Review

Not peer-reviewed version

Metal Forming of Metallic Aircraft Wing Covers: Process Origins, Industrial Development and Programme-Level Evidence

Andrew Levers *

Posted Date: 15 June 2026

doi: 10.20944/preprints202605.1979.v2

Keywords: wing cover; wing skin; shot peen forming; stress peen forming; laser peen forming; creep age forming; aluminium alloys; residual stress; aircraft manufacturing; process selection

Review

Metal Forming of Metallic Aircraft Wing Covers: Process Origins, Industrial Development and Programme-Level Evidence

Andrew Levers

University of Liverpool Department of Aerospace and Mechanical Engineering, Liverpool, United Kingdom; alevers@liverpool.ac.uk

Abstract

Metallic wing covers are defined here as wing skins plus mechanically attached or integrally machined stringers; an integrally stiffened panel is the monolithic case in which the skin and stiffeners are machined from one plate. This structured narrative review examines upper and lower metallic wing covers as manufacturing objects in civil transport, business-aircraft, and selected military fixed-wing programmes. Aircraft-level evidence is concentrated from 1950 onward, with earlier peen-forming origins included only where they explain later industrial adoption. The evidence base combines peer-reviewed papers, SAE Technical Papers, patents, trade literature, government reports and supplier disclosures, so the review uses explicit source weighting rather than statistical aggregation. Evidence is graded by source strength, and patents are treated as capability evidence rather than proof of production use unless independently corroborated. The synthesis shows that route selection is governed by structural scale, cover role, curvature class, alloy and temper, inherited stock state, panel architecture, and compensation or validation capability. The upper/lower cover divergence that emerges is directly evidenced for selected Airbus, Gulfstream and B-1B cases and is treated, for Boeing and other lineages where cover-separated routes are not publicly disclosed, as a mechanistically supported inference rather than a demonstrated production rule. The strongest public evidence supports peen and particle-impact routes for selected directional or inflected lower-cover cases, Creep Age Forming (CAF) for large smooth heat-treatable covers, and specialised laser or hybrid routes where corroborated by supplier, patent, or named-programme evidence. Modern, non-Western, business-jet, and many military programmes are frequently supported only by patent, supplier, lineage, or contextual evidence and are therefore interpreted cautiously.

Keywords: wing cover; wing skin; shot peen forming; stress peen forming; laser peen forming; creep age forming; aluminium alloys; residual stress; aircraft manufacturing; process selection

---

1. Introduction and Scope

Metallic wing covers, comprising the wing skin and attached or integrally machined stringers, are among the most demanding panel-formed components in aircraft manufacture. They define external aerodynamic shape, close the fuel volume, transfer distributed loads into ribs and spars, and, in integral-panel architectures, incorporate part of the stiffening system through machined or formed stringers, pads, and thickness transitions. For brevity, this review sometimes uses the term 'wing skin' to describe the outer plate alone, but 'wing cover' denotes the integrated skin-plus-stringer structure. The manufacturing problem is therefore intrinsically coupled: the same part must satisfy outer-surface fidelity, inner-surface stiffness architecture, dimensional stability, residual-stress control, and assembly repeatability, often over very large areas and under severe thickness variation [1–4].

This paper reviews metallic upper and lower wing covers in civil transport aircraft, major business-jet families, and selected military fixed-wing aircraft. The principal aircraft-programme

 doi:10.20944/preprints202605.1979.v2

evidence begins in the 1950s; earlier interwar and immediate post-war peening developments are included as process-origin context rather than as a claim of complete pre-1950 aircraft-programme coverage. Military examples are included only where they contribute directly to forming-process knowledge, transfer history, or manufacturing comparison.

The technical development is interpreted through four stages, consistent with Figure 5: Stage 1, Origins (1920–1969); Stage 2, Industrialisation (1970–1989); Stage 3, CAF expansion (1990–2010); and Stage 4, Specialisation (2011–present). These stage labels describe changes in manufacturing problem rather than a complete chronological catalogue of every aircraft programme.

The paper's analytical centre of gravity is process mechanics. The synthesis is built around foundational shot-peening mechanics, aircraft-level industrial evidence, experimental and numerical studies of peen and stress-peen forming, and the CAF modelling and tooling literature. These scholarly sources are read alongside industrial anchors from Curtiss-Wright/Metal Improvement Company, Airbus, Textron, Electronics Inc./The Shot Peener, Vacu-Blast and Lawrence Livermore National Laboratory to connect process theory to programme-level evidence [3–16].

This review develops four linked contributions. First, it treats the wing cover, not the aircraft type or forming process alone, as the unit of analysis. Second, it distinguishes upper and lower cover geometry and loading when interpreting process selection. Third, it combines process-level comparison with aircraft-level attribution inside an explicit evidence hierarchy. Fourth, it shows that forming route choice is a manufacturing-systems decision shaped by alloy eligibility, curvature, inherited stock state, surface integrity, compensation capability, production rate and supply-chain ownership.

1.1. Related Work and Literature Positioning

Adjacent literature is substantial but fragmented: it is organised around process families, modelling methods, or individual programme cases rather than around metallic wing covers as a distinct manufacturing object. The present review addresses that gap by treating the wing cover itself, upper and lower, structural, and aerodynamic, civil, and military, as the unit of analysis across the full range of forming processes and aircraft programmes, from the origins of peen-based forming in the interwar period through to the current composite-transition era.

The closest conceptual predecessor is Zeng and Huang [17], who survey large integral aircraft panels and foreground both shot peen forming and CAF as enabling technologies for civil-aircraft development. That paper is important, but it is centred on integral-panel technology in general and on Chinese large-aircraft development rather than on a global aircraft-by-aircraft account. A broader framing of aluminium panel-forming technology is offered by Zheng et al. [129], who provide the clearest survey of cold, warm, and hot forming routes for lightweight complex-shaped aluminium panels, and by Zhang and Li [19], who review bend-forming routes for integral panels with particular attention to buckling, fracture, and process defects. These papers are valuable for process-selection logic and mechanics, but they are not wing-cover specific, and they do not distinguish upper from lower covers or map processes to named aircraft programmes.

Process-specific review literature provides depth in individual routes but not their comparative deployment. Zhan et al. [4] remains the foundational CAF review, covering experiments, modelling, tooling, springback prediction, and aircraft applications, while Zhang et al. [20] concentrate on springback control and tooling design in CAF. For laser peen forming, Yocom, Zhang and Liao [21] review process design, forming mechanisms, and simulation methods. Shot peen forming, by contrast, is served more strongly by handbook chapters, modelling papers, patents, and industrial proceedings literature than by a single modern review article, an asymmetry that reflects the process's longer industrial history and more dispersed knowledge base.

Programme-specific literature is equally dispersed but industrially indispensable. Moore [3] on DC-10 and DC-9 Super 80 shot peen forming, Brandel and Klass [22] on L-1011 ball forming, Tatton [13] on Airbus A310/A320 geometry and peen forming, Cook [14] and Vacu-Blast [15] on Gulfstream IV production peen-forming systems, and Hambrick [23] and Holman [24] on autoclave age forming

 doi:10.20944/preprints202605.1979.v2

each illuminate a significant part of the problem. None, however, attempts an integrated review across manufacturers, aircraft classes, upper-versus-lower cover roles, patents, and open industrial evidence, which is precisely the gap this review addresses.

The present paper is therefore positioned as an evidence-based synthesis across process physics and industrial application rather than as another single-process review. Its process selection framework, governing variables, elimination screens, ranking of feasible survivors, follows the logic of process selection methodology codified by Ashby [25], applied here to the specific geometry-and-alloy constraints of metallic wing-cover manufacture rather than to the general component design context for which that framework was originally developed. Its distinctive contributions are: explicit upper/lower wing-cover differentiation; a common geometry-and-curvature framework; a process comparison spanning mechanical forming, shot peen forming, stress peen forming, particle-impact forming, laser peen forming, CAF, and hybrid routes; aircraft-level and manufacturer-level mapping grounded in patents, industrial disclosures, technical papers, and review literature; and a manufacturing-level synthesis in which route choice is interpreted as the coupled outcome of structural scale, cover role, curvature regime, inherited stock state, panel architecture, and compensation or validation burden.

1.2. Review Method, Evidence Sources and Attribution Rules

This study is a structured narrative review designed to make source selection, evidence grading and claim attribution auditable across heterogeneous public source classes. A PRISMA-style systematic review or meta-analysis was not appropriate because the relevant evidence includes patents, SAE Technical Papers, trade articles, official supplier disclosures, government reports, standards, laboratory communications and proprietary manufacturing accounts as well as peer-reviewed papers. These source classes do not share a standard reporting format, and the scarcity of direct production disclosure is itself a finding of the review. The purpose of the method is therefore not statistical aggregation, but transparent, conservative synthesis.

1.2.1. Review Objective

The review objective was to identify, evaluate and synthesise publicly available evidence linking metallic aircraft wing-cover forming processes to named aircraft programmes and manufacturing lineages. The review specifically distinguishes demonstrated production use from capability evidence, source-type convergence, and mechanistic inference.

1.2.2. Source Domains and Search Perimeter

Searches were updated through April 2026. Scholarly searching covered Google Scholar, Crossref, Scopus, Web of Science, ScienceDirect, SpringerLink and publisher-hosted journal platforms represented in the bibliography. SAE Mobilus was used for SAE Technical Papers and AMS/J-series standards. Patent searching used public patent-family registers, primarily Google Patents and Espacenet. Industrial searching was restricted to official manufacturer or supplier disclosures, laboratory disclosures, government, or committee reports, and archived industrial papers with identifiable provenance.

1.2.3. Search Strategy and Query Families

Searches combined aircraft-family names, manufacturer names and process terms such as shot peen forming, peen forming, stress peen forming, ball forming, particle-impact forming, laser peen forming, laser shock forming, creep age forming, age forming, stretch forming, press forming, integral panel, integrally stiffened panel, wing skin, wing cover, aluminium-lithium, residual stress and springback. Representative Boolean search families included: ("shot peen forming" OR "peen forming") AND ("wing skin" OR "wing cover" OR "integral panel"); ("creep age forming" OR "age forming") AND ("aircraft wing" OR "wing cover" OR "integrally stiffened panel"); and ("laser peen

 doi:10.20944/preprints202605.1979.v2

forming" OR "laser shock forming") AND ("wing panel" OR "integral stiffened panel"). Named-aircraft searches combined process terms with programme names, including DC-10, L-1011, 747, A300, A310, A320, A330, A340, A380, Gulfstream IV, B-1B, C-130, F-15, Embraer E2 and COMAC C919. Chinese-language assignees and Russian programme lineages were searched in English transliteration and, where a patent record was used, confirmed against the original public register entry.

1.2.4. Screening and Retention Procedure

Records were screened sequentially by title or patent title, abstract or summary, and full text where accessible. A source was retained if it contributed at least one of the following: process-mechanics evidence; named-aircraft or supplier/manufacturer process attribution; patent-supported capability, tooling, or control evidence; source-status qualification; or boundary evidence needed to prevent over-attribution. Sources were excluded from aircraft-route attribution if they did not identify a forming process, did not connect the process to a wing cover or relevant panel class, or resolved to an unrelated patent or generic manufacturing capability. Where full text could not be accessed, the source was not used as a Class A anchor; it was used only as context or retained as a limitation if independently cited by accessible sources.

1.2.5. Evidence Classes and Attribution Rules

Evidence is graded conservatively. Class A denotes direct serial-production or supplier/manufacturer disclosure of a named-aircraft wing-cover route. Class B denotes named-aircraft public evidence that clearly relates to wing-cover forming but leaves the upper/lower split, exact production stage or full route incompletely disclosed. Class C denotes patent-supported capability, adjacent aircraft-specific manufacturing evidence, or lineage-level evidence consistent with but not proving serial use. Class D denotes structural comparators, boundary cases, or searched lineages without firm public route attribution. In Tables 6A and 6B, upper and lower covers are recorded separately. Where a source is ambiguous, the lower defensible evidence class is retained.

1.2.6. Source Reliability and Claim Weighting

Source convergence increased confidence but did not override the intrinsic evidential limits of a source class. For example, a patent and a supplier capability page may jointly support industrial capability, but they do not by themselves prove serial use on a named aircraft. Conversely, a named-aircraft SAE paper or manufacturer disclosure may justify Class A or B attribution even without a supporting patent.

1.2.7. Patent Treatment and Verification

Patents are classified independently of evidence class. Proc. patents claim the curvature-generating route itself, Tool. patents claim enabling fixtures, dies, delivery systems or preloading hardware; Dev. patents claim compensation, control, residual-stress management, microstructural control, or analysis-enabled process design; Adj. patents are adjacent lineage patents that support development context but not programme-specific use. Every patent cited in this version was re-checked directly against Google Patents or Espacenet for number, title, assignee, and subject matter. Misidentified identifiers from earlier drafts were removed and are documented in the supplementary audit record.

1.2.8. Distinguishing Evidence, Interpretation, and Hypothesis

The synthesis uses four explicit claim levels. Evidence-supported findings are anchored in Class A or Class B programme evidence and process-mechanics literature. Mechanistic interpretations explain why the observed route is technically coherent but do not by themselves establish production use. Industrial inferences combine mechanism, source convergence and lineage evidence where direct programme disclosure is absent. Hypotheses and future-work statements are used only for propositions that require additional archive, programme-level or metrological evidence.

1.2.9. Tables, Supplementary Material, and Reproducibility Limits

Tables 1 and 2 define the source-domain and claim-weighting frameworks; Table 3 summarises the curvature taxonomy; Table 4A synthesises contour-forming routes; Table 4B isolates upstream stock-state conditions; Table 5 summarises the evidence distribution for Tables 6A and 6B; Tables 6A and 6B capture aircraft-level attributions retained in the main manuscript; Table 7 summarises the evidence-weighted basis for the principal conclusions; and Appendix A provides the corresponding aircraft-manufacturer lineage map. The supplementary material documents search domains, query families, source-status rules, patent verification and lower-evidence aircraft catalogues. It preserves breadth and traceability; it does not upgrade patent-only, supplier-level, or contextual cases into production evidence unless independently corroborated in Tables 6A or 6B.

Table 1. Source domains and evidential roles used in the review.

Source domain	**Primary use in the review**	**Typical evidential role**
Peer-reviewed journals and reviews	Process mechanics, modelling, residual-stress, and metallurgy evidence	High weight for mechanistic claims; not automatically proof of production use
SAE Technical Papers / ICSP papers / standards	Named programme evidence, process-control rules, and industrial practice	High weight when named aircraft, process and manufacturing context are explicit
Manufacturer, supplier, laboratory, and government disclosures	Programme route, facility, application lineage or independent corroboration	High to moderate weight depending on specificity and stability
Patents and patent families	Capability, tooling, control, or development trajectory	Capability evidence only unless independently corroborated by programme or supplier evidence
Trade literature and historical supplier publications	Historical attributions and otherwise unavailable industrial context	Moderate to low weight; not elevated to Class A without corroboration

Table 2. Claim-weighting framework used to distinguish evidence, interpretation, and inference.

Claim type	**Minimum evidence expected for use in main text**	**How the claim is worded**
Documented production route	Class A or strong Class B named-aircraft evidence	Demonstrated, disclosed, directly evidenced
Named aircraft but incomplete route	Class B evidence with stated uncertainty	Associated with, publicly linked to, incompletely disclosed
Capability or development trajectory	Verified patent, supplier capability, modelling, or adjacent lineage evidence	Capability evidence, development logic, mechanistically consistent

Industrial inference	Mechanistic reasoning plus Class B/C context	Inferred, plausible, consistent with the evidence, not demonstrated
Boundary or negative-evidence case	Searched lineage without route attribution	No public route located; not evidence of absence

1.3. Aircraft Classification Method

Because forming requirements are governed primarily by structural scale, wing-cover geometry, material state, and panel architecture, no standard regulatory or operational classification scheme is sufficient on its own for the analysis developed here. CS-25 and FAR Part 25 define large civil transport aircraft, but airport, market, and wake-turbulence classifications use different criteria, and neither family addresses military aircraft in manufacturing terms.

This review therefore adopts a hierarchical classification framework purpose-built for manufacturing analysis. Civil aircraft are classified first by certification category, with large transport aircraft treated as CS-25/FAR Part 25 platforms where applicable; military aircraft are mapped to equivalent structural classes based on configuration and scale, with military transports, tankers, and large bombers treated as CS-25 analogues while retained fast-jet or patrol benchmarks are identified explicitly as non-transport comparators. A secondary classification then applies structural scale, wingspan, and associated wing-cover size, grouping aircraft into Class I (small transports, <30 m wingspan), Class II (medium transports, 30–50 m), and Class III (large transports, >50 m). A final configuration or mission modifier is applied where it materially affects wing-cover geometry or forming relevance.

Where a programme family crosses a threshold, or where the smallest baseline variant understates the wing-cover scale of the family, the class is assigned conservatively upward to preserve manufacturing comparability. These certification analogues are construction tools for the present analysis; they are not intended as retrospective legal certification claims for legacy or military aircraft. The framework is illustrated in Figure 1 and provides the consistent basis for interpreting wing-cover forming processes across the aircraft families addressed in Sections 5 through 7.

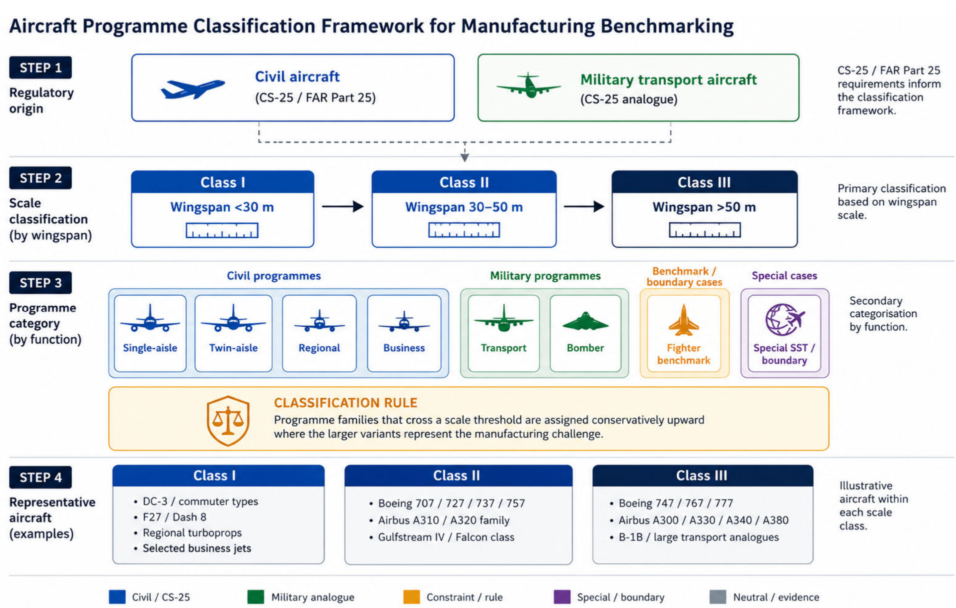

Figure 1. Hierarchical aircraft-classification framework used to compare civil, business, and selected military fixed-wing programmes in manufacturing terms. The diagram links regulatory/analogue class to structural scale, configuration/mission, and representative aircraft examples; scale classes are assigned conservatively

 doi:10.20944/preprints202605.1979.v2

upward for programme families crossing threshold values, and CS-25 analogue labels are used only for manufacturing comparison. Section 1.3.

2. Geometry and Structural Requirements of Wing Covers

2.1. Upper vs Lower Wing Cover Roles

Throughout this review, ‘wing skin’ denotes the aerodynamic sheet or plate alone, whereas ‘wing cover’ denotes the wing skin together with its stiffening stringers, whether those stringers are mechanically attached or integrally machined. An integrally stiffened panel (ISP) is the monolithic sub-class of wing cover in which skin, stringers and local pads are machined from one thick plate. Several historical sources use ‘wing skin’ for what would now be described as a wing cover; this review preserves source terminology where necessary but uses ‘wing cover’ analytically. Upper and lower wing covers are not symmetric manufacturing problems. In the strongest public evidence base, particularly the Airbus family and selected CAF programmes, upper covers are more often associated with smooth large-radius curvature and CAF, whereas lower covers are more often associated with inflected, saddle-back, or dihedral-driven geometry requiring peen-based, stress-assisted, or mechanically assisted routes [3,4,13,26].

This divergence is not incidental; it is one of the principal drivers of process choice. A route capable of generating large, smooth compound curvature with acceptable springback on a thick, upper panel is not automatically the best route for a lower panel whose geometry is dominated by localised dihedral changes, inflected sections, or strong through-thickness property constraints. The strongest Airbus evidence in particular points to an upper/lower split rather than to a single universal process route across both covers [13,16,26–28].

2.2. Curvature Taxonomy

Understanding why particular forming routes recur on aircraft families requires a working taxonomy of wing-cover geometry. The open literature rarely publishes numerical curvature maps for production covers, but it does disclose a sufficiently robust qualitative taxonomy for process analysis. The recurring geometries, reconstructed here from process papers, patents, and programme accounts rather than from proprietary loft data, are single curvature, compound curvature, inflected or lazy-S lower-surface shapes, saddle-back geometries, and double curvature driven by dihedral and twist [3,4,13,14,22,29]. Table 3 summarises these classes and their principal process implications.

doi:10.20944/preprints202605.1979.v2

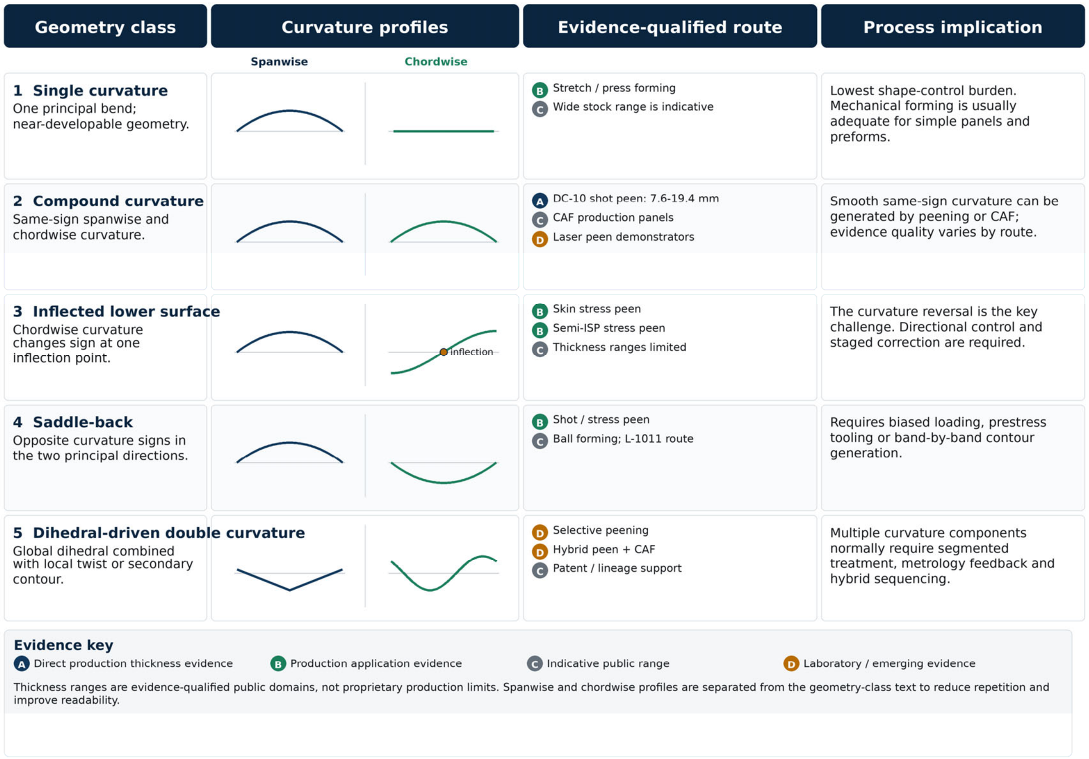

Figure 2. Curvature taxonomy used to relate metallic wing-cover geometry to feasible forming routes. The spanwise and chordwise profiles are schematic, and the thickness or stock ranges are indicative, evidence-qualified ranges derived from public process evidence and Table 4A rather than proprietary production limits. The figure highlights why single-curvature, compound-curvature, inflected lower-surface, saddle-back and dihedral-driven cases require different levels of directional control. Section 2.2 and Table 3.

