and more favourable deformation/contact conditions, although this requires further metallurgical verification.

3.4 Lightweighting and inertia reduction

The bimetallic architecture provides weight reduction by replacing the low-stress central steel region with aluminium. Based on the simplified design model in Eqs. (1) and (2), the achievable reduction depends on the ratio between the Al-core radius and the total gear radius. For the small-scale prototypes considered here, the concept is consistent with mass and rotational-inertia reductions of up to approximately 50% compared with equivalent all-steel geometries, depending on the selected ring thickness and core size. In aerospace transmission systems, this inertia reduction is particularly valuable because it can reduce transient loads and improve acceleration/deceleration response.

3.5 Dynamic testing and scale-up toward industrial representation

The next stage is to move from prototype manufacture to validated gear performance. A dynamic test rig has been assembled to support fatigue, transmission-efficiency and noise-vibration studies. This testing is essential because cyclic tooth loading can introduce shear and peel components at the annular interface that are not captured by static strength measurements alone.

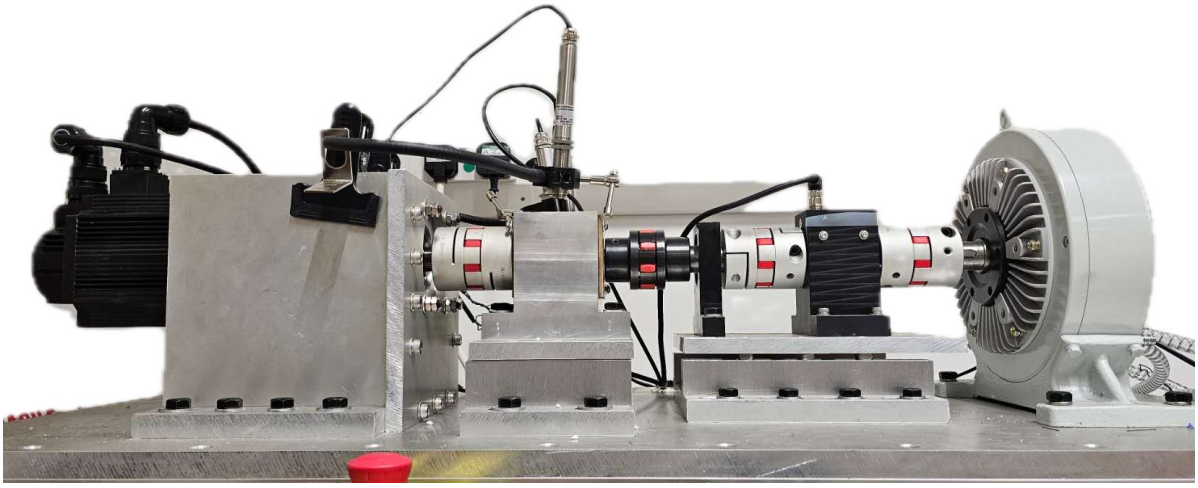


Figure 4 - Dynamic gear testing facility for fatigue, transmission efficiency and noise-vibration validation.

Scale-up from a 40 mm laboratory prototype to an industrially representative gear introduces several coupled manufacturing challenges. Coating uniformity must be maintained over larger annular surfaces, the pressure field must be aligned to avoid local under-bonding or excessive plastic deformation, and temperature distribution must be controlled to avoid microstructural gradients. The proposed translation workflow therefore combines gear design, finite-element simulation, scaled manufacturing trials, non-destructive inspection, dynamic testing and feedback-driven process refinement.

4. Conclusions

- A steel-aluminium bimetallic gear architecture can reduce mass and rotational inertia while retaining steel at the tooth ring, where contact fatigue, wear resistance and tooth bending strength are required.
- The main manufacturing barrier is the Al-Fe interface. The proposed low-temperature solid-state route uses oxide removal, an oxidation-resistant metallic coating and pressure-assisted bonding to enable joining under open-air conditions.
- Laboratory-scale gear prototypes with an Fe ring and Al core have been manufactured. Preliminary radiography and SEM-BSE inspection indicate a continuous interface without obvious macroscopic voids at the inspected regions.
- Future work should quantify interface chemistry, bond strength statistics, fatigue resistance, dimensional accuracy, corrosion durability and process repeatability during scale-up to industrially representative gears.

Acknowledgements

The authors acknowledge support from Imperial College London and the UKRI Impact Acceleration Account. The authors also acknowledge Rolls-Royce, DEPE gear technical discussions and support associated with gear design, manufacturing scale-up and performance validation.

Copyright statement

The authors confirm that they, and/or their company or organization, hold copyright on all of the original material included in this paper. The authors also confirm that they have obtained permission, from the copyright holder of any third party material included in this paper, to publish it as part of their paper. The authors confirm that they give permission, or have obtained permission from the copyright holder of this paper, for the publication and distribution of this paper as part of the ICAS proceedings or as individual off-prints from the proceedings.

References

[1] Politis N J, Wang Y, Lin J and Dean T A. Advances in multi-metal gear manufacturing. Production Engineering, Vol. 15, pp 235-262, 2021.

[2] Wang W, Politis N J, Lin J and Dean T A. Solid-state hot forge bonding of aluminium-steel bimetallic gears: deformation mechanisms, microstructure and mechanical properties. International Journal of Machine Tools and Manufacture, Vol. 180, 103930, 2022.

[3] Laberge K, Saponara V L, Griffiths P R and Lepage M. Performance investigation of a full-scale hybrid composite bull gear. Conference paper, 2016.

[4] Joost W J. Reducing vehicle weight and improving U.S. energy efficiency using integrated computational materials engineering. JOM, Vol. 64, pp 1032-1038, 2012.

[5] Mordor Intelligence. Global gear market - growth, trends, and forecast. Industry report, accessed for project market context.