Table 3. Curvature taxonomy for metallic wing covers and process implications.

Curvature class	Descriptor	Illustrative aircraft / programme	Process implication
Single curvature	Predominantly cylindrical or quasi-cylindrical bend in one principal direction.	Simple stretch-formed or mechanically preformed panels; some early skin applications.	Accessible to stretch or press forming; lowest springback complexity.
Compound curvature	Chordwise and spanwise curvature of the same sign over a large area.	General peen-formed wing skins; large upper panels.	Well suited to shot peen forming or CAF when curvature is smooth and large radius.
Lazy-S lower surface	Inflected convex-to-concave lower contour with local directional bias.	Airbus A300/A310 and A320-family lower covers.	Requires staged peening plus mechanical / press assistance; isotropic peening alone is insufficient.

 doi:10.20944/preprints202605.1979.v2

Curvature class	Descriptor	Illustrative aircraft / programme	Process implication
Saddle-back	Convex in one principal direction and concave in the other.	DC-10 lower cover; severe compound contours discussed in Boeing patent.	Often needs stress peen bias, prestress tooling, or mechanical preform assistance.
Dihedral-driven double curvature	Global dihedral plus local secondary contour or twist.	Integral panels with rib sections or winglet / outboard sections.	Favours stress peen forming, selective impact trajectories, or hybrid mechanical-plus-peen routes.

The five classes in Table 3 are not gradations of the same problem but qualitatively distinct manufacturing challenges, each of which has historically favored a different process family. Single curvature is the simplest class and the one for which conventional die-based methods remain adequate: a cylindrical bend in one principal direction is accessible to stretch forming or press forming with well-understood springback, and it provides the baseline against which the more complex geometries should be understood. Compound curvature, chordwise and spanwise curvature of the same sign, is the natural domain of shot peen forming, where a nominally isotropic impact field generates a broadly spherical bending response over large areas without a conformal die. The difficulty increases markedly with the lazy-S inflected lower surface, in which the chordwise curvature reverses sign from concave to convex across the chord: isotropic peening cannot produce this geometry without directional assistance, which is why the Airbus lower-cover record is consistently associated with staged mechanical preforming followed by peening rather than peening alone [13]. Saddle-back geometry, convex in one principal direction and concave in the other, requires the forming mechanism itself to be directionally biased, either through externally applied prestress or through the band-by-band control available in ball forming; the DC-10 lower cover, treated by Moore [3], is the canonical production case. Dihedral-driven double curvature combines a global fold with secondary chordwise contour and is the geometry most consistently associated with hybrid or selective peening approaches because no single-pass method can simultaneously generate two independent curvature components with different principal directions. These distinctions underlie the process-selection logic of Table 4A and the aircraft-level attributions of Tables 6A and 6B: the curvature class of a wing cover largely predetermines the feasible forming routes before any consideration of panel scale, alloy, or thickness.

2.3. Implications for Forming Processes.

Three implications follow directly from this curvature taxonomy, each of which will recur throughout the process-mechanics discussion in Section 4.

First, directionality matters: a method that naturally induces quasi-isotropic curvature must be modified when chordwise curvature must dominate spanwise curvature, or when one principal curvature reverses sign relative to the other. Second, panel architecture matters. In a built-up cover, the skin and stringers can in principle be formed or corrected separately before assembly; in an ISP, stringers, pads, pockets, and thickness transitions are already present and alter the local bending stiffness before contour forming begins. Third, surface-integrity constraints matter. Aerodynamic outer surfaces cannot tolerate arbitrary roughness, contamination, or residual-stress patterns, which explains the industrial emphasis on saturation control, media selection, checking fixtures, low-velocity ball media, laser loading and controlled post-peen restoration [4,9,11,14,22].

 doi:10.20944/preprints202605.1979.v2

2.4. Inherited Stock State and Pre-Form Residual Stress

The curvature taxonomy and process implications in Sections 2.2 and 2.3 describe what a forming route must achieve. An equally important question is what state it must start from. No industrial wing-cover route begins from a stress-free flat blank. Thick aerospace 2xxx, 7xxx, and aluminium-lithium plate carries an inherited state from casting, rolling, quenching, stress relief, and any subsequent saw-cutting or pre-machining. Prime and Hill [30] showed that even after stretch stress relief, 7050 plate retains self-equilibrated through-thickness residual stresses of hundreds of MPa, shaped by through-thickness inhomogeneity in strength and texture. Li et al. [31] generalises this into a multi-process view in which rolling, quench, pre-stretch, machining, and forming should be treated as a coupled chain, because each stage redistributes rather than erases the stress field passed to the next.

That chain has a direct consequence for how process capability should be interpreted. A forming route does not begin from a neutral datum; it begins from stock whose quench path, rolling history, stress-relief treatment, and pre-machining sequence have already defined a residual-stress field and a through-thickness property gradient. This point has become progressively more important across the four-stage evolution shown in Figure 5: in the origins and industrialisation stages, peen forming was often applied to relatively thin skins and covers where quench stress was a smaller part of the public record; by the CAF expansion stage, the process began from thick 7xxx plate with inherited quench stresses of hundreds of MPa that materially affect springback prediction. Industry responses such as Tx51 stretching, controlled quench practice, or edge-on stress-relief concepts reduce that inherited field but do not abolish it. For large, machined covers, those upstream measures should therefore be understood as constitutive parts of the manufacturing route rather than as invisible material pedigree, a point Table 4B makes explicit [30,32,33].

2.5. Alloy Metallurgy and Temper Designations for Wing Covers

The alloy families and temper designations used for metallic wing covers appear throughout the review as constraints on process selection, particularly for CAF, and are summarised here for reference. Full alloy composition specifications are available from primary producer datasheets and the MMPDS handbook [34].

Upper cover alloys: 7xxx series (Al–Zn–Mg–Cu)

Upper covers of large civil transport aircraft are predominantly manufactured from 7xxx-series alloys. The principal alloy sequence follows a progression of increasing specific strength and damage tolerance: 7075 (used widely from the 1960s), 7150, 7055, and more recently 7085. For CAF, the T7451 and T6151 (Tx51) overaged tempers are required because the artificial ageing response during the forming cycle must coincide with the precipitation of strengthening phases; solution-treated or naturally aged tempers (T3, W) cannot be age-formed in the metallurgical sense [4,35]. The key alloy-selection driver for upper covers is therefore the compatibility between required temper, CAF process window (typically 150–180°C dwell), and the final mechanical property target. Chen et al. [36] reported systematic reductions in UTS, yield strength (≈6%), and elongation (≈14%) after CAF of 7050 relative to stress-free ageing, which must be reflected in structural allowables.

Lower cover alloys: 2xxx series (Al–Cu and Al–Cu–Mg)

Lower covers, which carry predominantly tensile loads and are fatigue-critical over the full service life, use 2xxx-series alloys. The principal production alloys are 2024-T3 (widely used since the 1950s), 2324, and the damage-tolerant 2524 introduced for the B777 lower covers [110]. The T3 temper is incompatible with CAF because the natural-ageing response of 2xxx alloys occurs at room temperature and is largely complete before any elevated-temperature cycle; artificial ageing of 2024-T3 panels typically over-ages the alloy without providing useful forming strain [37]. Shot peen forming and mechanical preforming remain the dominant routes for 2xxx lower covers precisely because they do not require a specific temper response.

Aluminium–lithium alloys and the forming-process connection

 doi:10.20944/preprints202605.1979.v2

Al-Li alloys (8090, 8150 in second generation; 2099, 2196, 2050, 2055 in third generation) offer density reduction of 8–10% and stiffness improvement [72]. Their introduction created direct forming challenges: anisotropic mechanical behaviour and higher quench residual stresses relative to conventional 7xxx plate complicated both peen forming trajectories and CAF springback prediction [38]. Three alloy-temper developments were undertaken explicitly to enable specific forming processes: the Tx51 pre-stretch specification suppresses quench residual stress to make CAF springback prediction reliable; controlled quench practice (slow quench followed by cold water quench) was developed for thick 7xxx plate to reduce through-thickness stress gradients; and Pechiney's edge-on stress-relief patent for thick aluminium plates [32] illustrates the broader industrial effort to tailor residual-stress and ageing response in thick plate products for aircraft structural components.

3. Forming Process Families

3.1. Die-Based and Mechanical Baseline Routes

Before the stress-based and thermo-mechanical processes that dominate modern wing-cover manufacture are described, the mechanical baseline they displaced, or more precisely, the baseline they supplemented, must be established. This baseline has the longest history of any process family in the review: press forming, stretch forming, and bump forming of wing skins were the universal methods in the wartime manufacturing environment described in Section 5.0, and they remain part of the production toolkit today, particularly for preforms, edge corrections, and developable geometry. Stretch forming is that baseline: tensile loading over a die to impose predominantly single curvature on convex open shapes, with well-known thinning and springback penalties [1,2,39]. Press forming, hot forming, brake forming, and local mechanical preforming belong to the same family. They are not peripheral to wing-cover manufacture: many industrial routes continue to use them as preparatory or complementary operations, and that role is important. Their limitation, however, is mechanical rather than merely historical. Press brakes bend along straight lines, and bump forming generates large radii through discrete line bends rather than native continuous double curvature. Both are therefore useful for preforms, edge conditions, and relatively developable geometry, but inadequate as stand-alone solutions for large wing covers with strong double curvature, inflection, or abrupt stiffness variation [24,40,41].

Rolling and machining from rolled plate occupy a different analytical position, and their relationship to the wing skin / wing cover / ISP hierarchy is important. For a plain wing skin (outer sheet only), rolling and machining are essentially background operations that supply a flat or pre-bent blank of defined thickness. For a built-up wing cover, the skin is formed separately and then the stringer extrusions are attached; the machining operations are modest. But for an ISP, rolling and machining are constitutive parts of the structural object: the rolled plate must be thick enough to provide full stringer height after pocket milling; the quench and stretch sequence determines the residual-stress field that the ISP will carry into the forming cell; and the pocket milling itself redistributes that stress in ways that directly affect the subsequent forming response. For an ISP lower cover, rolled stock, quench path, pre-stretch, solution treatment, and heavy machining can determine the structural and residual-stress state of the panel before any dedicated contour-forming step begins. These operations are therefore treated here as upstream material-state conditions rather than contour-generation routes, separated from the true forming routes in Table 4A and captured instead in Table 4B, where their influence on residual-stress inheritance, anisotropy, machining distortion, and downstream compensation is made explicit. The material-supplier community has independently codified the same coupled-chain view through its residual-stress patenting, exemplified by the verified Pechiney Rhenalu edge-on stress-relief patent for thick aluminium plates [32] and the residual-stress control patent of Alnan Aluminium [101], which treat rolling, stress relief, machining and contour forming as an integrated sequence rather than independent operations.

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 15 June 2026 doi:10.20944/preprints202605.1979.v2

3.2. Stress-Based / Dieless Forming

The central stress-based family comprises conventional shot peen forming, stress peen forming, particle-impact or ball forming, and laser peen forming. These methods differ in loading mechanism and in the depth, spatial control, and anisotropy of the induced strain field, but all exploit stress or eigenstrain rather than a fully conformal hard die to generate macroscopic curvature. The unifying principle is that a spatially non-uniform plastic strain field, when self-equilibrated against an elastic substrate, produces a net bending moment that drives panel curvature toward the treated face. The four sub-families differ in how that field is created and controlled: shot peen forming uses high-velocity shot impacts to create a shallow isotropic eigenstrain layer; stress peen forming biases that layer by applying external elastic prestress before or during peening; ball forming uses larger, lower-velocity media to produce a shallower, smoother strain field with lower surface damage; and laser peen forming uses laser-induced shock waves to create a much deeper compressive layer capable of acting on thick or stiff sections that conventional shot cannot reach. A useful analytical distinction within the family is whether directional control comes primarily from the impact field itself, from externally applied prestress, or from deeper shock penetration into the thickness [5–7,9,10,42]. The term ‘dieless’ should nevertheless be read narrowly in wing-cover production: it denotes the absence of a dedicated full-contour forming die, not the absence of checking fixtures, prestress rigs, masking, restraint, or iterative correction. Contemporary process-planning literature still describes peen-based contouring as incremental and strongly dependent on measurement and replanning precisely because practical reproduction of a target contour is not a one-pass free-form event [43,44].

3.3. Thermo-Mechanical Forming

Where stress-based routes rely on plasticity introduced at ambient temperature, CAF, the key thermo-mechanical process in this review, generates its forming strain over time through creep and stress relaxation during a concurrent artificial ageing cycle while the panel is held on a tool. The result is a coupled forming-and-heat-treatment route in which curvature development and precipitation strengthening occur simultaneously, making CAF mechanically distinct from a hot version of stretch forming [4,12,24,38,45,46]. In industrial aerospace practice the method is associated with large heat-treatable aluminium panels, high dimensional stability, and the need to manage springback through tool compensation and flexible or reconfigurable tooling.

That coupling of forming and ageing imposes a hard selection limit. Creep age forming in the strict sense is available only on precipitation-hardening or otherwise heat-treatable alloys, because the ageing response is part of the forming mechanism itself. Non-age-hardening alloys may still be thermally creep formed, but not creep age formed in the metallurgical sense relevant to aerospace production [4,47].

This constraint, absent from every stress-based route, is the most consequential single discriminator in the process selection logic discussed in Section 8.3, because it acts before any geometric or scale consideration: regardless of panel size, curvature demand, or stiffness distribution, CAF is simply unavailable on a non-precipitation-hardening alloy, whereas every stress-based route is in principle available on any metallic panel regardless of heat-treatment response. Scale and geometry filter the stress-based routes among themselves; alloy class determines whether CAF enters the candidate set at all.

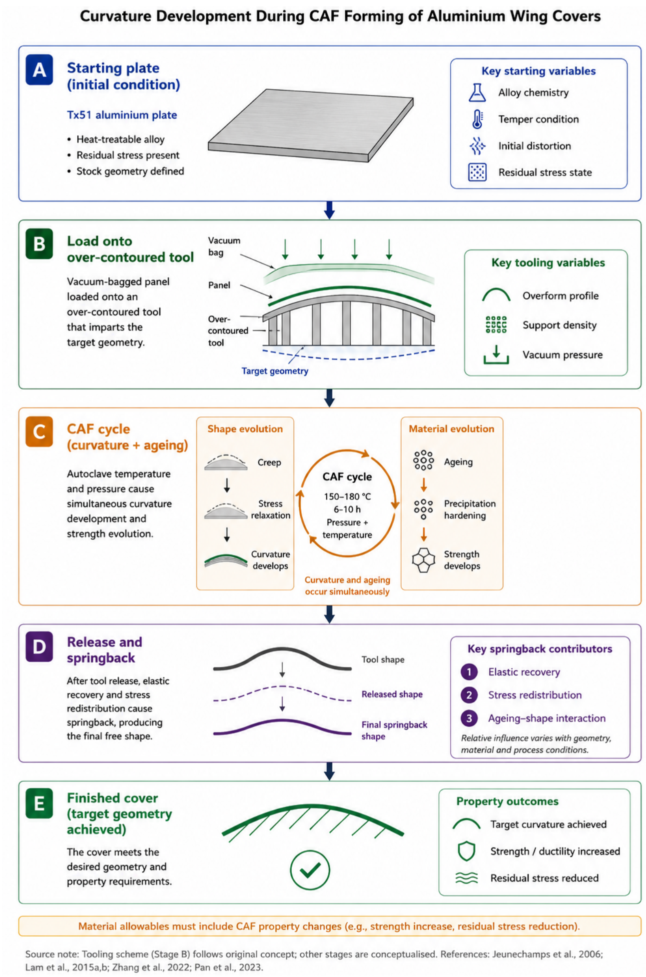

Figure 3. Creep age forming (CAF) sequence for heat-treatable aluminium wing covers. The figure shows the starting plate and stock-state variables, loading onto an over-contoured tool, concurrent curvature development and precipitation during the CAF cycle, release and springback contributors, and final cover/property checks. It illustrates the need for tool compensation and for material allowables to account for CAF-induced property and residual-stress changes. Section 4.5; source anchors include Hambrick [23], Holman [24], Lin et al. [12], Zhan et al. [4], Jeunechamps et al. [46], Lam et al. [38,114], and Zhang et al. [20].

3.4. Hybrid Processes

Hybrid routes combine two or more of the above families. The most important public example is the Gulfstream IV, where shot peen forming and creep-based forming were used in a complementary sequence. More generally, Boeing's compound-contour patent, the Sonaca/NMF shaped-panel patent, and later Russian hybrid patents show that industry often treats mechanical preform, peen-induced strain, stress-assisted loading, and thermal relaxation as sequential operations on the same part rather than as mutually exclusive alternatives [14,29,48,49].

4. Process Mechanics and Industrial Practice

Section 3 classified forming routes by mechanism. This section examines the mechanics of each route in sufficient depth to explain the industrial process-control choices, compensation strategies, and programme-level deployment patterns discussed in Sections 5 through 8. The historical origin of these mechanics, tracing from Almen's 1930s work through to the present, is addressed in Section 5.0; this section is concerned with the underlying physics rather than the history, and the two sections should be read together to understand both why each process works and why it was adopted when

 doi:10.20944/preprints202605.1979.v2

it was. The sequence follows the classification structure shot peen forming (Section 4.1), stress peen forming (4.2), particle-impact or ball forming (4.3), laser peen forming (4.4), CAF (4.5), hybrid forming (4.6), and the cross-cutting issues of process variables and compensation strategy (4.7) and residual-stress metrology (4.8).

4.1. Shot Peen Forming

In shot peen forming, macroscopic curvature is generated by the accumulation of local impact-induced plastic strain at a treated surface. Each shot impact creates a small indentation, radial plastic flow, and a thin layer of in-plane growth. Because that plastically extended layer is restrained by the thicker and more elastic substrate, the unloaded part reaches a self-equilibrated state consisting of near-surface compression, balancing subsurface tension, and a net bending moment. Al-Hassani's equivalent-stress treatment and Kirk's residual-stress analysis remain foundational because they explain the apparent paradox at the heart of the process: the surface undergoes tensile plastic strain during impact, yet is left in compression after unloading, and the panel bends towards the peened face [5,6].

From a structural viewpoint, shot peen forming is best interpreted as a shallow, spatially varying eigenstrain field imposed over only a small fraction of the panel thickness. Eigenstrain, the term coined by Mura [52] and applied systematically to peening by Kang et al. [51] and Gariepy et al. [10], denotes a permanent, non-elastic strain that a material element would develop if unconstrained but which, when embedded in a surrounding elastic body, is prevented from developing freely. Each shot impact imposes a thin layer of plastic in-plane growth. If that layer were free it would expand; because it is restrained by the elastic substrate beneath it, the misfit between the locally extended surface layer and the substrate creates a self-equilibrated stress field, compression near the surface, balancing tension in the interior, and a net bending moment that drives the panel towards the peened face. This eigenstrain interpretation is quantitatively important: Kang et al. [51] measured eigenstrain magnitude and depth profile in 7075 aluminium as a function of shot size, velocity, and coverage, showing that the eigenstrain zone typically extends no more than 250–400 μm below the surface for aerospace-typical shot conditions (S110–S230 media, 0.15–0.25 mm Almen intensity). Gariepy et al. [10] extended this to a full FE implementation for wing-cover geometries, demonstrating that the same eigenstrain magnitude at the surface generates curvature that scales with the square of the panel thickness, a critical result for production process planning, because it means the same peening condition will under-form a locally thicker region (stringer foot, pad-up) relative to the adjacent thin skin. In thin wing covers that shallow strain layer is magnified by the very large panel area and low bending stiffness of the skin, so comparatively small changes in intensity, coverage, shot size, or velocity can alter arc height appreciably. Because a nominally normal shot stream imposes an eigenstrain field that is close to isotropic, conventional peen forming tends naturally towards large-radius single curvature or quasi-spherical double curvature rather than strongly directional contour. This response is straightforward for a plain wing skin (uniform plate with no attached stiffeners), but integrally stiffened panels, in which stringers, pad-ups, and thickness steps are machined into the same plate as the outer skin, complicate it fundamentally. The stiffness of an ISP varies across the panel in proportion to the cube of the local thickness: a stringer root that is 20 mm thick is approximately 8× stiffer per unit width than the 10 mm skin beside it (illustrative dimensions, actual dimensions vary by programme and section; the cube-law relationship is exact, the specific values are representative), so the same peening condition generates roughly one-eighth of the curvature at the stringer root compared with the adjacent skin. Cut-outs, local pad-up regions, and root-to-tip thickness taper all add further stiffness discontinuities, so the same

 doi:10.20944/preprints202605.1979.v2

peening condition does not generate the same curvature everywhere on the panel, and the correction required to achieve a target loft is not a single adjustment but a spatially varying map across the entire ISP [7,10]. This point is confirmed by programme-specific studies on the Mitsubishi business-jet wing skin [50], on titanium aerospace panels [128], on early ISP peening modelling [51], and by recent industrial patents addressing curvature control across stiffness transitions in large integral panels, notably AVIC's CN105598851A [117]. AVIC's CN105598851A [117] explicitly addresses shot peen forming of large aircraft integral panels by controlling the curvature gradient across stiffness transitions, confirming that the ISP heterogeneity problem identified in the academic literature of the 2000s remained an active area of industrial development. The Yamada et al. [50] work was conducted at Mitsubishi Heavy Industries and relates to shot peening of integral wing skins for Continental Business Jets. The same manufacturing infrastructure at MHI is relevant to the Mitsubishi F-2 fighter programme, which is carried in Supplementary Table S5b.

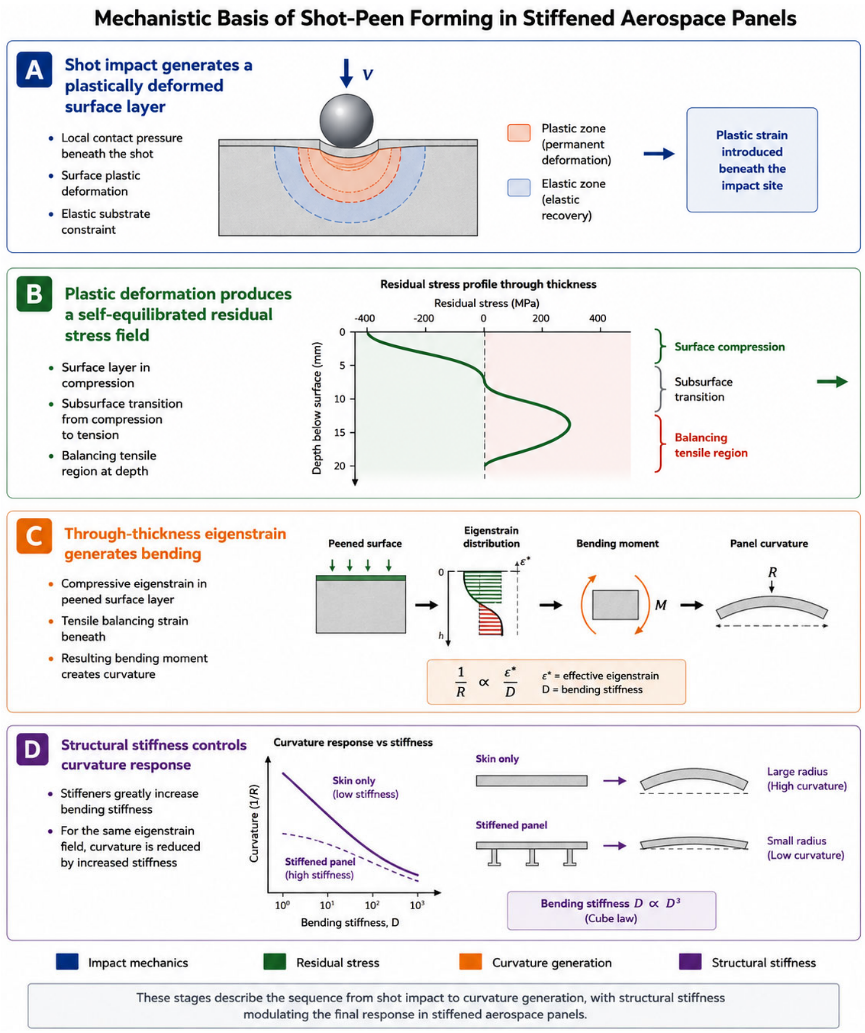

Figure 4. Mechanistic basis of shot-peen forming in stiffened aerospace panels. Panel A shows local shot-impact plasticity and the deformed surface layer; Panel B shows the associated self-equilibrated residual-stress profile, with surface compression balanced by subsurface tension; Panel C translates the near-surface eigenstrain field into bending curvature; and Panel D illustrates why increased ISP/stringer stiffness reduces curvature response for the same induced surface strain. Section 4.1; source anchors include Al-Hassani [5], Wang et al. [7], Gariepy et al. [10,11], Mura [52], and Kang et al. [51].

Industrial control is therefore a problem of mapping required curvature onto a controlled combination of Almen intensity (SAE J442/J443) [126,127], coverage, shot size, velocity, incidence angle, stand-off, pass count, and trajectory. Fathallah et al. [53] provided an analytical framework that connects Almen intensity directly to the depth and peak magnitude of the compressive residual stress layer for high-strength aluminium alloys, demonstrating that both parameters scale predictably with shot velocity and size, a result that underpins the industrial use of Almen intensity as the primary process control parameter. Coverage is a second critical variable: Bagherifard et al. [55] showed on aluminium alloys that the transition from partial to full coverage is non-linear in its effect on the near-surface residual stress profile, with significant changes in peak compressive stress occurring as coverage approaches 100%. Once full coverage is reached, further peening achieves saturation, a state in which additional impacts do not substantially deepen the compressive zone, and the saturation point is identified via the SAE J443 arc height doubling criterion. Cao et al. [54] established the mechanics of curvature saturation: beyond full coverage, incremental impacts begin to re-plastify the previously treated layer, reducing rather than increasing net curvature, which explains why over-peening in production can cause contour errors that are difficult to correct. Gariepy and co-workers showed that nozzle path and local constraint can generate markedly different radius distributions even on simple specimens, which helps explain the industrial importance of feed-through machines, fixtures, masking strategies, and iterative pass planning in production wing-skin contouring [11,53,54]. Industrial guidance from Metal Improvement Company, as archived in ICSP proceedings, is consistent with that picture: the method is best suited to large bend radii within the elastic range, yet it remains unusually tolerant of variable thickness, reinforcements, cut-outs, and pre-existing distortion, while leaving both faces of the finished wing skin in compression rather than imposing a predominantly tensile forming history.

This is also why the common shorthand of shot peen forming as a fully dieless process is misleading when applied to finished wing skins. The dedicated hard contour die may disappear, but contour verification and correction do not. Supplier applications literature explicitly illustrates wingskins on checking fixtures, and severe applications may additionally require stress-peen fixtures or staged correction passes. Modern closed-loop and pattern-segmentation papers reach the same conclusion from the modelling side: production contour is normally achieved through incremental treatment, intermediate measurement, and replanning rather than by a single deterministic exposure [7,43,44]. Industrial and applied patent literature codifies the same conclusion: WO2019051616A1 [56] (Polyvalor, 2019) and EP4703951A1 [112] (Shanghai Aircraft Manufacturing) implement peen-forming and inverse-flattening simulation that formalise the measure-and-correct loop as a production design step, the patent-level equivalent of the closed-loop academic papers cited here.

4.2. Stress Peen Forming

The directional limitation of conventional shot peen forming, its tendency towards quasi-isotropic curvature, is addressed by stress peen forming, which adds an externally imposed elastic stress state before or during peening. The workpiece is prebent or otherwise tensioned in a fixture so that peening occurs on a surface already carrying elastic strain. When the part is released, the retained contour is the net result of fixture-induced prestress, peening-induced eigenstrain, and elastic recovery. The mechanics therefore change fundamentally: instead of allowing the part to seek an almost isotropic doubly curved response, the process biases growth into the required principal-curvature direction and suppresses unwanted curvature in the orthogonal direction [8,9].

The experimental and numerical literature shows that prebending moment affects not only final arc height but also the residual-stress profile. In the Miao studies, the relation between prebending moment and resulting curvature was close to linear over the tested range, which is industrially important because it turns fixture load into a controllable process variable rather than a qualitative adjustment. In shell terms, prestress changes membrane-bending coupling during peening: the same shot stream produces different spanwise and chordwise curvature components depending on the sign and magnitude of the prior elastic state, panel aspect ratio, and boundary restraint [8,9,11].

 doi:10.20944/preprints202605.1979.v2

Mylonas and Labeas [57] extended this analysis in a shell-level finite-element model that treats the prestressed peening problem directly, showing that the orthogonal curvature suppression and the principal curvature amplification are both predictable from the initial elastic prestress state, a result that transforms stress peen forming from a qualitative trick into a calculable process parameter.

Boeing's compound-contour patent remains the clearest production-oriented codification of this logic. It distinguishes spanwise curvature, chordwise curvature, and severe saddle-back contour, and it treats shot peening as one element in a broader curvature-management strategy that may also require auxiliary mechanical or creep-based operations when one principal curvature must be intensified while another is restrained [29]. The Sonaca/NMF patent extends the same logic to integrally stiffened panels by selectively peening rib sections in V-shaped zones to generate dihedral while retaining continuous ribs. That is structurally significant because it shows prestress and selective peening being used not simply on flat skins, but on panels in which the stiffener geometry itself participates in the bending mechanism [48].

4.3. Particle-Impact / Ball Forming

A third variant within the stress-based family trades impact velocity and area rate for surface quality and forming control. Particle-impact or ball forming uses much larger media, much lower impact velocity, and a deliberately low-penetration regime than conventional shot peen forming. Brandel and Klass [22] describe the AVCO L-1011 process as one in which the larger balls generate wider, shallower indentations and lower local cold work for a given contour than a conventional high-velocity shot stream. That combination improves aerodynamic surface finish and reduces risk to clad outer skins while still allowing substantial curvature to be generated. It should be noted that Brandel and Klass [22] was published in Metal Progress, a trade magazine rather than a peer-reviewed journal, and it represents the sole primary technical source for this process route; no subsequent peer-reviewed corroboration of the L-1011 specific process parameters have been identified.

Mechanically, the process still relies on surface growth restrained by the remaining thickness, but the lower specific impact energy changes both texture and controllability. Fewer, larger impacts make it easier to localise growth in selected bands and to combine free forming with prestressed forming. In the published L-1011 route, localised inner-surface contouring was first used to establish lengthwise contour, the clad outer surface was then ball formed over special tooling in an over-contoured elastic condition to generate chordwise and double curvature, and a conventional saturation-peening pass finally restored a more uniform compressive stress state over the whole panel [22].

That sequence explains why particle-impact forming remained a niche but industrially important route. It is slower and more specialised than conventional shot peen forming, yet attractive when outer-surface smoothness, cladding integrity, thicker stock, or explicit separation of spanwise and chordwise contour steps matters more than raw throughput. In structural terms, it is a method for trading higher local control and lower surface damage against greater process complexity [6,22].

An independent confirmation of large-ball peen forming as a production route comes from Russian aerospace practice. Pashkov et al. [58] describe a complex forming method developed at Irkutsk National Research Technical University for the Irkutsk Aviation Plant (a branch of JSC Irkut Corporation, which manufactures the Sukhoi Su-30 family), in which 3 to 4 mm diameter ball peen forming of the outer skin surface generates transverse curvature, followed by surface sanding to restore finish after the deeper ball indentations, and then conventional shot peening with 0.6 to 0.8 mm shot for fatigue enhancement and residual stress uniformisation. This sequence is mechanically analogous to the L-1011 ball forming approach: large ball media generate the dominant curvature, and a subsequent fine-shot pass restores surface integrity. The Irkutsk authors explicitly cite Boeing's US4329862 compound-contour patent as prior art, confirming that the Western peen forming intellectual framework was known to Russian process engineers and that the Irkutsk development was a deliberate independent adaptation rather than a derivative of a transferred process. It should

 doi:10.20944/preprints202605.1979.v2

be noted that the L-1011 case is the only identified production instance of ball forming for aircraft wing covers; no post-1971 production disclosure for this route has been identified in the sources searched for this review. Ball forming should therefore be regarded as a historically documented route that was optimal for the L-1011's specific requirements rather than as a currently active alternative to conventional shot peen forming in the broader wing-cover manufacturing community.

4.4. Laser Peen Forming

Where particle-impact forming trades velocity for surface quality within broadly the same depth regime as conventional shot peening, laser peen forming operates on a fundamentally different depth scale. It replaces discrete particle impacts with short, high-energy laser pulses fired through a transparent tamping layer onto an absorptive coating. Rapid plasma formation and confinement beneath the water layer generate a high-amplitude shock wave that drives plastic strain much deeper than conventional shot while introducing comparatively little surface cold work. The mechanism of pressure generation was established quantitatively by Fabbro et al. [59], whose physical study of laser-produced plasma in confined geometry derived the pressure-time model that underpins all subsequent laser shock processing work. Fabbro et al. showed that the peak pressure at the surface is proportional to the square root of the laser power density and is confined to the gigapascal range for typical laser shock peening parameters, far more than the dynamic yield stress of aerospace aluminium alloys (typically 300–500 MPa at high strain rates for 7xxx alloys, see Ding and Ye [60], Chapter 2 for dynamic material response data). This pressure level drives a plastic zone that can extend to depths of 1–3 mm in aluminium, compared with the 0.25–0.4 mm typical for aerospace shot peening conditions, and it is this depth differential, not merely higher surface pressure, that distinguishes laser peen forming mechanically from all impact-based alternatives [59,60]. The treated zone again behaves as a constrained eigenstrain growth layer (in the same sense as Section 4.1), but one that extends far deeper below the surface and therefore produces substantially larger bending moments in thick or stiff panels. The primary production codification of this process is the foundational LLNL patent work of Hackel and Harris [42], US6410884B1, and Hackel, Halpin and Harris [61], US6670578B2, supplemented by the standard process monograph Ding and Ye [60], peer-reviewed characterisation by Clauer [62], and materials response studies by Peyre et al. [63].

Process control therefore shifts from shot size and coverage to pulse energy, spot size, overlap, raster pattern, traverse speed, absorptive-layer condition, and any external preloading. Ocana et al. [64] developed a mechanics-based curvature prediction model for laser peen forming directly analogous to the eigenstrain models of Gariepy et al. for shot peening, demonstrating that pulse energy, spot size, and spatial overlap pattern can be mapped to a predictable curvature output on aluminium panels, a result that transforms laser peen forming process planning from empirical trial-and-error towards a model-based approach equivalent to what SAE J443 saturation testing provides for shot peening. The foundational LLNL patents codified the manufacturing framework: line-by-line or area rastering builds one- or two-dimensional curvature, while pre-loading the component in a jig allows the shock-induced strain field to be combined with elastic bias in much the same spirit as stress peen forming. Because the compressive field extends millimetres below the surface, laser peen forming can generate tighter radii and act on thicker integrally stiffened sections than conventional shot peen forming [42,61,64].

Its structural significance is therefore not merely thicker-section capability, but improved compatibility with high-strength 7xxx and aluminium-lithium panels whose machined stringers and pads raise bending stiffness sharply. Independent confirmation that the aerospace industry developed laser peen forming in parallel comes from several verified streams: Airbus Operations GmbH's US20190118302A1 [100] (2019) covers a mobile laser-shock treatment station for metallic structures; Metal Improvement Company's US8207474B2 [65] (2012) and US8698040B2 [66] (2014) cover laser-peening process and beam-delivery methods within the Curtiss-Wright/LLNL lineage; and Shanghai Jiao Tong University's CN105033462A [111] (2015) covers thermal-assisted laser peen forming. The presence of distinct European, North American, and Chinese patent streams across the

 doi:10.20944/preprints202605.1979.v2

2012–2019 window indicates parallel industrial development rather than linear transfer from a single source. Peer-reviewed and patent literature presents laser peen forming as an enabler for integral-stiffener architectures, citing thicker 7050 sections and machined Al-Li panels as demonstrators [21,42,61]. The Boeing 747-8 evidence aligns with that logic: the strongest public record is at supplier level, but it shows that laser peen forming had moved beyond laboratory feasibility into serial wing-panel contouring where section stiffness and curvature demand exceeded comfortable shot-peen limits [67–69].

4.5. Creep Age Forming (CAF)

All four stress-based routes described above generate their forming strain through impact plasticity at ambient temperature. CAF is categorically different: the principal forming strain is generated over time by creep and stress relaxation during artificial ageing rather than by instantaneous impact plasticity. A heat-treatable aluminium panel, commonly in a solution-treated, quenched, and stretch-stress-relieved temper such as Tx51, is forced onto a compensated tool and held there throughout a thermal dwell. The process is therefore restricted to precipitation-hardening alloys: without concurrent precipitation kinetics there is no industrial rationale for accepting CAF cycle times and thermal tooling burden [4,23,24]. The starting material state is itself part of the process design: quench residual stress, prior stretch relief, and any machining-induced surface stress are inherited by the forming cycle and alter both the stress relaxation trajectory during the thermal dwell and the elastic springback on unloading, because the creep and relaxation rates at any point in the panel depend on the local net stress, which is the sum of the applied clamping stress and the pre-existing residual stress. A panel entering the autoclave with a non-zero inherited residual field will therefore creep differently from a nominally stress-free panel under the same tool geometry, producing a different on-tool shape and a different springback magnitude [30,38].

A further complication is that CAF does not only accumulate creep curvature and elastic recovery. Because ageing changes lattice parameter and precipitate population, a small permanent dimensional and volumetric change is superposed on the bending response. Ageing studies on rolled 2xxx aluminium show measurable net contraction during isothermal ageing associated with lattice-parameter change and S-phase precipitation [71].

Stress-ageing studies on Al–Cu (2xxx) alloys show that applied stress can influence precipitation and yield response relative to stress-free ageing [37]. This result is alloy-specific and should not be assumed to transfer directly to 7xxx systems, which strengthen primarily through GP zones, η′ and η phases in the Al–Zn–Mg–Cu system [72]. 7xxx-specific age-forming work, including Chen et al. [36] and Zheng et al. [18], is therefore used here when discussing 7050 and related alloys.

Aluminium-lithium alloys extend the same process-selection logic but with different property and residual-stress constraints. Their lower density and higher specific stiffness make them attractive for large structural panels, but anisotropy, quench sensitivity and narrower process windows require separate validation rather than direct transfer of 7xxx CAF or peen-forming compensation rules [72].

The B-1B provides the clearest military illustration of both the capability and the limits of CAF selection. Hambrick [23] describes Avco's autoclave age-forming route for 2124 and 2419 wing skins approximately 50 ft long, with integrally machined stiffeners and thickness varying from about 0.1 to 2.5 in across a single panel, as stated in Hambrick [23], Section 3, panel geometry discussion. Those dimensions matter mechanically: they imply very large stiffness gradients and high bending resistance in local pad and stiffener regions. A panel with a 25:1 thickness ratio lies outside the viable operating envelope of cold forming methods, the local springback at the thick stiffener roots is of a different order from the springback in the adjacent skin, and no single cold mechanical boundary condition can accommodate both simultaneously without inducing local instability or permanent dimensional error at the root regions. This is the mechanical basis for the CAF selection on the B-1B, independent of any historical account of failed cold-forming attempts [23]. The National Research Council (1996) subsequently summarised production experience on both upper and lower B-1B skin

 doi:10.20944/preprints202605.1979.v2

panels; this source is treated as a secondary synthesis that corroborates Hambrick's primary programme paper rather than as an independent Class A anchor (see Table 6B qualification note).

4.6. Hybrid Forming

The logic of hybridisation is not additive but partitive: the panel's total curvature requirement is decomposed into components that each process family can generate reliably, then assigned to successive operations. The preceding sections have shown that each process excels at a different part of the curvature problem: peen-based routes supply directional surface growth and beneficial near-surface compression; CAF supplies smooth global curvature with low net residual stress and concurrent strengthening. Hybrid forming is therefore best understood as process decomposition rather than simple process addition, assigning each curvature feature within a wing cover to the process most capable of generating it predictably. Edge lift, dihedral breaks, and saddle-back regions typically require directed surface growth; broad centre-shrink or smooth global fairing is more reliably achieved by time-dependent stress relaxation during ageing [14,24,47].

The Gulfstream IV case makes that logic unusually explicit. Cook [14] describes a saturation-peen-first strategy on the 12 ft by 45 ft upper skin to build a uniform compressive structure, followed by controlled peen forming to develop dihedral and saddle-back contour across a panel with severe thickness variation. The same source also makes clear, however, that peen forming alone could not deliver the required centre-shrink behaviour, so Textron resolved the remaining shape requirement by creep forming in the autoclave [14]. The hybrid sequence therefore couples a surface-growth process with a stress-relaxation process: peen forming supplies directional growth, local curvature, and beneficial compressive stress, while the creep or age-forming stage redistributes the remaining stress field and solves shape features that cannot be produced economically by impact alone [14,15,47].

4.7. Process Variables, Inherited Material State and Compensation Strategy

The route-by-route discussion in Sections 4.1 through 4.6 describes how each process generates curvature. A complementary question, and in production arguably the more practically significant one, is how accurately the target geometry is achieved given the starting state of the panel. Across all routes, process variables cannot be separated from the inherited state of the panel on which they act. Aerospace wing covers rarely enter the forming cell stress-free or isotropic. Thick 7xxx plate can retain substantial quench stress after primary processing; measurements on 7050 plate show through-thickness tensile and compressive residual stresses on the order of 229 and 268 MPa after conventional quenching, while stretch-stress-relieved Tx51 plate greatly suppresses those plate-scale stresses relative to unstretched stock [30,33]. Even so, the remaining internal stress can be reactivated by asymmetric stock removal, and machining-induced surface layers may dominate final part movement once monolithic pockets and pads are milled [31,73].

For shot peen forming and stress peen forming, the dominant variables are impact intensity (measured to SAE J442/J443 Almen arc height; production process governed by SAE AMS2430 [125]), coverage, media size and hardness, angle of incidence, stand-off, nozzle speed, overlap, masking strategy, pass count, and, in stress peen forming, the magnitude and distribution of elastic prestress before release. Their directional effects on curvature and surface state are as follows.

Intensity is the primary curvature driver: increasing Almen intensity from A4 to A10 on 7075-T73 aluminium approximately doubles the depth of the compressive layer but also raises surface roughness Ra from approximately 1.5 μm to 3.5 μm and increases the risk of surface damage at high values [74]. Higher intensity therefore increases forming capability at the cost of surface integrity. Media size controls the balance between depth and surface finish: increasing from S110 to S230 shifts the depth of peak compressive stress from approximately 50 μm to 150 μm while reducing the peak compressive magnitude at the surface; larger media also reduce coverage rate for a given pass, increasing process time. Coverage controls the uniformity of the induced eigenstrain field: below approximately 98% coverage the induced stress field is spatially non-uniform and arc height is not

 doi:10.20944/preprints202605.1979.v2

yet saturated; above 100% coverage, additional passes add little incremental curvature but measurably increase cold work hardening and surface damage risk, narrowing the structural life benefit [6,7]. Angle of incidence affects the in-plane symmetry of the induced strain: a nominally normal stream produces a quasi-isotropic growth layer, while inclined impingement biases growth in the direction of incidence, providing a supplementary directional control mechanism used in some production trajectories [11]. Stand-off and nozzle speed together govern local exposure time and coverage uniformity across the panel; in feed-through machines they are the primary means of modulating curvature along the traverse path [108]. Masking strategy determines which regions are shielded from treatment and is the principal method of achieving differential curvature across a panel with variable stiffness; masked boundaries must be managed carefully because abrupt intensity gradients at mask edges can produce local springback anomalies.

For stress peen forming specifically, the magnitude of the externally applied elastic prestress before release is the variable that most directly controls the principal curvature direction and magnitude of the recovered shape: Miao et al. [8] showed experimentally that the relationship between prebending moment and resulting arc height is approximately linear over the range tested (prebending moments of 0 to 90 Nm. on 300 × 100 mm 2024-T3 specimens), which makes prestress the most controllable single variable for directional curvature generation within that envelope; extrapolation to larger panels or higher prestress levels requires separate validation. The distribution of prestress across the fixture determines which curvature components are amplified and which are suppressed; mismatched distribution is the primary cause of unintended twist or warp after release.

Across all shot-based routes, these variables interact strongly with panel stiffness heterogeneity from pads, pockets, and stringers [11,43], and no single variable can be optimised for forming without simultaneously considering its effect on the compressive layer depth, surface roughness, and residual life contribution. A comprehensive sensitivity analysis and the corresponding parameter-selection logic for production wing-skin peening is beyond the scope of this review but is available in the process-modelling literature of Gariepy et al. [10,11], Miao et al. [8,9], and the industrial guidance of Curtiss-Wright Surface Technologies [108,109].

For CAF, relevant variables include alloy chemistry and initial temper, prior quench, and stretch-stress-relief history, starting residual stress and initial distortion, tool overcamber, support density, ageing temperature, and time, applied stress level, and dwell duration. Their effects on springback, curvature outcome, and material state are distinct and, in several cases, counterintuitive.

Ageing temperature is the most sensitive single variable: increasing temperature accelerates creep and stress relaxation, increasing the amount of curvature developed during the dwell, but also accelerates precipitation kinetics, which raises strength and stiffness during the cycle and reduces the creep compliance available later in the dwell. In practice this means there is an optimum temperature window for each alloy-temper combination, typically 150–180 °C for 7xxx alloys, above which diminishing curvature returns and property loss accelerate together [4,12]. Dwell duration controls the completeness of stress relaxation: short dwells leave residual elastic stress in the panel that contributes to springback; longer dwells approach full relaxation but also over-age the alloy, degrading strength. The trade-off is programme-specific because the ratio of creep compliance to precipitation rate is alloy- and temper-dependent. Tool overcamber is the geometric compensation for elastic springback: it must be calibrated against the final aged, unloaded geometry rather than the hot-on-tool shape, and it absorbs contributions from three sources, elastic springback, inherited residual stress redistribution, and small permanent dimensional change from lattice-parameter evolution during ageing [38,71]. Support density affects the through-thickness pressure distribution and, through it, the local applied stress state: regions of low support density are under lower applied bending stress and therefore relax less completely during the dwell, producing locally higher springback. Applied stress level, governed by the ratio of tool overcamber to panel thickness, directly controls the initial stress-relaxation rate; at low applied stress the creep contribution is small and springback dominates, while at high applied stress local yielding can occur at pad-up regions, introducing non-elastic deformation that is difficult to model.

 doi:10.20944/preprints202605.1979.v2

Starting residual stress and initial distortion both affect springback because the creep and relaxation rates at any cross-section depend on the local net stress, which is the sum of applied clamping stress and the pre-existing residual field. As quantified in Section 4.5, stress-ageing of 7050 can produce systematic reductions of approximately 6% in UTS and yield strength and approximately 14% in elongation relative to stress-free ageing [36], differences that must be accounted for in structural analysis and material allowables. The sensitivity of springback to initial distortion is not negligible: Lam et al. [38] showed that a machining-induced initial bow of 2–5 mm can produce springback errors of the same order as the finished-cover tolerance, meaning that upstream machining quality directly sets a lower bound on CAF accuracy that tool compensation alone cannot overcome.

A complete parametric treatment of CAF variable interactions, constitutive modelling approaches, and tooling compensation methods is available in the dedicated reviews of Zhan et al. [4] and Zhang et al. [20], and in the programme-level modelling literature of Lin et al. [12], Lam et al. [38,114], and Li et al. [70]. The present review provides directional summaries; readers requiring quantitative parameter sensitivity for process design should consult those sources directly.

Hybrid routes inherit the full variable sets of their constituent steps, with the additional problem of sequence partitioning. The critical decision is which curvature features are assigned to local surface-growth mechanisms and which are assigned to global thermal stress relaxation [4,7,14,15]. Their advantage is that residual stress can be redistributed between stages and final accuracy can exceed that of either route used alone; their disadvantage is the high qualification burden and the need to manage property and stress inheritance explicitly between process stages.

4.8. Residual-Stress Metrology and Validation

The compensation strategies described in Section 4.7 all depend on knowing the actual stress state of the panel, before, during, and after forming. Residual-stress arguments are therefore only as strong as the metrology route used to support them. Guo et al. [77] and Withers and Bhadeshia [78] show that no single method spans the surface-to-core scales relevant to metallic wing covers. X-ray diffraction is well suited to the near-surface compressive field created by peening and to fatigue-critical skin layers; Prevéy [75] established the standard depth-penetration limits for XRD on aluminium alloys, typically 10–25 μm per electrolytic layer removal step for Cu Kα radiation, which quantify why XRD is the correct tool for the peened surface layer but cannot characterise the bulk quench stress field without layer-removal depths impractical in production. Layer-removal variants extend that capability modestly. Hole drilling, slitting, and related semi-destructive methods provide intermediate-depth information; the contour method, originally described by Prime [76], provides full two-dimensional through-thickness stress maps on cut surfaces and is the most powerful technique for characterising the large through-thickness fields inherited from quenching or heavy machining without the measurement uncertainty of layer-removal XRD. Neutron diffraction provides equivalent or greater depth with the advantage of non-destructive measurement on complete parts. Each method trades destructiveness, spatial coverage, and depth resolution against cost and accessibility [75–77].

For wing-cover manufacture, metrology is therefore part of process definition rather than post hoc inspection. Peen-formed surfaces are usually controlled by Almen intensity (SAE J442/J443), local curvature checks, and near-surface stress measurement; inherited stock stress and machining distortion require bulk methods and full-field geometry measurement. Seger et al. [79] make the point sharply: low-fidelity or spatially sparse characterisation can mis-predict distortion, whereas dense neutron-diffraction mapping coupled to stress-field reconstruction captured distortion tendencies that simpler methods can miss.

The trade-off between these methods is therefore one of depth resolution against cost and destructiveness. X-ray diffraction with layer removal is non-destructive to the finished part, rapid, and well-understood for the peened layer, but its depth reach is limited to roughly 300–500 μm without impractical electropolishing depths; it cannot characterise the quench stress field that may

 doi:10.20944/preprints202605.1979.v2

be causing macroscopic bow. The contour method can map through-thickness stress to millimetre resolution on a cut cross-section and is the correct choice for distortion diagnosis in thick ISPs [76], but it requires sectioning the part. Neutron diffraction provides comparable depth without destruction but demands access to a research reactor or spallation source, making it a characterisation tool rather than a routine production method. In practice, a peen-formed wing cover is validated by Almen intensity (SAE J442/J443), local curvature checks, and a checking fixture, methods that confirm the forming outcome but do not directly measure the residual stress state, while a CAF cover may require periodic coupon testing and constitutive model validation to confirm that the ageing cycle was executed correctly. The manufacturing consequence is that process validation methods should be specified not by convention but by the scale of the stress field that matters to the next operation: near-surface XRD for a peened skin whose fatigue life is at stake, but bulk contour or neutron methods when macroscopic distortion of a deep-pocketed ISP is the risk.

5. Aircraft-Level Industrial Evidence (Periodised)

The process mechanics established in Section 4 now provide the vocabulary for interpreting named aircraft programmes. This section applies the curvature taxonomy of Section 2, the process classification of Section 3, and the variable and metrology framework of Section 4 to the public industrial record through the four-stage evolution shown in Figure 5. The stage structure is the analytical lens, not the subject: each sub-section asks what changed in the nature of the manufacturing problem in that stage, and what the public evidence shows about how industry responded. The stage structure is therefore built upward from manufacturing constraints, scale, geometry, material state, and structural requirement, rather than downward from programme chronology. Where evidence is strong enough to support upper/lower cover differentiation, it is stated; where it is not, that absence is recorded explicitly rather than filled by inference. Aircraft-level process attribution is summarised in Table 6A for commercial transport and business aircraft and Table 6B for military fixed-wing aircraft, with full manufacturer lineage in Appendix A. Lower-evidence boundary cases and completeness entries are preserved in Supplementary Tables S2–S5.

The process variables, alloy and temper windows, curvature categories, and surface-cleaning constraints for each forming route are summarised in Table 4A and in the variable discussion of Section 4.7.

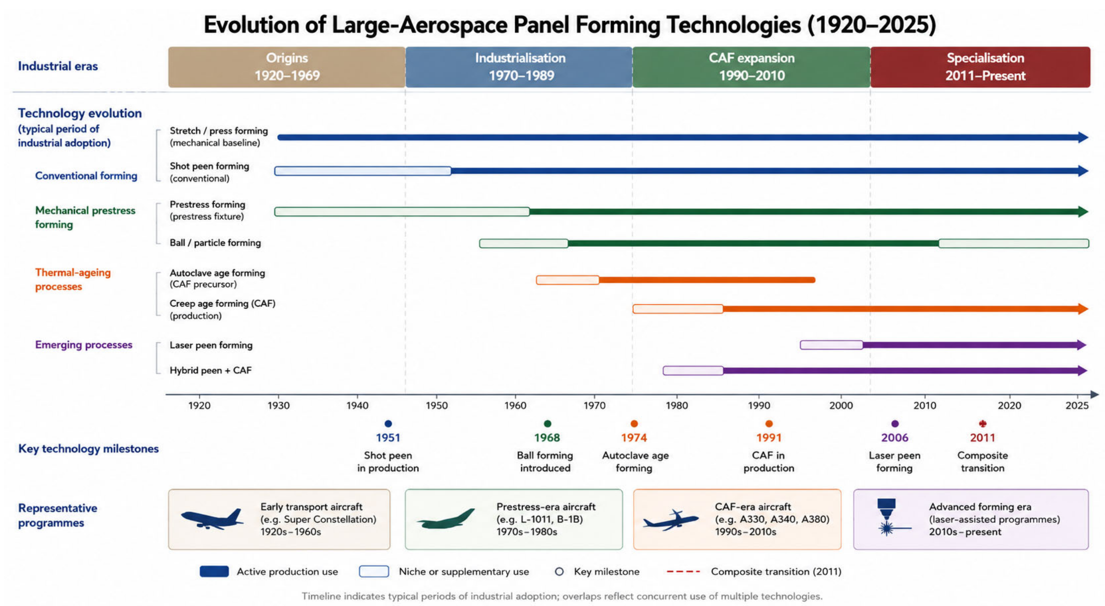

Figure 5. Four-stage evolution of large aerospace panel and metallic wing-cover forming, 1920–2025. Stage 1 shows process origins (1920–1969), Stage 2 industrialisation (1970–1989), Stage 3 CAF expansion (1990–2010),

 doi:10.20944/preprints202605.1979.v2

and Stage 4 specialisation after the composite transition (2011–present). Horizontal bars indicate typical periods of industrial adoption or supplementary use; milestones and representative programme groups are shown below the timeline. Sections 5.0–5.4a and Section 8.1.

5.1. Stage 1: Origins (1920–1969)

The origin of the shot peening process as an industrial practice lies in the 1920s and 1930s, not in the 1950s. John O. Almen's work at General Motors in this period established the fundamental relationship between media size, velocity, arc height, and the resulting compressive surface layer, a relationship codified in the Almen strip test that remains the universal intensity measurement system today [80]. Almen's primary motivation was fatigue life enhancement of automotive springs and gears, not forming; the recognition that the same induced surface stress could drive macroscopic curvature in a large panel came later and by a different route. Wohlfahrt [81] traced the transition from fatigue treatment to intentional contouring and identified systematic residual stress profiles in aluminium alloys under aerospace-relevant peening conditions, establishing the quantitative link that Al-Hassani [5] and Kirk [6] would formalise analytically.

The structural context for wing-cover forming before this transition was entirely mechanical, and the components being formed were, in modern terminology, primarily wing skins rather than wing covers or ISPs. The earliest wing-skin contouring was achieved mechanically, by press, stretch and bump forming over hard dies, the wartime techniques later supplemented by peen forming; the verified Lockheed stretch-forming patent US3238753A [115] (1966) marks the mature mechanical endpoint of this lineage. Wartime transport and bomber aircraft, the Lancaster, B-17, B-24, and their contemporaries, used built-up wing structures in which the skin was a formed sheet (typically 1–3 mm aluminium alloy, 2024-T3 or Alclad variants) attached by mechanical fasteners to separately formed and extruded stringers. The forming problem was therefore the simpler one of contouring a plain thin sheet, manageable by press forming, stretch forming, and bump forming over hard dies, with hand finishing to achieve aerodynamic accuracy. The skin and stringer were separate objects at the point of forming; the forming problem for each was tractable by single-curvature or limited-compound methods. These approaches were adequate for the curvature demands and thicknesses of the 1940s but were already straining at the limits of scale and throughput in the late wartime period, particularly for the large-span surfaces of heavy bombers. The critical post-war transition, from built-up structures (separate skin, attached stringers, mechanically fastened) to integrally machined panels (ISPs), fundamentally changed the forming problem. An ISP carries all its structural geometry before forming begins: the stringer roots, pad-ups, pocket floors, and varying skin thickness are present as a complex three-dimensional topography that must be simultaneously contoured to the required aerodynamic loft. The same operation that previously shaped a thin, relatively homogeneous skin sheet now had to work through a plate 30–100 mm thick, with stiffness varying by a factor of 5–10 across the width of a single panel. It is this structural transition, driven by aerodynamic and fatigue requirements rather than by manufacturing capability, that made peen forming necessary. The fatigue failure mode at fastener holes, discussed in the fretting corrosion context by Waterhouse [83], was one of the primary drivers: peening of fastener-hole arrays had been adopted industrially by the mid-1940s, and the step from peening holes to peening large panel areas was short once the curvature-generating effect was recognised [82].

The industrial adoption of shot peen forming in production aerospace programmes from the early 1950s is treated here as part of the origins stage because it established the process credibility, equipment base and production vocabulary that enabled the subsequent industrialisation stage.

5.2. Stage 1 to Stage 2 Transition: Early Aircraft Adoption (~1950–1972)

The transition from the early 1950s to the early 1970s connects Stage 1 origins to Stage 2 industrialisation. In this interval peen forming moved from an experimental and retrospective process account into a standard production method deployed across multiple manufacturers and aircraft classes. Section 5.0 establishes that the preconditions for this adoption, Almen strip intensity

 doi:10.20944/preprints202605.1979.v2

measurement, industrially mature peening equipment, and fatigue-driven adoption at fastener arrays, were in place before the first wing-cover application. The additional step taken in this transition was the recognition that the same process could serve as a contouring mechanism on large panels, not just a surface treatment at discrete features. The recognition that the same process could contour large panels rather than merely treat discrete features is documented in the supplier and programme literature of the period (Champaigne [84]; Moore [3]) rather than in any verifiable contemporaneous patent; it is the open technical record, not the patent record, that marks this transition.

Evidence from this origins-to-industrialisation transition is less fine-grained than it becomes later. The public record rarely separates upper and lower covers aircraft by aircraft, and many disclosures are retrospective. Even so, the early Lockheed material is historically important because it establishes the industrial credibility of peen forming before the widebody era and explains why 1970s programmes could adopt an already industrial, rather than merely experimental, process family [3,84]. Other Lockheed and contemporaneous types from this era, the Lockheed L-188 Electra (1957 turboprop transport), Convair 880/990 (1959–1961 civil jets produced at Fort Worth alongside military programmes with established peening infrastructure), are retained in Supplementary Table S5a as transitional-era comparators for which no separate forming-route disclosure has been located.

An important control case in this origins-to-industrialisation transition is the Boeing 707. Its literature is rich on configuration, aerodynamic development, and service introduction, but the sources located for this review do not disclose a named upper- or lower-cover contouring route. The 707 is therefore retained only as a supplementary baseline comparator in Supplementary Table S5a rather than a core Table 6A programme. This distinction matters methodologically: temporal proximity to a known process adoption is not the same as evidence of that adoption [86]. The Douglas DC-8 occupies an equivalent position: a contemporaneous large civil jet transport first flown in 1958, with metallic wing covers in the same structural class as the 707 but without a publicly identified forming route; it is retained in the extended civil lineage catalogue in Supplementary Table S5a. Concorde and the Tupolev Tu-144, both highly curved delta-planform aircraft with prestretched planks and chemically milled or machined panels, are retained in Supplementary Table S5a as mechanically formed and machined boundary cases; available sources support their construction methods but do not convert them into CAF or peen-forming production evidence.

5.3. Stage 2: Industrialisation and Widebody Scale Challenge (1970–1989)

Stage 2, industrialisation, begins with the widebody scale challenge: the DC-10 first flight in 1970, the L-1011 in 1970, and the 747 entering service in January 1970 (first flight February 1969). These programmes transformed the scale of the wing-cover forming problem and, in doing so, sharpened the public record considerably. Where Stage 1 established peen forming as credible, Stage 2 exposed its limits: panels grew to widths and curvature combinations that isotropic peening alone could not reliably produce, driving both process diversification (stress peen forming, ball forming) and, by the late 1970s, the first systematic investigation of age-forming as an alternative route. It provides the clearest programme-level industrial evidence in the entire review. McDonnell Douglas DC-10 wing skins are the canonical shot peen forming case in the open literature, and Moore's paper remains the standard reference because it treats the process explicitly as a selected production solution for commercial aircraft wing skins rather than as a laboratory curiosity [3]. Moore [3] explicitly discusses the lower-cover saddle-back geometry and its management through shot peen forming; the upper-cover treatment, while named, remains less separately documented.

Lockheed’s L-1011 introduces a second, mechanically distinct solution within the same era. Brandel and Klass [22] describe production of both top and bottom covers by low-velocity ball media with prestress tooling and final saturation peening, demonstrating that particle-impact forming could be preferred when surface finish, cladding integrity, and curvature control made conventional shot peening less attractive. It should be noted that Brandel and Klass [22] is a trade magazine article (Metal Progress) rather than a peer-reviewed paper, and it represents the sole primary source for this

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 15 June 2026 doi:10.20944/preprints202605.1979.v2

process route; the L-1011 entries in Table 6A are therefore classified as Class B rather than Class A, reflecting that the source does not separately disclose upper and lower cover production sequences. Boeing 747 evidence is also strong, although it is less cleanly separated into upper and lower public narratives. Moore, MIC material, and later retrospective accounts together make a robust case that 747 wing skins belonged to the peen-forming family, with some lower-cover evidence appearing in supplier retrospectives even when shipset-by-shipset disclosure remains incomplete [3].

Airbus's first metallic families reveal a particularly informative upper/lower split. The strongest synthesis from Tatton, Airbus-related patents, and later supplier retrospectives is that A300/A310 lower covers were shot peen formed and press formed, with upper covers not publicly disclosed as having an equivalent dedicated contour-forming route. The same pattern extends into the A320 family, where all bottom covers are most strongly associated with shot peen forming plus press or mechanical assistance, whereas the upper covers remain effectively undisclosed in the public record apart from normal fabrication, machining, and assembly operations. For the A320 family, the repeatedly described convex-to-concave or lazy-S lower-surface geometry helps explain why purely isotropic peening would have been inadequate without directional or mechanical assistance [13,27,28].

Military fixed-wing evidence in the same period is more fragmented than the civil widebody record, but it is still substantial for peen-based routes. Troka's 1972 trade account reports MIC forming F-15 wing skins, Grumman Intruder centre-section covers, Northrop Freedom Fighter wing skins, Lockheed anti-submarine Viking wing skins, and NC shot-peening of the Grumman F-14 centre section. Tatton [13] later generalised the mature peen-forming lineage to include Lockheed C-130, McDonnell Douglas F-15, and Fairchild A-10 within the same North American and European aerospace practice. It should be noted that Troka [85] is also a trade publication (Metal Fabricating) rather than a peer-reviewed source; these military attributions are therefore treated as Class B or C evidence and are not elevated to Class A. To keep the main table focused, the lower-evidence fighter and patrol comparators are shifted to Supplementary Tables S4a and S4b, while the core military transport and benchmark cases remain in Table 6B.

5.4. Stage 3: CAF Expansion and Property Management (1990–2010)

Stage 3, CAF expansion, runs from approximately 1990 to 2010 and is the era in which integrally stiffened panels and high-strength aluminium alloys imposed property-management constraints alongside geometry constraints at production scale. Where Stage 2 asked whether peen forming could produce the required shape, Stage 3 asked whether the resulting material state, residual stress, surface integrity, and precipitate structure were acceptable. CAF emerged as the answer for large upper covers, where the concurrent forming-and-ageing mechanism could deliver both geometry and metallurgical state in a single operation. Peen-based routes continued for lower covers and smaller panels, but increasingly within a process framework that treated eigenstrain, surface integrity, and compensation strategy as inseparable from curvature generation. The stage is therefore characterised by coexistence and process divergence, peen forming for lower covers, CAF for upper covers, rather than by replacement. The B-1B is the clearest military CAF anchor: Hambrick's SAE paper describes autoclave age forming of approximately 50-ft 2124/2419 wing skins with integrally machined stiffeners and abrupt thickness variation, while later CAF literature generalises the mechanism to heat-treatable aluminium wing covers [4,23,24].

Military CAF evidence beyond the B-1B is narrower but still informative. Review and modelling literature repeatedly cite the BAe Hawk upper wing panel as a production CAF application, albeit one that is mediated mainly through later CAF literature rather than a readily accessible programme paper. In evidence terms the B-1B therefore remains the stronger named-aircraft case, while Hawk is best treated as a literature-supported upper-panel CAF application with a more qualified public record [12,46,88].

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 15 June 2026 doi:10.20944/preprints202605.1979.v2

The Gulfstream IV programme of this same period provides the strongest public hybrid benchmark across both peen forming and CAF in a single production route and is examined in detail in Section 5.6.

5.5. Stage 4: Specialisation and Composite Transition (2011–Present)

Stage 4 is defined by a structural contraction of the metallic wing-cover manufacturing domain and, simultaneously, by its technical deepening. The 787 Dreamliner (first delivery 2011) and the A350 XWB (first delivery December 2014) use composite primary wing structures, progressively narrowing the market for large metallic upper and lower covers in those programmes. The COMAC C919 (first delivery 2023) represents a contrasting choice: its wings use conventional aluminium alloy construction, making it a modern metallic wing programme in the same general category as the Boeing 737 family and Airbus A320 family rather than a composite-wing type. The metallic wing-cover domain has not disappeared, it remains central to military platforms, business aviation, the Boeing 737 and 777 families, the Airbus A220, and most regional aircraft, but it has become more concentrated and more technically demanding, with the remaining metallic applications disproportionately involving the large, stiff, high-strength panels that are hardest to form. The result is a manufacturing environment served by a more specialised and capital-intensive set of capabilities than at any previous point in the development sequence.

Within this context, laser peen forming has emerged as the production route for sections too stiff for conventional shot peening, the 747-8 being the clearest documented case. The Boeing 747-8 belongs in this period not because the basic 747 lacked peen-forming history, but because its supplier-level laser peen forming evidence marks a new technological branch within metallic wing-cover contouring [67–69]. The Airbus A220, the Bombardier C Series acquired by Airbus in 2018 and manufactured at Mirabel, Québec, deserves note as a modern single-aisle type with metallic wing covers and an Al-Li alloy wing box. Its wing is manufactured by Bombardier/Airbus at the Mirabel facility; no public serial forming-route disclosure for the A220 upper or lower covers has been located, and the programme is carried in Supplementary Table S5a as a modern metallic single-aisle comparator. Embraer and COMAC broaden the manufacturer scope but with a weaker evidence grade. Embraer's patent portfolio shows explicit interest in CAF for aircraft components, while COMAC-linked and wider Chinese patent literature show active work on integral-panel CAF and related metallic-wing manufacture. What remains absent in public sources is a clean aircraft-by-aircraft disclosure of the serial upper- and lower-cover contouring route on named Embraer E2 or COMAC C919 shipsets [89,90]. The broader scope of the NPU/CSU academic CAF programme, which encompasses published work on creep forming of aluminium rail vehicle structural panels alongside the aerospace ISP work catalogued in the patent record, is consistent with a national programme designed with multi-sector transport applications in mind rather than with aerospace alone. This context helps explain both the scale of the academic investment relative to the current maturity of Chinese commercial aircraft ISP production and the parallel academic and industrial patenting activity discussed in Section 8.7.

5.6. Military Fixed-Wing Aircraft and Transport Lineages Within the Evidence Hierarchy

The military programmes that can be directly connected to a forming process have been discussed across Sections 5.0 through 5.4a, covering the full four-stage evolution from 1920s process origins to the current specialisation stage. Beyond them, the military fixed-wing field is dominated by metallic lineages that are historically important but whose forming routes remain publicly unresolved. Supplementary Table S5b catalogues major United States, British/European, Soviet/Russian, Ukrainian, Indian, Brazilian, Japanese, Korean, Chinese, and other manufacturers across fighters, bombers, patrol aircraft and transports. In most of these programmes the open record is much stronger on airframe configuration, structural role, alloy selection, fatigue retrofits or repair practice than on serial upper/lower cover contouring. The principal families catalogued include: US types, Lockheed F-104 Starfighter, General Dynamics/Lockheed Martin F-16 Fighting Falcon, Boeing

doi:10.20944/preprints202605.1979.v2

F/A-18 Hornet/Super Hornet, Northrop B-2 Spirit, Boeing P-8 Poseidon, Lockheed P-3 Orion, and Northrop E-2 Hawkeye; UK/European types, English Electric Canberra, Panavia Tornado, SEPECAT Jaguar, Eurofighter Typhoon, Dassault Mirage / Rafale, Saab Viggen / Gripen, and BAE Systems Hawk; Soviet/Russian/Ukrainian types, Tupolev Tu-95, Tu-22M, Tu-160, Ilyushin Il-76, Antonov An-124 and An-225; Indian and Asian types, HAL Tejas, Mitsubishi F-2, Kawasaki P-1 / C-2, Korea Aerospace Industries T-50 / KF-21; Chinese types, Xian H-6, Y-20, JH-7, J-10 and J-20; and Latin American examples such as Embraer EMB-312 Tucano / EMB-314 Super Tucano and KC-390. These entries are retained as boundary evidence rather than treated as production-route proof.

Military transports deserve special mention. C-130 is the strongest public peen-forming transport case; Antonov heavy transports add documented very long metallic wing panels but not a disclosed final contouring route; and later age-forming references to aircraft such as the C-17 Globemaster III (McDonnell Douglas / Boeing, in service 1993, a large strategic transport with metallic structural wing elements) remain too indirect for aircraft-level route confirmation. The C-17 is carried in Supplementary Table S5b as a lineage comparator. The result is an intentionally tiered treatment: direct process cases stay in Table 6B; lower-evidence military comparator rows are shifted to Supplementary Tables S4a and S4b; broader transport families remain in Supplementary Table S5b unless the process route can be defended [13,47].

5.7. Global Business-Jet Lineages and Benchmark / Boundary Cases

The transport aircraft in Sections 5.1 through 5.5 represent the largest and most publicly documented cases across the four-stage evolution. Business-jet lineages deserve separate treatment because metallic wing-cover manufacture did not remain confined to airline transports, and because the Gulfstream IV provides the clearest hybrid process benchmark in the entire review. The broader review therefore retains the Hawker 125, Citation, Gulfstream, Falcon, Learjet, Challenger, Global, Embraer Executive Jets, HondaJet, Pilatus PC-24, and IAI Westwind / Astra / Galaxy / G280 families within the contextual Supplementary Table S5a catalogue. Regional transport and commuter aircraft with metallic wing covers are also carried in Supplementary Table S5a, including the Embraer ERJ-145/135/140 family, Bombardier CRJ family, Bombardier Q400 (Dash 8), ATR 42/72 (Airbus/Leonardo joint venture), Fokker 70/100, Saab 340/2000, Mitsubishi MRJ/SpaceJet, COMAC ARJ21, and Xian MA700. These programmes share the same manufacturing-relevant issue as the military boundary cases: many have metallic wing covers and important industrial lineage, but only a smaller subset provide public upper/lower forming-route evidence strong enough for Tables 6A or 6B.

6. Comparative Process Capability

The aircraft-level evidence in Section 5, organised around the four stages shown in Figure 5, shows which processes have been used on which programmes. This section draws the comparison in mechanics terms, setting out the conditions under which each route is capable, conditional, or eliminated. Table 4A compares the contour-forming routes themselves. Table 4B isolates the upstream stock-state and precursor manufacturing conditions that condition the starting residual-stress field, distortion sensitivity, and achievable accuracy before any dedicated forming step begins. Because several columns deal explicitly with residual-stress state and compensation, the tables should be read together with the metrology discussion in Section 4.8: near-surface peened layers and bulk stock-driven distortion are not validated by the same measurement methods, and the compensation logic for each differs accordingly.

Table 4. A, part 1. Mechanical and peen-forming routes.

Route	Deformation mechanism	Curvature class generated	Material / ISP window	Key process variables	Compensation strategy	Typical deployment and principal limits	Patent support
Press / hot mechanical forming	Tool-imposed bending or local plastic hinging	Single curvature; limited double curvature	Sheet/plate Al; hot forming widens window / ISP: Low to moderate	Tool radius, hit pitch, clamp state, temperature, sequence	Overbend, restrike, local re-hit	Mechanical preforms, local corrections, delta/high sweep covers	Limits: Developable-surface bias; high tooling burden for smooth compound covers
Stretch forming	Membrane tension over die or mandrel	Single curvature; mild same-sign compound	Ductile Al sheet/plate / ISP: Limited for deep ISPs	Clamp path, grip force, tool radius, strain path, lubrication	Tool offset, clamp-path tuning	Simple transport or trainer/fighter skins and mechanical preforms	Limits: Thinning, grip constraints, limited inflection control
Shot peen forming	Near-surface impact plasticity imposing eigenstrain field (intensity per SAE J442/J443)	Large-radius compound curvature built incrementally	Primarily Al alloys / ISP: High, but local stiffness heterogeneity matters	Almen intensity (SAE J442/J443), coverage, media, angle, exposure map, masking, sequence, starting stress state	Peen-measure-correct loops; iterative correction passes (WO2019051616A1, Polyvalor; EP4703951A1, Shanghai Aircraft Mfg — simulation Dev.);	Large lower covers and selected upper covers; civil transports and C-130/F-15/A-10-type skins	Limits: Large-radius bias; directional control weak without patterned/prestressed peening

 doi:10.20944/preprints202605.1979.v2

Route	Deformation mechanism	Curvature class generated	Material / ISP window	Key process variables	Compensation strategy	Typical deployment and principal limits	Patent support
Stress peen forming	Shot peen eigenstrain superposed on elastic prestress	Directionally biased compound curvature; improved saddle-back control	Primarily Al alloys / ISP: High	Prestress magnitude, fixture shape, load path, release path, intensity, coverage, trajectory (SAE J442/J443 for intensity)	Prestress calibration; fixture load as controllable variable	Severe lower-cover zones, dihedral/aero break work, directional correction	Limits: Fixture complexity and preload qualification burden

Table 4. A, part 2. Particle-impact, laser, CAF, and hybrid routes.

Route	Deformation mechanism	Curvature class generated	Material / ISP window	Key process variables	Compensation strategy	Typical deployment and principal limits	Patent support
Particle-impact / ball forming	Low-velocity large-sphere impact; shallow surface growth	Smooth double curvature over large areas	Al sheet/plate / ISP: Good to moderate	Ball size, impact velocity, pass spacing, prestress and follow-on saturation peen	Band-by-band control; finishing peen equalises surface condition	Selected upper and lower covers where surface finish is critical; L-1011-type panels	Limits: Slow, specialised; difficult to scale; primary source is trade literature [22]

Route	Deformation mechanism	Curvature class generated	Material / ISP window	Key process variables	Compensation strategy	Typical deployment and principal limits	Patent support
Laser peen forming	Laser-shock-induced plastic strain under confined plasma [42,61]	Tighter radii and stiffer sections than conventional peen forming	High-strength precipitation-hardening Al, Ti, and other metals / ISP: Good for stiff thick panels	Pulse energy, spot size, overlap, raster path, traverse speed, coating, water layer, preload	Scan-path redesign and local re-treatment	Advanced thick/stiff wing sections, including 747-8-type and candidate military panels	Limits: High capital cost; lower area rate; sparse public shipset disclosure
Creep age forming (CAF)	Time-dependent creep strain and stress relaxation during artificial ageing under tool restraint	Smooth large-radius compound curvature with calibrated overform	Precipitation-hardening Al only / ISP: Excellent for large ISPs	Alloy/temper, prior quench and stretch relief, time-temperature path, applied stress, tool overcamber, pressure, support density	Tool offset absorbs springback and inherited residual stress; allow for ageing-related shape change and strength knockdown	Large upper covers and selected lower covers; B-1B/Hawk/A330–A380-type panels	Limits: Unavailable for non-age-hardening alloys; long cycles; major calibration burden
Hybrid peen + creep	Sequential partitioning of local cold-work curvature and global thermal creep/age curvature	Complex curvature not reached robustly by one route alone	Precipitation-hardening Al when CAF included / ISP: Excellent	Route partitioning, interim metrology, sequence, dwell, local re-peen, stress state transferred between stages [7,11]	Inter-stage measurement allocates correction between peen and thermal stages	Complex upper skins and corrective hybrid routes; Gulfstream IV-type cases	Limits: Integration complexity; high qualification burden; limited public disclosure

Note: Table 4A uses eight columns in the published document (landscape orientation). Route = forming process family. Deformation mechanism summarises the physical origin of the curvature-generating strain. Curvature class = the principal geometry reliably generated by the route in production. Material / ISP window = the alloy

 doi:10.20944/preprints202605.1979.v2

and panel-architecture constraints on process selection. Key process variables list the primary industrial control parameters (for peen routes, intensity is measured per SAE J442/J443 and governed by SAE AMS2430). Compensation strategy describes how residual-stress-driven distortion and springback are managed. Typical deployment and limits combine the production context and the principal selection constraints. Patent support lists key Proc. (process), Tool. (tooling), and Dev. (development/compensation) patents by number; Adj. = adjacent lineage patent not programme specific. ISP = integrally stiffened panel.

Table 4. B. Upstream stock state and precursor manufacturing conditions that condition metallic wing-cover accuracy before dedicated contour forming. Note: Table 4B is intentionally not a process-ranking table. It isolates inherited material state from deliberate contour generation.

Upstream stock state / operation	Mechanics and inherited state	Representative property / stress consequence	Typical compensation route	Effect on finished-cover accuracy	Representative sources
Hot rolling / plate reduction	Develops texture, anisotropy, and through-thickness property gradients	Directional springback response and local stiffness/yield asymmetry	Stock-orientation selection, coupon characterisation, symmetric machining	Can bias fairness and local springback before contour forming	Prime and Hill [30]; Zheng et al. [18]
Solution treatment and quench of thick plate or forging	Creates self-equilibrated through-thickness residual stress field during rapid cooling	Surface/core residual stresses of hundreds of MPa in high-strength Al stock	Stretch stress relief, stock mapping, conservative stock allowance, correction forming	Major driver of out-of-plane distortion after unclamping or machining	Prime and Hill [30]; Li et al. [31]
Mechanical stretch-stress relief (Tx51/Tx651-type)	Controlled tensile overstretch redistributes quench stress but does not eliminate it	Lower but non-zero residual stress; local gradients persist through thickness	Combine with machining symmetry, interim metrology, process-specific compensation	Improves starting stability but does not guarantee distortion-free covers	Prime and Hill [30]

 doi:10.20944/preprints202605.1979.v2

Upstream stock state / operation	Mechanics and inherited state	Representative property / stress consequence	Typical compensation route	Effect on finished-cover accuracy	Representative sources
Heavy machining / chemical milling / pre-pocketing	Asymmetric material removal redistributes inherited residual stress and changes local panel stiffness	Distortion can change sign between zones as stock is removed and supports released	Symmetric removal, interim supports, staged stock removal, final contour correction	Direct threat to fairness and assembly accuracy in large ISPs if untreated	Li et al. [31]

Quantitative selection envelopes (evidence-qualified). The public sources reviewed support the following indicative envelopes, consolidated here from Section 4 and offered as evidence-qualified ranges rather than design allowables. Conventional shot peen forming imposes a near-surface eigenstrain layer of approximately 0.25–0.4 mm depth for aerospace-typical media (S110–S230, 0.15–0.25 mm Almen intensity), with the depth of peak compressive stress shifting from roughly 50 to 150 μm as media size increases from S110 to S230, and a natural bias toward large-radius single or quasi-spherical curvature. Stress peen forming makes prestress the dominant directional variable, with an approximately linear prebending-moment-to-arc-height relationship reported over 0–90 N·m on 300 × 100 mm 2024-T3 coupons (extrapolation to production panels requires separate validation). Laser peen forming drives a plastic zone of approximately 1–3 mm depth, against roughly 0.25–0.4 mm for shot peening, which is the mechanical basis for its application to thick or stiff integrally stiffened sections. Creep age forming is restricted to precipitation-hardening alloys and operates in a dwell window of approximately 150–180 °C for 7xxx alloys, with reported knockdowns of approximately 6% in UTS and yield strength and approximately 14% in elongation for 7050 (alloy- and temper-specific). Integrally stiffened panel response scales with the cube of local thickness, giving representative skin-to-stringer-root stiffness ratios of order 5–10 across a single panel and plate thicknesses of roughly 30–100 mm; the B-1B case, with an approximately 25:1 thickness ratio across one panel, is cited as lying beyond the viable cold-forming envelope and is the mechanical basis for its CAF selection. These ranges are drawn from public process evidence and should be read alongside the capability columns of Table 4A, not as production limits.

7. Aircraft-Level Mapping of Metallic Wing-Cover Forming Processes

The process mechanics of Section 4, the four-stage historical evidence of Section 5, and the comparative assessment of Section 6 together provide the analytical framework; this section applies it systematically to named programmes through Tables 6A and 6B. Aircraft-level process attribution is summarised in Table 6A for commercial transport and business aircraft and in Table 6B for military fixed-wing aircraft, with full manufacturer lineage in Appendix A. Upper and lower covers are attributed separately throughout, so that the asymmetry in the public record, which is often richer for one cover than the other, is preserved rather than collapsed into a single aircraft-level label.

doi:10.20944/preprints202605.1979.v2

Table 5. Evidence-distribution summary for Tables 6A and 6B. To make the attribution framework auditable, the following summary separates programme-level best evidence from cover-level attribution cells. Programme-level best evidence records the strongest public evidence available for each aircraft row in Tables 6A and 6B. Cover-level cells record upper and lower entries separately; mixed labels are retained because they represent genuine source ambiguity rather than a hidden upgrade or downgrade.

Evidence category	**Programme-level best evidence (n = 25 rows)**	**Cover-level attribution cells (n = 50)**	**Interpretation**
Class A present / direct production anchor	9	8 Class A cells plus 2 A/B mixed cells	Strongest aircraft-level support; used for core conclusions
Class B best evidence / named aircraft but incomplete route	14	28 Class B cells	Named aircraft or supplier/manufacturer evidence; route or upper/lower split may be incomplete
Class C only / capability or lineage evidence	2	8 Class C cells plus 3 B/C mixed cells	Capability, patent, or lineage evidence; not treated as production proof
Class D only / no firm route attribution	0	1 Class D cell	Boundary evidence or explicitly unresolved route

Only Class A and Class B evidence is used to support aircraft-level production conclusions. Class C and D entries are retained to show search breadth, capability context, negative evidence, and unresolved lineages.

Table 6A. Core aircraft-level mapping of metallic wing-cover forming routes in commercial transport and business aircraft.

Note: Tables 6A and 6B separate upper and lower evidence because public aircraft records are often asymmetric. Class A = direct serial-production or supplier/manufacturer disclosure. Class B = named-aircraft evidence but upper/lower split, exact production stage, or full route incompletely disclosed. Class C = patent-supported capability or lineage-level evidence. Class D = boundary cases or no firm attribution. Scale class: Class I <30 m wingspan; Class II 30–50 m; Class III >50 m. Conservative upward rounding applied where families span thresholds.

 doi:10.20944/preprints202605.1979.v2

Table 6. A, part 1. Programme classification and upper/lower process attribution.

Aircraft / programme	Manufacturer / lineage	Classification	Upper cover attribution	Upper evidence	Lower cover attribution	Lower evidence
Lockheed Super Constellation	Lockheed Aircraft Corporation	CS-25 analogue Class II Civil piston transport	Shot peen formed wing covers (built-up skin era; plain skin contouring); upper/lower split not public	Supplier disclosure (B)	Shot peen formed wing covers (built-up skin era; plain skin contouring); upper/lower split not public	Supplier disclosure (B)
Boeing 727	Boeing	CS-25/Part 25 Class II Civil narrow-body jet	Shot peen formed wingskins; upper/lower split not public	Supplier historical disclosure (B)	Shot peen formed wingskins; upper/lower split not public	Supplier historical disclosure (B)
Boeing 737 family	Boeing	CS-25/Part 25 Class II Civil single-aisle transport	Shot peen formed wingskins; upper/lower split not public	Supplier historical disclosure (B)	Shot peen formed wingskins; upper/lower split not public	Supplier historical disclosure (B)
Boeing 747	Boeing	CS-25/Part 25 Class III Civil twin-aisle transport	Shot peen formed wingskins; upper/lower split not public	Supplier disclosure (B)	Shot peen formed wingskins; lower-cover lineage strongest publicly	Programme paper + supplier disclosure (B)

 doi:10.20944/preprints202605.1979.v2

Aircraft / programme	Manufacturer / lineage	Classification	Upper cover attribution	Upper evidence	Lower cover attribution	Lower evidence
Boeing 757	Boeing	CS-25/Part 25 Class II Civil single-aisle transport	Shot peen formed wingskins; upper/lower split not public	Supplier historical disclosure (B)	Shot peen formed wingskins; upper/lower split not public	Supplier historical disclosure (B)
Boeing 767	Boeing	CS-25/Part 25 Class III Civil twin-aisle transport	Shot peen formed wingskins; upper/lower split not public	Supplier historical disclosure (B)	Shot peen formed wingskins; upper/lower split not public	Supplier historical disclosure (B)
Boeing 777	Boeing	CS-25/Part 25 Class III Civil twin-aisle transport	Supplier-level peen-formed wingskin attribution; upper/lower split not public	Supplier + adjacent manufacturing evidence (B)	Supplier-level peen-formed wingskin attribution; upper/lower split not public	Supplier + adjacent manufacturing evidence (B)
Boeing 747-8	Boeing	CS-25/Part 25 Class III Civil twin-aisle transport	Laser-peen-formed wing panels; upper/lower split not public	Supplier + laboratory disclosure (B)	Laser-peen-formed wing panels; upper/lower split not public	Supplier + laboratory disclosure (B)

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 15 June 2026 doi:10.20944/preprints202605.1979.v2

Aircraft / programme	Manufacturer / lineage	Classification	Upper cover attribution	Upper evidence	Lower cover attribution	Lower evidence
McDonnell Douglas DC-10	Douglas Aircraft Company → McDonnell Douglas → Boeing	CS-25/Part 25 Class III Civil twin-aisle transport	Shot peen formed (Class B: Moore 1982 discusses but less explicitly than lower)	Named-aircraft programme paper (B)	Shot peen formed (Class A: Moore 1982 explicitly discusses lower-cover saddle-back)	Named-aircraft programme paper (A)
McDonnell Douglas DC-9-80 / MD-80	Douglas Aircraft Company → McDonnell Douglas → Boeing	CS-25/Part 25 Class II Civil short-haul jet	Shot peen formed wing skins; upper/lower split not public	Named-aircraft industrial literature (B)	Shot peen formed wing skins; upper/lower split not public	Named-aircraft industrial literature (B)
Lockheed L-1011 TriStar	Lockheed Aircraft Corporation	CS-25/Part 25 Class III Civil twin-aisle transport	Particle-impact / ball formed; upper/lower split not separately disclosed	Named-aircraft trade article (B)	Particle-impact / ball formed; upper/lower split not separately disclosed	Named-aircraft trade article (B)
Airbus A300	Airbus Industrie / Airbus	CS-25/Part 25 Class III Civil twin-aisle transport	No dedicated global upper cover contouring route disclosed publicly	Under-disclosed upper route (C)	Shot peen formed with press / mechanical assistance	Named-aircraft industrial paper + trade disclosure (A)

 doi:10.20944/preprints202605.1979.v2

Aircraft / programme	Manufacturer / lineage	Classification	Upper cover attribution	Upper evidence	Lower cover attribution	Lower evidence
Airbus A310	Airbus Industrie / Airbus	CS-25/Part 25 Class II Civil twin-aisle transport	No dedicated global upper cover contouring route disclosed publicly	Under-disclosed upper route (C)	Shot peen formed with press / mechanical assistance	Named-aircraft industrial paper + trade disclosure (A)
Airbus A320 family	Airbus Industrie / Airbus	CS-25/Part 25 Class II Civil single-aisle transport	No dedicated global upper cover contouring route disclosed publicly	Under-disclosed upper route (C)	Shot peen formed with press / mechanical assistance	Named-aircraft industrial paper + trade disclosure (A)
Airbus A330	Airbus Industrie / Airbus	CS-25/Part 25 Class III Civil twin-aisle transport	CAF upper covers	Supplier/manufacturer disclosure (A) — Vogeli et al. [16] AERAC programme	Shot peen formed lower covers	Supplier/manufacturer lineage disclosure (B)
Airbus A340	Airbus Industrie / Airbus	CS-25/Part 25 Class III Civil twin-aisle transport	CAF upper covers	Supplier/manufacturer disclosure (A) — Vogeli et al. [16] AERAC programme	Shot peen formed lower covers	Supplier/manufacturer lineage disclosure (B)
Airbus A380	Airbus / Airbus UK Broughton lineage	CS-25/Part 25 Class III Civil twin-aisle transport	CAF upper covers	Supplier/manufacturer disclosure (A)	Shot peen formed lower covers	Supplier/manufacturer lineage disclosure (B)

 doi:10.20944/preprints202605.1979.v2

Aircraft / programme	Manufacturer / lineage	Classification	Upper cover attribution	Upper evidence	Lower cover attribution	Lower evidence
Gulfstream IV	Gulfstream Aerospace with Textron Aerostructures	CS-25 analogue Class II Business aircraft / forming benchmark	One-piece upper skin formed by shot peen plus creep forming	Supplier/manufacturer disclosure (A)	Lower-cover route not publicly separated	Lower route unresolved (C)
Embraer E2 family	Embraer	CS-25/Part 25 Class II Civil regional-mainline jet	Public serial upper-cover route not disclosed	Patent capability + adjacent evidence (C)	Public serial lower-cover route not disclosed	Patent capability + adjacent evidence (C)
COMAC C919	COMAC	CS-25/Part 25 analogue Class II Civil single-aisle transport	Public serial upper-cover route not disclosed	Patent capability + adjacent evidence (C)	Public serial lower-cover route not disclosed	Patent capability + adjacent evidence (C)

Table 6A, part 2. Curvature/process route, patent anchor and qualification note.

Aircraft / programme	Curvature / process route	Patent anchor	Qualification / limitation
Lockheed Super Constellation	Smooth large-radius transport curvature; shot peen forming of formed skin sheets	Nondirect	MIC/Champaigne [84] identifies the programme directly, but the public record does not separate upper and lower covers.
Boeing 727	Supplier peen-forming lineage for transport wings	US4329862A (Adj.)	Family-level peen-forming attribution only; no cover-by-cover separation.

 doi:10.20944/preprints202605.1979.v2

Aircraft / programme	Curvature / process route	Patent anchor	Qualification / limitation
Boeing 737 family	Narrowbody transport wing within supplier peen-forming lineage	US4329862A (Adj.)	Family-level attribution; not separated upper/lower.
Boeing 747	Widebody transport wing; shot peen forming	US4329862A (Adj.); US4694672A (Adj.)	Historical peen-forming evidence is strong, but public upper/lower allocation remains incomplete.
Boeing 757	Transport wing in supplier peen-forming lineage	US4329862A (Adj.)	Public evidence stronger on supplier continuity than explicit cover routing.
Boeing 767	Transport wing in supplier peen-forming lineage	US4329862A (Adj.)	Named in peen-forming lineage sources but without explicit upper/lower separation.
Boeing 777	Large twin transport wing; public literature stronger on assembly automation than contouring	Nondirect	Wing-contour attribution weaker than assembly-tooling disclosure in public record.
Boeing 747-8	Advanced stiff sections with tighter curvature; laser peen forming [42,67]	US6410884B1 (Adj.); US6670578B2 (Adj.)	Serial wing-panel laser peen forming is public; cover allocation remains incomplete.
McDonnell Douglas DC-10	Severe compound contour with lower-cover saddle-back; shot peen forming	US4329862A (Adj.); US4694672A (Adj.)	Moore [3] provides the clearest civil transport case. Lower cover Class A; upper cover Class B under the conservative evidence-class rule.
McDonnell Douglas DC-9-80 / MD-80	Programme continuity from DC-10 practice; shot peen forming	US4329862A (Adj.); US4694672A (Adj.)	Public record links programme to peen-forming practice but does not fully separate upper and lower.
Lockheed L-1011 TriStar	Smooth double curvature with surface-finish sensitivity; particle-impact / ball forming	US3705511A (Proc.)	Brandel and Klass [22] is a trade magazine article (Metal Progress), not a peer-reviewed paper, and is the sole primary source.

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 15 June 2026 doi:10.20944/preprints202605.1979.v2

Aircraft / programme	Curvature / process route	Patent anchor	Qualification / limitation
Airbus A300	Inflected lower contour with lazy-S tendency; hybrid mechanical preforms plus shot peen finishing	US7195203B2; US20080042011A1 (Adj.)	Lower-cover route public; upper global contouring route under-disclosed.
Airbus A310	Inflected lower contour with lazy-S tendency; hybrid mechanical preforms plus shot peen finishing	US7195203B2; US20080042011A1 (Adj.)	Tatton [13] makes the A310 lower cover one of the clearest Airbus peen-forming cases.
Airbus A320 family	Inflected lower contour with lazy-S tendency; hybrid mechanical preforms plus shot peen finishing	US7195203B2; US20080042011A1 (Adj.)	Among the strongest public Airbus lower-cover cases.
Airbus A330	Large smooth upper covers and stiff metallic lower panels; split CAF/peen route	No verified programme patent; anchored on Vogeli et al. [16] AERAC SAE paper	Upper-cover case anchored by Vogeli et al. [16] AERAC SAE paper, which discloses Textron Aerostructures Nashville as the production forming facility. Distinct from A380 (Broughton).
Airbus A340	Large smooth upper covers and stiff metallic lower panels; split CAF/peen route	No verified programme patent; anchored on Vogeli et al. [16] AERAC SAE paper	Same upper/lower split as A330; upper covers formed at Textron Aerostructures Nashville (AERAC programme).
Airbus A380	Very large smooth metallic covers; split CAF/peen route	US7195203B2; US20080042011A1 (Adj.)	Broughton skin-and-creep facilities [87] anchor the A380 upper-cover case. Distinct from A330/A340, which were formed at Textron Aerostructures Nashville under the AERAC programme.

Aircraft / programme	Curvature / process route	Patent anchor	Qualification / limitation
Gulfstream IV	Complex upper skin requiring dihedral and saddle control; hybrid peen plus creep forming	US6938448B2 (Adj.)	Cook [14] and Vacu-Blast [15] give direct industrial account of one-piece upper skin. NRC [47] places this in same lineage as B-1B and A330/A340.
Embraer E2 family	Modern metallic transport-wing curvature; patent-supported capability only	US20200222967A1 (Proc./Dev.)	Patents demonstrate CAF capability; no named serial upper/lower route is public.
COMAC C919	Modern transport double curvature; patent-supported capability only	CN101988146B (COMAC, Proc./Dev.); CN102266887B [104] and CN111195677B [105] (Central South University, Proc./Dev.); CN102930115B [118] (AVIC, Dev.); CN104646475B [119] (Jilin University, Tool.); CN106955930A [120] (NPU, Tool.).	Chinese patents and process literature show integral-wing-panel CAF and shot-peen-forming capability, but no public shipset-level allocation for C919 upper/lower covers.

Table 6B. Core aircraft-level mapping of metallic wing-cover forming routes in military fixed-wing aircraft.

Note: Non-transport military aircraft are retained only where they materially illuminate forming-process development or transfer. Antonov An-124/225 has been relocated to Supplementary Table S5b. Lower-evidence fighter and patrol comparators are summarised in Supplementary Tables S4a and S4b.

Table 6. B, part 1. Programme classification and upper/lower process attribution.

Aircraft / programme	Manufacturer / lineage	Classification	Upper cover attribution	Upper evidence	Lower cover attribution	Lower evidence
Lockheed C-130 Hercules	Lockheed Aircraft Corporation → Lockheed Martin	CS-25 analogue Class II Military transport / medium tactical airlifter	Shot peen formed wing skins; upper/lower split not public	Named-aircraft industrial/conference disclosure (B)	Shot peen formed wing skins; upper/lower split not public	Named-aircraft industrial/conference disclosure (B)

doi:10.20944/preprints202605.1979.v2

Aircraft / programme	Manufacturer / lineage	Classification	Upper cover attribution	Upper evidence	Lower cover attribution	Lower evidence
Fairchild Republic A-10 Thunderbolt II	Fairchild Republic	Non-transport military benchmark Class I Attack aircraft	Shot peen formed wing skins or surfaces; upper/lower split not public	Named-aircraft industrial review (B/C)	Shot peen formed wing skins or surfaces; upper/lower split not public	Named-aircraft industrial review (B/C)
McDonnell Douglas F-15 Eagle family	McDonnell Douglas → Boeing	Non-transport military benchmark Class I Fighter / strike fighter	Shot peen formed wing skins; upper/lower split not public	Trade disclosure + conference review (B)	Shot peen formed wing skins; upper/lower split not public	Trade disclosure + conference review (B)
Rockwell B-1B	Rockwell International	CS-25 analogue Class II Military bomber / variable-geometry bomber	Autoclave age-formed upper wing skins (Class A: Hambrick [23] primary source)	Named-aircraft SAE Technical Paper (A/B) — Hambrick [23] primary production disclosure; NRC [47] secondary synthesis	Autoclave age-formed lower wing skins (Class A: Hambrick [23] primary source)	Named-aircraft SAE Technical Paper (A/B) — Hambrick [23] primary production disclosure; NRC [47] secondary synthesis
BAe Hawk family	Hawker Siddeley → British Aerospace → BAE Systems	Non-transport military benchmark Class I Trainer / light attack aircraft	CAF upper wing panel (Class B/C: repeated CAF review literature)	Repeated CAF review literature (B/C)	No direct public lower-cover route identified	No direct lower-cover route identified (D)

Table 6. B, part 2. Curvature/process route, patent anchor and qualification note.

Aircraft / programme	Curvature / process route	Patent anchor	Qualification / limitation
Lockheed C-130 Hercules	Military transport wing within mature peen-forming lineage	Nondirect; peen-forming patents only adjacent	Tatton [13] identifies C-130 directly in the application lineage, but direct cover-by-cover route and process sequence remain undisclosed.
Fairchild Republic A-10 Thunderbolt II	Military attack aircraft within peen-forming lineage	Nondirect	Tatton [13] includes A-10 in application lineage; public detail brief.
McDonnell Douglas F-15 Eagle family	Military fighter wing skins; shot peen forming	Nondirect; US4329862A only adjacent lineage	Troka [85] names F-15 wing skins in production; Tatton [13] includes the type in wider peen-forming lineage. Both are trade/conference sources; no peer-reviewed cover-by-cover route has been located.
Rockwell B-1B	Very large integrally stiffened wing covers (ISPs) with integral machined stiffeners and abrupt thickness transitions (~50 ft long, 0.1–2.5 in thick; Hambrick [23]); autoclave age forming.	No verified programme patent; anchored on Hambrick [23] (Class A) and NRC [47] (secondary)	Hambrick [23] provides direct panel geometry and autoclave age-forming route; NRC [47] is secondary.
BAe Hawk family	Trainer/light-combat upper panel with smooth compound curvature; CAF	No verified programme patent; anchored on CAF review/modelling literature [12,46,88]	Hawk upper-panel CAF is repeatedly cited in modelling and review literature (Jeunechamps et al. [12,46,88].

8. Thematic Analysis

The evidence assembled in Sections 5–7 is now interpreted thematically. Seven analytical threads are examined: the four-stage process evolution (Section 8.1); the upper/lower cover divergence (Section 8.2); process selection logic as a coupled multi-variable decision (Section 8.3); surface integrity and durability consequences of peen-based routes (Section 8.4); defect modes and failure envelopes in mechanical routes (Section 8.5); military-to-civil technology transfer (Section 8.6); and the principal limitations of the evidence base (Section 8.7).

8.1. Four-Stage Evolution

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 15 June 2026 doi:10.20944/preprints202605.1979.v2

Evidence-supported finding: The evidence assembled in Sections 5 through 7 supports the four-stage periodisation shown in Figure 5. Stage 1, Origins (1920-1969), covers the emergence of peening as a controlled residual-stress process, the development of mechanical forming baselines, and the first aircraft applications that established shot peen forming as a credible production route. Stage 2, Industrialisation (1970-1989), is defined by widebody scale and process diversification: DC-10, L-1011, Boeing 747, Airbus A300/A310/A320 lower-cover evidence, stress-assisted variants, particle-impact forming, and the first age-forming investigations. Stage 3, CAF expansion (1990-2010), adds property management to geometry control: large heat-treatable aluminium covers, B-1B age-forming evidence, Airbus A330/A340 and A380 CAF evidence, Gulfstream IV hybrid practice, and springback/tooling modelling. Stage 4, Specialisation (2011-present), is shaped by the composite transition and by the concentration of metallic wing-cover forming into high-value, specialised applications, including laser-assisted and hybrid routes, continuing metallic single-aisle and regional aircraft, business aircraft, and selected military platforms. The four stages are not mutually exclusive process replacements; they describe the dominant manufacturing problem in each era while older routes continue where they remain technically and economically appropriate.

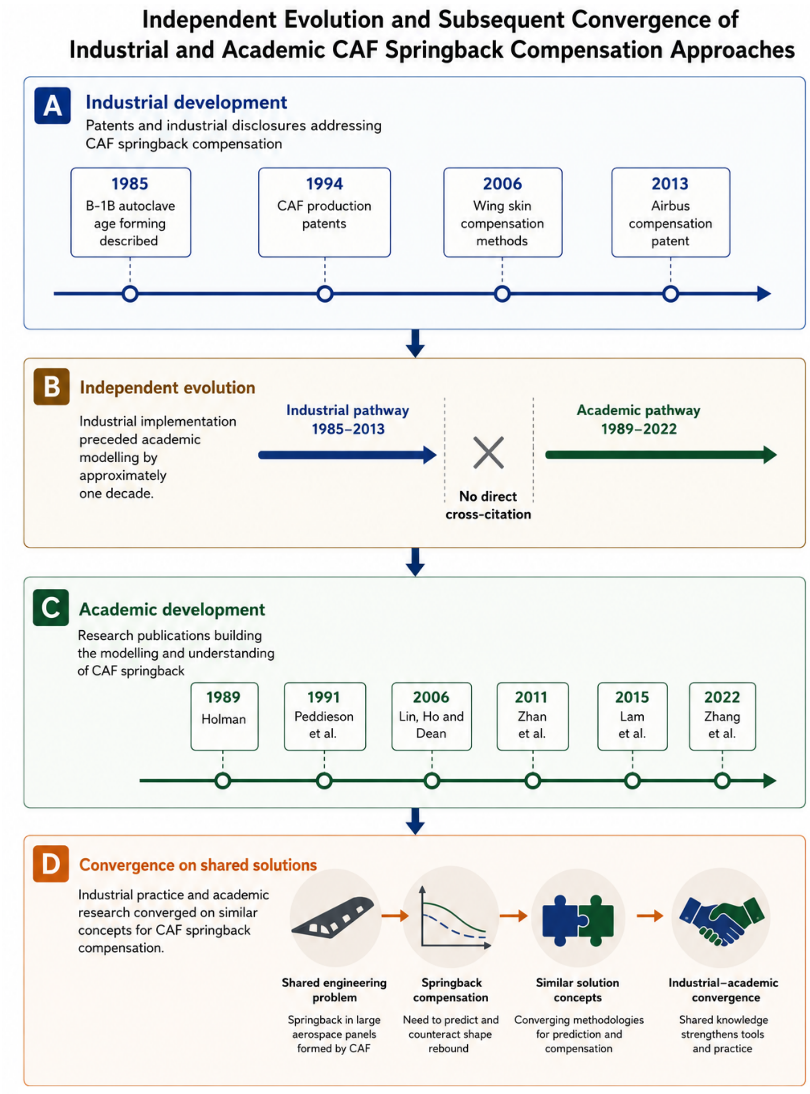

Figure 6. Cross-source development pattern for CAF springback compensation. The figure separates early industrial disclosure (SAE Technical Papers and production programmes, notably Hambrick [23] and Holman [24]), an interval of independent evolution, the later academic modelling literature, and convergence on similar compensation concepts. It illustrates how industrial and academic communities may address the same

 doi:10.20944/preprints202605.1979.v2

manufacturing problem in parallel without direct cross-citation; it is not evidence of direct technology transfer unless separately supported. Sections 4.5 and 8.1.

8.2. Upper vs Lower Divergence

Evidence-supported finding: The analytical distinction between upper and lower covers introduced in Section 2.1 is directly supported for the strongest Airbus lower-cover and upper-cover evidence, for the Gulfstream IV upper-cover hybrid case, and for selected B-1B age-forming evidence. The review therefore supports an upper/lower manufacturing divergence where named programme evidence exists. Mechanistic interpretation: this divergence is technically coherent because large smooth upper covers in precipitation-hardening alloys are compatible with CAF, whereas lower covers more often combine inflected geometry, tensile/fatigue-critical alloy choices, local stiffness transitions and directional-contour requirements that favour peen-based, mechanically assisted, stress-assisted or hybrid routes. Industrial inference: for Boeing and many other lineages, the same upper/lower logic is plausible but not directly demonstrated, because public sources rarely disclose cover-separated route data. Accordingly, the upper/lower divergence should be read as a documented Airbus/Gulfstream/B-1B pattern and a mechanistically supported inference elsewhere, not as a universal production rule.

8.3. Process Selection Logic

Mechanistic interpretation: The upper/lower divergence in Section 8.2 is one manifestation of a broader selection logic. Process selection emerges from the interaction of curvature class, thickness distribution, surface condition, alloy metallurgy, inherited residual-stress state, and the available compensation route, and Figure 7 maps that interaction visually. In the terminology of process selection methodology [25], the governing variables define the primary selection space, hard constraints eliminate ineligible routes, and the remaining feasible routes are ranked by secondary criteria including cost, throughput, accuracy, and qualification burden. The application of this logic to wing covers is not generic: it is specific to a component class in which the governing constraints change between upper and lower covers, between early and late aircraft-development periods, and between the structural classes defined in Section 1.3. Where the required shape is large-radius and the panel can benefit from compressive surface stress, shot peen forming is attractive. Where directional bias or saddle control is required, stress peen or ball forming becomes more compelling because the boundary condition can be tuned rather than left free. Where very large, smooth covers in precipitation-hardening alloys are involved, CAF becomes attractive because it can convert a calibrated elastic loading state into stable compound curvature with relatively low net residual stress. The Airbus A330/A340 and A380 upper-cover cases in the present review sit within that evidence-supported domain; cases outside the directly documented aircraft set remain industrial inferences unless independently corroborated.

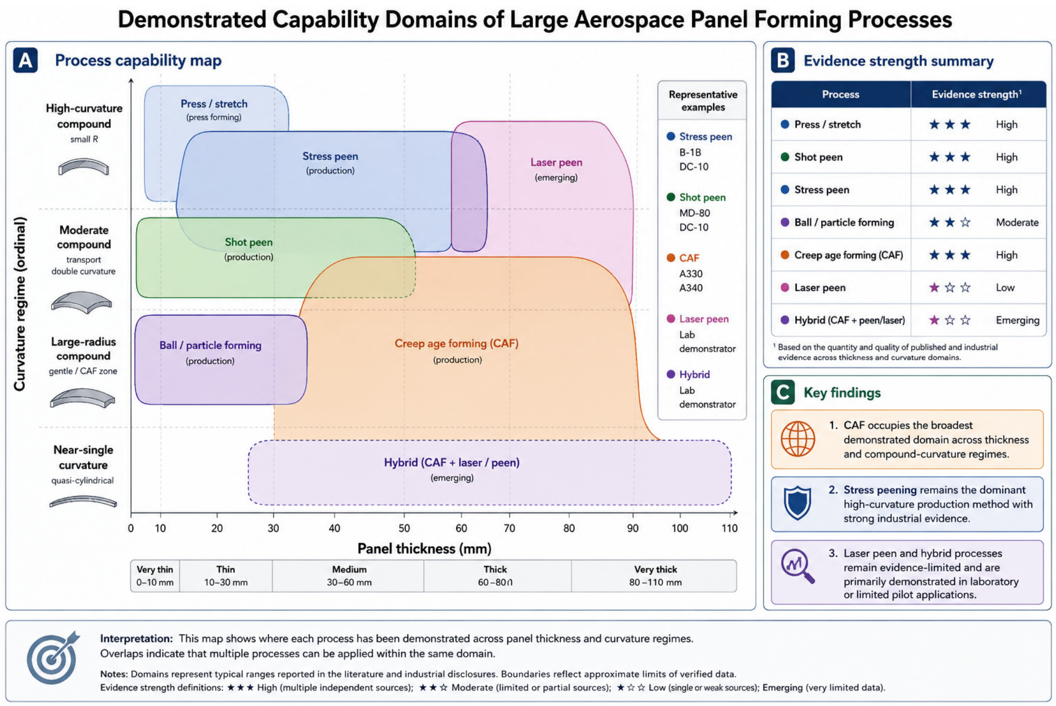

Figure 7. Evidence-qualified process-selection map for large metallic wing-cover forming. Panel A maps indicative process capability domains against curvature regime and panel thickness; Panel B summarises evidence strength for each route; and Panel C identifies the principal selection implications. The domains are schematic, derived from reviewed public evidence rather than design allowables or complete production envelopes, and the constraint lines represent material/temper and volume-economics screens. Section 8.3.

8.4. Surface Integrity and Durability Consequences of Peen-Based Routes

Evidence-supported and mechanistic finding: Process selection based on curvature capability and compensation burden, as discussed in Section 8.3, is necessary but not sufficient. The durability requirements of the structural role must be treated as a primary selection input rather than a post-selection constraint. Schijve [93] provides the standard framework for understanding how surface residual stress interacts with fatigue life in metallic structures: compressive mean stress shifts the effective stress ratio and moves the fatigue damage line on a Goodman diagram in the same direction as a reduction in applied mean stress, with the benefit being largest when fatigue initiation is surface-driven and smallest when it is sub-surface or notch-driven. For aerodynamic wing covers, where fatigue life is governed by a combination of fastener-hole fretting, stress concentrations at stiffener terminations, and free-surface crack initiation, the compressive surface layer introduced by peen-based forming routes is simultaneously a structural asset and a process constraint: it must be preserved, not destroyed, by subsequent machining, assembly, or repair operations. Peen-based routes do not only shape a panel; they simultaneously rewrite its surface state in a way that interacts with these fatigue mechanisms, and the durability consequences of that rewriting must be factored into the selection decision [93]. Surface roughness, work hardening, dislocation density, microstructural refinement, residual-stress depth, and potential surface damage are all process outputs. Huang et al. [94] review this interplay and show why shot size, intensity (SAE J442/J443), and coverage cannot be chosen on forming grounds alone. The common assumption that more peening is automatically better is mechanically naive. Beneficial curvature generation and beneficial durability often overlap, but they are not the same optimisation problem.

Yao et al. [74] showed on high-speed milled 7055 aluminium that shot peening substantially increased roughness while also deepening the compressive residual-stress field, hardening the surface, shifting fatigue initiation below the surface, and improving life. Benedetti et al. [95] further

 doi:10.20944/preprints202605.1979.v2

showed that fatigue benefit depends on the stability of the introduced residual-stress field: little relaxation occurs near the endurance limit, but higher compressive cyclic loading can redistribute the field. Gao [96] and Rodopoulos et al. [97] both provide direct comparisons of shot peen and laser peen fatigue performance on 2024 aluminium alloy, showing that deeper compressive layers from laser peening can deliver larger fatigue gains than conventional shot peening, though the magnitude is alloy-, temper-, and loading-condition-dependent.

8.5. Defect Modes and Failure Envelopes in Mechanical Routes

Mechanistic interpretation: Just as peen-based routes carry surface-integrity risks that must be managed alongside their forming function, mechanical routes carry structural defect risks that determine where they can and cannot be used. They are bounded less by nominal forming force than by defect envelopes. Zhang and Li [19] review integral-panel bend forming in terms of configuration accuracy, buckling and fracture, which is also the correct mechanics framing for wing covers. Once stiffener height, pitch and local pad thickness vary across the section, the neutral axis migrates, and local curvature demand becomes strongly non-uniform. The result is a persistent susceptibility to web buckling, local flange wrinkling, stiffener-root yielding or cracking, print-through and spatially variable springback.

These defects are not secondary shop-floor nuisances; they are the practical reason mechanical routes struggle to generate robust large-area double curvature in thick integrally stiffened covers. Vorkov et al. [41] show how even a single bend in large-radius bumping alters the response of subsequent hits, while Coelho et al. [40] emphasise the sensitivity of press-brake systems to load distribution and tooling stiffness. In a large integrally stiffened cover, double curvature is not simply 'more bend'; it implies compatible membrane strain over a non-developable surface. Without a distributed stress-based or thermo-mechanical mechanism, mechanical routes tend to approximate such geometry by segmented local bending, which raises defect risk and erodes contour fidelity.

The practical consequence for process selection is that mechanical routes carry a defect-avoidance screen in addition to a curvature-capability screen. A route may be geometrically capable of producing a required shape yet be rejected because it generates that shape via a sequence prone to stiffener-root wrinkling, springback hysteresis, or print-through that cannot be corrected reliably before assembly. The result is that combinations of processes, mechanical preform plus peen correction, or peen forming plus CAF dwell, survive in production even where each constituent step is nominally capable of producing the shape alone, because the combination manages defect risk that the single-step route cannot. This explains a recurring feature of the evidence base: the most demanding programmes (B-1B, Gulfstream IV, A380) consistently use hybrid or multi-step routes rather than the single most capable process, driven as much by defect avoidance as by curvature demand [4,19,41].

8.6. Military-to-Civil Transfer of Forming Technologies

Industrial inference: The discussion so far has been primarily analytical, about process mechanics and selection logic. The evidence base also supports a selective historical claim with practical implications across the four-stage structure of Section 5: some forming technologies moved between military, business-aircraft, and civil-transport manufacture, especially during Stage 2 industrialisation and Stage 3 CAF expansion, when civil-aircraft scale and geometric demands approached the severity that had driven process development in military programmes. The strongest public case is autoclave age forming and its later codification as creep age forming. Hambrick [23] describes the autoclave age-forming programme as developed in support of the B-1B through a joint Rockwell, United States Air Force Systems Command and Avco Aerostructures effort. The NRC (1996) review, treated as a secondary synthesis, then places production age-forming experience on B-1B upper and lower skin panels in the broader development path toward CAF for commercial transports. This does not prove a simple one-way transfer from military to civil manufacture, but it does show

doi:10.20944/preprints202605.1979.v2

that military programmes supplied some of the scale, alloy and contouring problems that made later civil CAF credible.

8.7. Evidence Limitations

Evidence limitation: The analytical claims in Sections 8.1 through 8.7 are bounded by asymmetry in the public record. Some aircraft programmes are documented through named technical papers or supplier disclosures, while others are visible only through patents, family-level supplier claims, trade literature or unresolved lineage evidence. The review therefore treats under-disclosure as a limitation on claim strength rather than as a manufacturing conclusion.

Patent limitation and revision control: An earlier draft contained misidentified patent numbers. Every patent citation in the present version has been re-verified against Google Patents or Espacenet, and identifiers that resolved to unrelated inventions have been removed or replaced. The supplementary patent-audit table documents these corrections transparently.

Programme-publication asymmetry: Moore [3] and Tatton [13] provide named-aircraft programme evidence for DC-10 and Airbus lower-cover forming, but no equivalent public Boeing wing-cover programme paper was located for the same period. This likely reflects publication culture and intellectual-property strategy as much as manufacturing practice. Recovery of archived Boeing, Russian or Chinese programme sources would materially change the evidence grading for several lineages.

Metrology and property asymmetry: Many sources name a forming route without publishing residual-stress measurement method, spatial sampling density, final geometry-validation method, surface-integrity consequences, or durability allowables. Consequently, several route attributions support process identification but not a full assessment of process capability, reliability, or production economics.

Non-English and proceedings limitation: Chinese-language and Russian-language material was searched mainly through English abstracts, patent summaries and transliterated assignees. ICSP proceedings not independently accessible in full were not elevated to primary anchors. These gaps define clear future research tasks rather than hidden evidence for stronger claims.

9. Discussion: Synthesis

The review's main contribution is to reposition metallic wing-cover forming as a manufacturing-systems problem rather than as a catalogue of individual forming methods. The analysis shows that the correct unit of analysis is the wing cover: a skin-plus-stringer structural panel whose forming response is controlled by curvature, thickness variation, alloy state, residual stress, and compensation strategy.

A second contribution is methodological. By combining process-level tables, aircraft-level attribution, patent typing and evidence classes, the review makes visible the limits of public knowledge without treating every source as equivalent. The resulting framework is more conservative than a purely historical account and more useful for manufacturing analysis than a single-process review.

The synthesis should therefore be read through an evidence-weighting lens. Direct and named-aircraft production evidence anchors only a subset of the aircraft catalogue, while other programmes contribute as supplier-level, patent-capability, or contextual comparators. This distinction is essential: the breadth of Appendix A and the supplementary catalogue demonstrates the search perimeter, whereas the strength of the main conclusions derives primarily from the Class A and B anchors in Tables 6A and 6B.

Structural scale also emerges as a useful manufacturing discriminator. Class III aircraft concentrate the highest public evidence for CAF, laser peen forming, and specialised supplier capability, while Class I and Class II aircraft more often appear in peen, mechanical, hybrid, or under-disclosed route categories. The classification framework is therefore not merely descriptive; it helps

 doi:10.20944/preprints202605.1979.v2

explain why process capability, compensation burden, and supplier ownership change with wing-cover scale.

Table 7. Evidence-weighted basis for the principal review conclusions.

Evidence tier / use in the review	Representative programme anchors	Conclusion supported	Boundary / interpretation
Class A — direct programme evidence	DC-10 lower-cover shot peen forming; Airbus A300/A310/A320 lower-cover peen + mechanical lineage; Airbus A330/A340/A380 upper-cover CAF; B-1B autoclave age forming; Gulfstream IV hybrid peen + creep forming.	Anchors the strongest aircraft-process attributions: peen forming for selected civil lower-cover and skin cases, CAF/age forming for large heat-treatable covers, and selected hybrid practice.	Applies only to the named programmes and disclosed covers. It should not be generalised to all aircraft families or to undisclosed upper/lower routes.
Class B — named but incomplete route evidence	L-1011 ball forming; Boeing 727/737/747/757/767/777 peen-forming lineage; Boeing 747-8 laser peen forming; C-130; F-15 and A-10 benchmark cases.	Supports route family, supplier capability, and lineage continuity where the public record names the aircraft or process family but does not fully disclose the cover-level route.	Upper/lower split, serial sequence, production stage, or full shipset allocation may remain incomplete. Use as corroborating evidence rather than complete route proof.
Class C — patent / adjacent capability evidence	Embraer E2; COMAC C919; verified Airbus, Boeing, LLNL, AVIC, MHI, COMAC/CSU and related patents; Russian and Chinese development lineages.	Shows claimed process, tooling, compensation, control, or development capability. Useful for identifying plausible technology direction where production disclosure is absent.	Patents and adjacent lineage evidence do not prove serial production use unless independently corroborated by named programme, supplier, or manufacturer evidence.

 doi:10.20944/preprints202605.1979.v2

Evidence tier / use in the review	Representative programme anchors	Conclusion supported	Boundary / interpretation
Class D — contextual and boundary evidence	Business jets, regional aircraft, many military comparators, historical reviews, family analogues, and searched lineages with no firm public route attribution.	Defines the search perimeter, boundary cases, and evidence gaps; supports cautious interpretation and future archival or programme-level work.	Does not drive the principal conclusions unless upgraded by stronger Class A or B programme evidence.
Note: Only Class A and Class B evidence is used for direct aircraft-process attribution in the main conclusions. Class C and Class D evidence informs capability assessment, search breadth, lineage interpretation, and future evidence targets; it is not treated as independent proof of production use.			

10. Conclusions

The conclusions are stated with explicit claim levels. Evidence-supported findings are anchored in Class A/B evidence and process mechanics; mechanistic interpretations explain why the observed evidence is technically coherent; industrial inferences identify plausible but not directly demonstrated extensions.

Evidence-supported finding: The central technical finding is that metallic wing-cover forming routes are selected through interacting constraints, not by nominal curvature capability alone. Structural scale, upper/lower cover role, curvature class, alloy and temper, inherited stock state, surface integrity, available tooling, compensation strategy and production economics jointly define the feasible route set. This conclusion is strongly supported by the process mechanics reviewed in Section 4, the process capability synthesis in Tables 4A and 4B, and the aircraft-level attribution structure in Tables 6A and 6B.

Evidence-supported finding: Process selection begins with hard gates. The alloy requirement for CAF (precipitation-hardening alloys only) functions as a binary filter that eliminates CAF entirely for all 2xxx-alloy lower covers, irrespective of curvature or scale. CAF is available only where the alloy and temper can support a precipitation-hardening ageing response and where property evolution during the thermal cycle remains acceptable. Mechanical and stretch routes are screened out by severe double curvature, inflection, and stiffness discontinuity. Peen-based routes remain metallurgically broad but are constrained by surface integrity, residual-stress redistribution, contamination control, roughness restoration, and fixture-based correction burden. Laser peen forming is a specialised capability where deep compressive stress, stiff sections, or tight local curvature justify cost and qualification complexity.

Evidence-weighted finding: The process map is evidence-weighted rather than uniform. Direct and named-aircraft evidence is strongest for shot peen forming in selected civil transport cases, particle-impact forming in the L-1011 case, age forming/CAF in the B-1B and Airbus upper-cover lineages, and selected hybrid practice in Gulfstream IV. Stress peen forming is the clearest mechanistic route for directional curvature control, but public named-aircraft deployment evidence is less complete than for conventional shot peen forming. Laser peen forming has strong supplier, patent, and 747-8 evidence but narrower public cover-level disclosure. Hybrid routes are therefore best treated as demonstrated in selected benchmark cases and mechanically plausible elsewhere, not as a universal production pattern.

 doi:10.20944/preprints202605.1979.v2

Evidence-supported finding and industrial inference: The upper/lower distinction is a robust finding for the strongest Airbus evidence and a mechanistically coherent, but less directly evidenced, inference elsewhere. For Boeing and other large airframers whose routes are not publicly disclosed, this inference rests on geometric arguments (Section 2.2), alloy compatibility (Section 2.5), and capability evidence from suppliers and patents, and should be read as mechanistically plausible rather than demonstrated. Airbus evidence directly supports a split between peen/mechanical lower-cover routes and CAF upper-cover routes for selected families. Boeing and many other lineages are better interpreted at supplier, family, or capability level because public sources rarely disclose upper/lower separation. The absence of public cover-separated route data should not be read as evidence of process absence; it is a limitation on claim strength.

Evidence-supported finding: Material state is a hard process gate and a property-management problem. CAF cannot be assumed for non-age-hardening alloys, unsuitable tempers, or panels whose allowable strength, ductility, corrosion behaviour, or dimensional stability cannot tolerate the ageing cycle. Peen-based and mechanical routes may remain physically available on a wider range of metallic panels, but their practical viability depends on inherited residual stress, surface roughness, ferrous contamination risk, fatigue/corrosion limits, and the accuracy of compensation metrology.

Evidence-weighting statement: The conclusions have unequal evidential strength. The strongest aircraft-level anchors are DC-10, L-1011, Airbus A300/A310/A320 lower-cover lineage, Airbus A330/A340/A380 upper-cover lineage, Gulfstream IV, and B-1B. Boeing family-wide peen-forming, Boeing 747-8 laser peen forming, Embraer E2, COMAC C919, Russian programmes, business-jet lineages, and many military examples are interpreted more cautiously because public evidence is supplier-level, patent-level, lineage-level, or unresolved. The supplementary material supports traceability and search breadth; it does not convert low-evidence cases into production attributions.

Industrial inference: Military-to-civil linkage is selective rather than universal. The evidence is strongest for age forming and CAF lineage, where military programme development, business-jet practice, and civil widebody production can be connected through named technical sources and reviews. For peen-forming lineages, public military evidence often identifies aircraft and process families without full cover-level separation, so the transfer conclusion should be treated as historically suggestive but not uniformly proven across all military cases.

Industrial inference: Manufacturing route choice can materially influence industrial organisation, but this conclusion remains qualitative. Specialist forming capability, large tools, metrology, compensation knowledge and surface-restoration control can shape the make/buy boundary and the choice between in-house production and specialised supplier capability. Public sources rarely disclose cycle times, tooling amortisation, rejection rates, rework burden, or supplier economics; therefore, the supply-chain conclusion should be read as an evidence-supported interpretation rather than a quantified causal law.

Future-work hypothesis: The highest-value future work is correspondingly specific: archival Boeing programme sources; Russian and Chinese programme-level forming papers; quantitative curvature, thickness, and residual-stress maps for representative covers; verified upper/lower route disclosures for A220, Embraer E2, COMAC C919 and major business jets; and cost-throughput studies that connect physical process capability to rate, rework, and supplier ownership. Such evidence would most directly upgrade Class B/C attributions and test the process-selection framework proposed here.

Supplementary Materials: The following supporting information is supplied with this manuscript: Table S0, a main-manuscript-to-supplement consistency crosswalk; Section S1, methods and search protocol (sources searched, query families, evidence-grading definitions, the main-text inclusion rule and the patent re-verification protocol); Section S2, the verified patent register; Section S3, the patent-verification audit record documenting misidentified identifiers removed or replaced at revision; Section S4, lower-evidence military fixed-wing comparators (Tables S4a, fighter and attack aircraft, and S4b, bomber, patrol and special-mission aircraft); and Section S5, civil, business-jet, regional and military-

 doi:10.20944/preprints202605.1979.v2

transport comparators (Tables S5a and S5b). The supplementary material preserves search breadth and traceability but does not upgrade Class C or Class D evidence into proof of production use.

Abbreviations

The following abbreviations are used in this manuscript: CAF, creep age forming; ISP, integrally stiffened panel; MIC, Metal Improvement Company; SAE, SAE International; Proc., process patent; Tool., tooling patent; Dev., development/compensation patent; Adj., adjacent lineage patent.

Appendix A. Core Aircraft-Manufacturer Traceability Tables

Appendix A provides the controlled aircraft-manufacturer reference set for the analytically central aircraft retained in the main manuscript. Table A1 lists the commercial transport and business-aircraft families retained in Table 6A together with their manufacturer lineage and classification field, while Table A2 does the same for the military fixed-wing aircraft retained in Table 6B. The Antonov An-124/225 has been removed from Table A2 and relocated to Supplementary Table S5b as a geometric scale comparator with no attributed forming route. See Section 5.5 and Supplementary Section S6.

Table A1. Commercial transport and business-aircraft families retained in Table 6A.

Aircraft / programme	Original manufacturer	Successor / current lineage	Classification	Traceability notes
Lockheed Super Constellation	Lockheed Aircraft Corporation	Lockheed legacy	CS-25 analogue Class II Civil piston transport	Early peen-forming anchor in Table 6A
Boeing 727	Boeing	Boeing	CS-25/Part 25 Class II Civil narrow-body jet	Supplier-lineage peen-forming case
Boeing 737 family (Classic / NG / MAX)	Boeing	Boeing	CS-25/Part 25 Class II Civil single-aisle transport	Supplier-lineage peen-forming case; MAX retains metallic wing of NG lineage
Boeing 747	Boeing	Boeing	CS-25/Part 25 Class III Civil twin-aisle transport	Major peen-forming widebody anchor

 doi:10.20944/preprints202605.1979.v2

Aircraft / programme	Original manufacturer	Successor / current lineage	Classification	Traceability notes
Boeing 757	Boeing	Boeing	CS-25/Part 25 Class II Civil single-aisle transport	Supplier-lineage peen-forming case
Boeing 767	Boeing	Boeing	CS-25/Part 25 Class III Civil twin-aisle transport	Supplier-lineage peen-forming case
Boeing 777 / 777X	Boeing	Boeing	CS-25/Part 25 Class III Civil twin-aisle transport	Large transport lineage case; 777X has composite outer wing panels but metallic inner wing — outer panels screened from forming scope
Boeing 747-8	Boeing	Boeing	CS-25/Part 25 Class III Civil twin-aisle transport	Laser peen-forming case; technical anchors Hackel and Harris [42], Hackel et al. [61]
McDonnell Douglas DC-10	Douglas Aircraft Company	McDonnell Douglas → Boeing	CS-25/Part 25 Class III Civil twin-aisle transport	Core named-aircraft peen-forming anchor; lower cover Class A, upper cover Class B
Douglas DC-9 (original)	Douglas Aircraft Company	McDonnell Douglas → Boeing	CS-25/Part 25 Class II Civil short-haul jet	Lineage origin for DC-9-80/MD-80; no separate forming disclosure located

Aircraft / programme	Original manufacturer	Successor / current lineage	Classification	Traceability notes
McDonnell Douglas DC-9-80 / MD-80	Douglas Aircraft Company	McDonnell Douglas → Boeing	CS-25/Part 25 Class II Civil short-haul jet	Programme-continuity peen-forming case from DC-9 lineage
McDonnell Douglas MD-11	McDonnell Douglas	Boeing	CS-25/Part 25 Class III Civil twin-aisle transport	DC-10 derivative widebody; wing in DC-10 peen-forming lineage; Class C lineage attribution
Lockheed L-1011 TriStar	Lockheed Aircraft Corporation	Lockheed legacy	CS-25/Part 25 Class III Civil twin-aisle transport	Particle-impact / ball-forming anchor; evidence Class B (trade article, no upper/lower split)
Airbus A300	Airbus Industrie	Airbus	CS-25/Part 25 Class III Civil twin-aisle transport	Lower-cover peen-forming case
Airbus A310	Airbus Industrie	Airbus	CS-25/Part 25 Class II Civil twin-aisle transport	Lower-cover peen-forming case
Airbus A320 family (A318/A319/A320/A321)	Airbus Industrie	Airbus	CS-25/Part 25 Class II Civil single-aisle transport	Strong Airbus lower-cover peen-forming case; all variants share the A320-family wing box.
Airbus A330	Airbus Industrie	Airbus	CS-25/Part 25 Class III Civil twin-aisle transport	Split CAF upper / peen lower; primary anchor Vogeli et al. [16] AERAC programme

 doi:10.20944/preprints202605.1979.v2

Aircraft / programme	Original manufacturer	Successor / current lineage	Classification	Traceability notes
Airbus A340	Airbus Industrie	Airbus	CS-25/Part 25 Class III Civil twin-aisle transport	Split CAF upper / peen lower; primary anchor Vogeli et al. [16] AERAC programme
Airbus A380	Airbus / Airbus UK Broughton lineage	Airbus	CS-25/Part 25 Class III Civil twin-aisle transport	Large-scale CAF upper / peen lower case
Gulfstream IV	Gulfstream Aerospace	Gulfstream / Textron subcontract context	CS-25 analogue Class II Business aircraft / forming benchmark	Hybrid peen + creep upper-skin benchmark
Embraer E2 family	Embraer	Embraer	CS-25/Part 25 Class II Civil regional-mainline jet	Patent-capability comparator
COMAC C919	COMAC	COMAC	CS-25/Part 25 analogue Class II Civil single-aisle transport	Patent-capability comparator

 doi:10.20944/preprints202605.1979.v2

Table A2. Military fixed-wing aircraft retained in Table 6B, with manufacturer lineage and classification fields. Note: Antonov An-124/225 has been relocated to Supplementary Table S5b as a geometric scale comparator with no attributed forming route. Aircraft mentioned in Section 5.2 narrative but not retained in Table 6B (Grumman F-14, Grumman A-6, Northrop F-5, Lockheed S-3) are carried in Supplementary Tables S4a and S4b with Class B/C attributions. The broader military catalogue including F-104, F-16, F/A-18, B-52, B-2, C-141, C-5, C-17, C-9, P-3, P-8, Nimrod, Tornado, Jaguar, Typhoon, Mirage, Rafale, Su-27/30, Tu-95/142, Tu-22M/Tu-160, Il-76/78, AMX/A-1, Tejas, F-2, and T-50/FA-50 is held in Supplementary Table S5b.

Aircraft / programme	Original manufacturer	Successor / current lineage	Classification	Traceability notes
Lockheed C-130 Hercules	Lockheed Aircraft Corporation	Lockheed Martin lineage	CS-25 analogue Class II Military transport / medium tactical airlifter	Strongest public military transport peen-forming case
Fairchild Republic A-10 Thunderbolt II	Fairchild Republic	Legacy programme	Non-transport military benchmark Class I Attack aircraft	Named-aircraft industrial review case; Class B/C evidence
McDonnell Douglas F-15 Eagle family	McDonnell Douglas	Boeing lineage	Non-transport military benchmark Class I Fighter / strike fighter	Trade and conference disclosure; Class B; Troka [85] and Tatton [13]
Rockwell B-1B	Rockwell International	Boeing / sustainment lineage context	CS-25 analogue Class II Military bomber / variable-geometry bomber	Core military autoclave age-forming / CAF benchmark; Hambrick [23] primary anchor (Class A); NRC [47] secondary synthesis
BAe Hawk family	Hawker Siddeley	British Aerospace / BAE Systems lineage	Non-transport military benchmark Class I Trainer / light attack aircraft	Military CAF upper-panel benchmark; Class B/C; review literature anchor

Author Contributions: The manuscript was conceived, researched, and written by the sole author, A.L. The author has read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: No new data were created in this study. All evidence is drawn from the publicly available sources cited in the reference list and in the supplementary material.

Conflicts of Interest: The author declares no conflict of interest. The author has previously published research in the field of metallic wing-cover forming, including works cited here as references [7,26], and [51]; these are cited on their technical merits.

References

1. Hosford, W.F. and Caddell, R.M. (2011) Metal forming: mechanics and metallurgy. 4th edn. Cambridge: Cambridge University Press.
2. Wagoner, R.H., Wang, J.F. and Li, M. (2006) 'Springback', in ASM Handbook, Vol. 14B: Metalworking: Sheet Forming. Materials Park, OH: ASM International, pp. 733–755. https://doi.org/10.31399/asm.hb.v14b.a0005131.
3. Moore, D. (1982) 'The application of shot peen forming technology to commercial aircraft wing skins'. SAE Technical Paper 821456. https://doi.org/10.4271/821456.
4. Zhan, L., Lin, J., and Dean, T.A. (2011) 'A review of the development of creep age forming: experimentation, modelling and applications', *International Journal of Machine Tools, and Manufacture*, 51(1), pp. 1–17. https://doi.org/10.1016/j.ijmachtools.2010.08.007.
5. Al-Hassani, S.T.S. (1982) 'The shot peening of metals – mechanics and structures'. SAE Technical Paper 821452. https://doi.org/10.4271/821452.
6. Kirk, D. (2004) 'Residual stresses in shot peened components', The Shot Peener, 18(4).
7. Wang, T., Platts, M.J. and Levers, A. (2006) 'A process model for shot peen forming', Journal of Materials Processing Technology, 172(2), pp. 159–162. https://doi.org/10.1016/j.jmatprotec.2005.09.006.
8. Miao, H.Y., Larose, S., Perron, C. and Levesque, M. (2010) 'Experimental study of shot peening and stress peen forming', Journal of Materials Processing Technology, 210(15), pp. 2089–2102. https://doi.org/10.1016/j.jmatprotec.2010.07.016.
9. Miao, H.Y., Larose, S., Perron, C. and Levesque, M. (2011) 'Numerical simulation of the stress peen forming process and experimental validation', Advances in Engineering Software, 42(11), pp. 963–975. https://doi.org/10.1016/j.advengsoft.2011.05.025.
10. Gariepy, A., Larose, S., Perron, C. and Levesque, M. (2011) 'Shot peening and peen forming finite element modelling – Towards a quantitative method', International Journal of Solids and Structures, 48(20), pp. 2859–2877. https://doi.org/10.1016/j.ijsolstr.2011.06.003.
11. Gariepy, A., Larose, S., Perron, C., Bocher, P. and Levesque, M. (2013) 'On the effect of the peening trajectory in shot peen forming', Finite Elements in Analysis and Design, 69, pp. 48–61. https://doi.org/10.1016/j.finel.2013.02.003.
12. Lin, J., Ho, K.C. and Dean, T.A. (2006) 'An integrated process for modelling of precipitation hardening and springback in creep age-forming', International Journal of Machine Tools and Manufacture, 46(11), pp. 1266–1270. https://doi.org/10.1016/j.ijmachtools.2006.01.026.
13. Tatton, R.J.D. (1987) 'Shot peen forming – an economical solution', in Wohlfahrt, H., Kopp, R. and Vöhringer, O. (eds) Proceedings of the 3rd International Conference on Shot Peening (ICSP-3), Garmisch-Partenkirchen, Germany, 12–17 October 1987. Oberursel: DGM Informationsgesellschaft Verlag, pp. 309–318.
14. Cook, D.F. (1991) 'Shot peen forming the widest wing in the world', The Shot Peener, 4(4), pp. 15–16.
15. Vacu-Blast Ltd. (1996) 'Peen forming – a look under the surface', The Shot Peener, 10(3).
16. Vogeli, P., Zieve, P., Hopkins, T., Howard, S. and Bratten, J. (1991) 'Process development for use of AERAC'. SAE Technical Paper 912650. https://doi.org/10.4271/912650.
17. Zeng, Y. and Huang, X. (2008) 'Forming technologies for integral panel', Acta Aeronautica et Astronautica Sinica, 29(3), pp. 721–727.
18. Zheng, J.H., Pan, R., Li, C., Zhang, W., Lin, J., and Davies, C.M. (2018) 'Experimental investigation of multi-step stress-relaxation-ageing of 7050 aluminium alloy for different pre-strained conditions', Materials Science and Engineering A, 710, pp. 111–120. https://doi.org/10.1016/j.msea.2017.10.066.

19. Zhang, X.-X. and Li, Y.-H. (2023) 'Bend forming of aluminum alloy integral panel: a review', *Metallurgical Research & Technology*, 120(6), 601. https://doi.org/10.1051/metal/2023070.
20. Zhang, L., Li, H., Bian, T., Wu, C., Gao, Y. and Lei, C. (2022) 'Advances and challenges on springback control for creep age forming of aluminum alloy', Chinese Journal of Aeronautics, 35(10), pp. 8–34. https://doi.org/10.1016/j.cja.2021.10.019.
21. Yocom, C.J., Zhang, X. and Liao, Y. (2018) 'Research and development status of laser peen forming: A review', Optics & Laser Technology, 108, pp. 32–45. https://doi.org/10.1016/j.optlastec.2018.06.032.
22. Brandel, W.W. and Klass, L.S. (1971) 'Ball forming solves contouring problems', Metal Progress, 99(March), pp. 56–57.
23. Hambrick, D.M. (1985) 'Age forming technology expanded in an autoclave'. SAE Technical Paper 850885. https://doi.org/10.4271/850885.
24. Holman, M.C. (1989) 'Autoclave age forming large aluminum aircraft panels', Journal of Mechanical Working Technology, 20, pp. 477–488. https://doi.org/10.1016/0378-3804(89)90055-7.
25. Ashby, M.F. (2005) Materials Selection in Mechanical Design. 3rd edn. Oxford: Elsevier Butterworth-Heinemann.
26. Levers, A. (2010) 'Broughton: From Wellington Bombers to the A380', International Journal for the History of Engineering & Technology, 80(1), pp. 55–79. https://doi.org/10.1179/175812109X12547332071308.
27. Airbus UK Ltd. and Airbus Operations Ltd. (2007) Wing skin and method of manufacture thereof. US Patent US7195203B2. Published 27 March 2007.
28. Airbus Operations Ltd. (2008) Cover panel for an aircraft wing and a method of forming thereof. US Patent US20080042011A1. Published 21 February 2008.
29. Boeing Co. (1982) Shot peen forming of compound contours. US Patent US4329862A. Published 18 May 1982.
30. Prime, M.B. and Hill, M.R. (2002) 'Residual stress, stress relief, and inhomogeneity in aluminum plate', Scripta Materialia, 46(1), pp. 77–82. https://doi.org/10.1016/S1359-6462(01)01201-5.
31. Li, Y., Gan, W., Zhou, W. and Li, D. (2023) 'Review on residual stress and its effects on manufacturing of aluminium alloy structural panels with typical multi-processes', Chinese Journal of Aeronautics, 36(5), pp. 96–124. https://doi.org/10.1016/j.cja.2022.07.020.
32. Pechiney Rhenalu SAS (2004) Edge-on stress-relief of thick aluminium plates. WO Patent WO2004053180A2. Published 24 June 2004.
33. Ye, S., Chen, K., Zhu, C. and Chen, S. (2019) 'A new path of quench-induced residual stress control in thick 7050 aluminum alloy plates', Metals, 9(4), 393. https://doi.org/10.3390/met9040393.
34. Battelle Memorial Institute (2012) *Metallic Materials Properties Development and Standardization (MMPDS) Handbook—07*. Warrendale, PA: SAE International.
35. Ho, K.C., Lin, J., and Dean, T.A. (2004) 'Constitutive modelling of primary creep for age forming of an aluminium alloy', Journal of Materials Processing Technology, 153–154, pp. 122–127. https://doi.org/10.1016/j.jmatprotec.2004.04.304.
36. Chen, J.F., Zhen, L., Jiang, J.T., Yang, L., Shao, W.Z. and Zhang, B.Y. (2012) 'Microstructures and mechanical properties of age-formed 7050 aluminum alloy', Materials Science and Engineering A, 539, pp. 115–123. https://doi.org/10.1016/j.msea.2012.01.067.
37. Zhu, A.W. and Starke, E.A. Jr (2001) 'Materials aspects of age-forming of Al-xCu alloys', Journal of Materials Processing Technology, 117(3), pp. 354–358. https://doi.org/10.1016/S0924-0136(01)00795-6.
38. Lam, A.C.L., Shi, Z., Lin, J. and Huang, X. (2015b) 'Influences of residual stresses and initial distortion on springback prediction of 7B04-T651 aluminium plates in creep-age forming', International Journal of Mechanical Sciences, 103, pp. 115–126. https://doi.org/10.1016/j.ijmecsci.2015.09.004.
39. Kurukuri, S., Miroux, A., Wisselink, H. and van den Boogaard, T. (2011) 'Simulation of stretch forming with intermediate heat treatments of aircraft skins', International Journal of Material Forming, 4(2), pp. 129–140. https://doi.org/10.1007/s12289-010-1013-8.
40. Coelho, P.G., Faria, L.O. and Cardoso, J.B. (2005) 'Structural analysis and optimisation of press brakes', *International Journal of Machine Tools, and Manufacture*, 45(12–13), pp. 1451–1460. https://doi.org/10.1016/j.ijmachtools.2005.01.030.

41. Vorkov, V., Aerens, R., Vandepitte, D. and Duflou, J.R. (2015) 'Influence of a single bend in the bumping process of large radius air bending', Key Engineering Materials, 651–653, pp. 1090–1095. https://doi.org/10.4028/www.scientific.net/KEM.651-653.1090.
42. Hackel, L.A. and Harris, F.B. (2002) Contour forming of metals by laser peening. US Patent US6410884B1. Published 25 June 2002.
43. Siguerdidjane, W., Khameneifar, F. and Gosselin, F. (2022) 'Closed-loop shot peen forming with in-process measurement and optimization', CIRP Journal of Manufacturing Science and Technology, 38, pp. 500–508. https://doi.org/10.1016/j.cirpj.2022.05.010.
44. Sushitskii, V., Miao, H.Y., Levesque, M., and Gosselin, F.P. (2024) 'Segmentation of peen forming patterns using k-means clustering', Journal of Manufacturing Processes, 119, pp. 867–877. https://doi.org/10.1016/j.jmapro.2024.04.009.
45. Peddieson, J., Buchanan, G.R. and Gong, S.W. (1991) 'A mathematical model of autoclave age forming', Journal of Materials Processing Technology, 28(1–2), pp. 211–219. https://doi.org/10.1016/0924-0136(91)90220-9.
46. Jeunechamps, P.-P., Ho, K., Lin, J., Ponthot, J.-P. and Dean, T.A. (2006) 'A closed form technique to predict springback in creep age-forming', International Journal of Mechanical Sciences, 48(6), pp. 621–629. https://doi.org/10.1016/j.ijmecsci.2006.01.005.
47. National Research Council (1996) 'Chapter 3: Metallic materials and processes', in National Research Council Committee on New Materials for Advanced Civil Aircraft (ed.) New materials for next-generation commercial transports. Washington, DC: National Academy Press, pp. 39–80. https://doi.org/10.17226/5070.
48. Sonaca NMF Canada Inc. (2005) Shaped metal panels and forming same by shot peening. US Patent US6938448B2. Published 6 September 2005.
49. OAO Komsomolsk-on-Amur Aircraft Production Association named after Yu.A. Gagarin (2013) Method of forming parts. RU Patent RU2475322C1. Published 20 February 2013.
50. Yamada, T., Takahashi, T., Ikeda, M., Sugimoto, S. and Ohta, T. (2002) 'Development of shot peening for wing integral skin for Continental Business Jets', Mitsubishi Heavy Industries Technical Review, 39(2), pp. 57–61.
51. Kang, X., Wang, T., Platts, J. and Levers, A. (2010) 'Multiple impact modelling for shot peening and peen forming', Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 224(5), pp. 689–697. Available at: https://doi.org/10.1243/09544054JEM1672.
52. Mura, T. (1987) Micromechanics of Defects in Solids. 2nd edn. Dordrecht: Martinus Nijhoff.
53. Fathallah, R., Inglebert, G. and Castex, L. (1996) 'Modelling of shot peening residual stresses and plastic deformation induced in metallic parts', in *Proceedings of the 6th International Conference on Shot Peening (ICSP-6)*, San Francisco, CA, USA, pp. 464–480.
54. Cao, W., Fathallah, R. and Castex, L. (1995) 'Correlation of Almen arc height with residual stresses in shot peening process', *Materials Science and Technology*, 11(9), pp. 967–973. https://doi.org/10.1179/mst.1995.11.9.967.
55. Bagherifard, S., Ghelichi, R. and Guagliano, M. (2012) 'Numerical and experimental analysis of surface roughness generated by shot peening', Applied Surface Science, 258(18), pp. 6831–6840. https://doi.org/10.1016/j.apsusc.2012.03.111.
56. Polyvalor, Limited Partnership (2019) Method and system for performing peen forming simulation. WO Patent WO2019051616A1. Published 21 March 2019.
57. Mylonas, G.I. and Labeas, G. (2011) 'Numerical modelling of shot peening process and corresponding products: residual stress, surface roughness and cold work prediction', Surface and Coatings Technology, 205(19–20), pp. 4480–4494. https://doi.org/10.1016/j.surfcoat.2011.03.080.
58. Pashkov, A.E., Koltsov, V.P. and Pashkov, A.A. (2017) 'Complex method of peen forming and shot peening of aircraft structural components', in Proceedings of the International Conference "Actual Issues of Mechanical Engineering" 2017 (AIME 2017). Advances in Engineering Research, 133, pp. 585-591. Available at: https://doi.org/10.2991/aime-17.2017.95.

 doi:10.20944/preprints202605.1979.v2

59. Fabbro, R., Fournier, J., Ballard, P., Devaux, D. and Virmont, J. (1990) 'Physical study of laser-produced plasma in confined geometry', Journal of Applied Physics, 68(2), pp. 775–784. https://doi.org/10.1063/1.346783.
60. Ding, K. and Ye, L. (2006) Laser Shock Peening: Performance and Process Simulation. Cambridge: Woodhead Publishing. ISBN 978-1845690526.
61. Hackel, L.A., Halpin, J.M. and Harris, F.B. (2004) Pre-loading of components during laser peenforming. US Patent US6670578B2. Published 6 January 2004.
62. Clauer, A.H. (2019) 'Laser shock peening, the path to production', Metals, 9(6), 626. https://doi.org/10.3390/met9060626
63. Peyre, P., Fabbro, R., Merrien, P. and Lieurade, H.P. (1996) 'Laser shock processing of aluminium alloys. Application to high cycle fatigue behaviour', Materials Science and Engineering A, 210(1–2), pp. 102–113. https://doi.org/10.1016/0921-5093(95)10084-9.
64. Ocana, J.L., Morales, M., Molpeceres, C., Garcia, O., Porro, J.A. and Garcia-Ballesteros, J.J. (2004) 'Predictive assessment and experimental characterisation of the influence of irradiation parameters on surface deformation and residual stresses in laser shock processed metallic alloys', Proceedings of SPIE 6606. https://doi.org/10.1117/12.548859.
65. Metal Improvement Company LLC (Curtiss-Wright) (2012) Self-seeded single-frequency laser peening method and apparatus. US Patent US8207474B2. Published 26 June 2012.
66. Metal Improvement Company LLC (Curtiss-Wright) (2014) Active beam delivery system with variable optical path segment. US Patent US8698040B2. Published 15 April 2014.
67. Curtiss-Wright Corporation (2008) Curtiss-Wright awarded laser peen contract from Boeing. Press release, 14 January 2008.
68. Lawrence Livermore National Laboratory (2012) Fifteen scientists, engineers to be inducted into LLNL Entrepreneurs Hall of Fame. News release, 11 October 2012.
69. Lawrence Livermore National Laboratory (2017) 'Ready, set, innovate! Entrepreneurship flourishes at the Laboratory', Science & Technology Review, June.
70. Li, Y., Rong, Q., Shi, Z., Sun, X., Meng, L. and Lin, J. (2019) 'An accelerated springback compensation method for creep age forming', International Journal of Advanced Manufacturing Technology, 102, pp. 121–134. https://doi.org/10.1007/s00170-018-3175-3.
71. Pan, R., Wang, P., Jiang, S., Yang, W., Wu, P., Qiao, J., Chen, G. and Wu, G. (2023) 'Effect of lattice constants and precipitates on the dimensional stability of rolled 2024Al during isothermal aging', Materials, 16(4), 1440. https://doi.org/10.3390/ma16041440.
72. Starke, E.A. Jr and Staley, J.T. (1996) 'Application of modern aluminium alloys to aircraft', Progress in Aerospace Sciences, 32(2–3), pp. 131–172. https://doi.org/10.1016/0376-0421(95)00004-6.
73. Yang, Y., Jin, L., Du, J., Li, L. and Yang, W. (2020) 'Residual stress relaxation of thin-walled long stringer made of aluminum alloy 7050-T7451 under transportation vibration', Chinese Journal of Mechanical Engineering, 33, 39. https://doi.org/10.1186/s10033-020-00456-0.
74. Yao, C., Ma, L., Du, Y., Ren, J. and Zhang, D. (2017) 'Surface integrity and fatigue behavior in shot-peening for high-speed milled 7055 aluminum alloy', Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 231(2), pp. 243–256. https://doi.org/10.1177/0954405415573704.
75. Prevéy, P.S. (1986) 'X-ray diffraction residual stress techniques', in ASM Handbook, Volume 10: Materials Characterization. Materials Park, OH: ASM International, pp. 380–392.
76. Prime, M.B. (2001) 'Cross-sectional mapping of residual stresses by measuring the surface contour after a cut', Journal of Engineering Materials and Technology, 123(2), pp. 162–168. https://doi.org/10.1115/1.1345526.
77. Guo, J., Fu, H., Pan, B. and Kang, R. (2021) 'Recent progress of residual stress measurement methods: A review', Chinese Journal of Aeronautics, 34(2), pp. 54–78. https://doi.org/10.1016/j.cja.2019.10.010.
78. Withers, P.J. and Bhadeshia, H.K.D.H. (2001) 'Residual stress. Part 1 – Measurement techniques', Materials Science and Technology, 17(4), pp. 355–365. Available at: https://doi.org/10.1179/026708301101509980.

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 15 June 2026 doi:10.20944/preprints202605.1979.v2

79. Seger, M., Mathews, R., Marais, D., Venter, A.M., Halley, J., Wang, J. and Malik, A. (2024) 'Effects of aluminum plate initial residual stress on machined-part distortion', *Journal of Manufacturing Science and Engineering*, 146(10), 101006. https://doi.org/10.1115/1.4066155.
80. Almen, J.O. and Black, P.H. (1963) Residual Stresses and Fatigue in Metals. New York: McGraw-Hill.
81. Wohlfahrt, H. (1984) 'The influence of peening conditions on the resulting distribution of residual stress', in Proceedings of the 2nd International Conference on Shot Peening (ICSP-2), Chicago, USA. Oberursel: DGM Informationsgesellschaft Verlag, pp. 316–331.
82. Juvinall, R.C. (1967) Engineering Considerations of Stress, Strain, and Strength. New York: McGraw-Hill.
83. Waterhouse, R.B. (1972) Fretting Corrosion. Oxford: Pergamon Press.
84. Champaigne, J. (2001) Shot peening overview. Mishawaka, IN: Electronics Inc./The Shot Peener. Available at: https://www.shotpeener.com/library/pdf/2001012.pdf.
85. Troka, A.G. (1972) 'Shot-peening contour-forms and strengthens wing skin', Metal Fabricating, September. Available at: https://www.shotpeener.com/library/pdf/1972014.pdf.
86. Pennell, M.L. (1954) 'Design considerations of the Boeing Model 707'. SAE Technical Paper 540137. https://doi.org/10.4271/540137.
87. Airbus (2003) UK's biggest new factory opens at Airbus, Broughton. Press release.
88. Inforzato, D.J., Costa Junior, P.R., Fernandez, F.F. and Travessa, D.N. (2012) 'Creep-age forming of AA7475 aluminum panels for aircraft lower wing skin application', Materials Research, 15(4), pp. 596–602. https://doi.org/10.1590/S1516-14392012005000080.
89. Embraer S.A. (2020) Methods for producing creep age formed aircraft components. US Patent US20200222967A1. Published 16 July 2020.
90. Commercial Aircraft Corp of China Ltd. and Shanghai Aircraft Manufacturing Co. Ltd. (2012) Creep age forming method of integral wing panel. Chinese Patent CN101988146B. Published 5 September 2012.
91. Wagoner, R.H., Lim, H. and Lee, M.-G. (2013) 'Advanced issues in springback', International Journal of Plasticity, 45, pp. 3-20. https://doi.org/10.1016/j.ijplas.2012.08.006.
92. Shen, R., Zheng, J., Zheng, Y. and Wang, Y. (2021) 'Research progress on creep age forming technology of large integral aluminium alloy panel for aviation', Journal of Plasticity Engineering, 28(3), pp. 1–15.
93. Schijve, J. (2009) Fatigue of Structures and Materials. 2nd edn. Dordrecht: Springer. ISBN 978-1402068072.
94. Huang, H., Niu, J., Xing, X., Lin, Q., Chen, H. and Qiao, Y. (2022) 'Effects of the shot peening process on corrosion resistance of aluminum alloy: A review', Coatings, 12(5), 629. https://doi.org/10.3390/coatings12050629.
95. Benedetti, M., Fontanari, V., Scardi, P., Ricardo, C.L.A. and Bandini, M. (2009) 'Reverse bending fatigue of shot peened 7075-T651 aluminium alloy: The role of residual stress relaxation', International Journal of Fatigue, 31(8–9), pp. 1225–1236. https://doi.org/10.1016/j.ijfatigue.2008.11.017.
96. Gao, Y.K. (2011) 'Improvement of fatigue property in 7050-T7451 aluminum alloy by laser peening and shot peening', Materials Science and Engineering A, 528(10–11), pp. 3823–3828. https://doi.org/10.1016/j.msea.2011.01.077.
97. Rodopoulos, C.A., Romero, J.S., Curtis, S.A., de los Rios, E.R. and Peyre, P. (2003) 'Effect of controlled shot peening and laser shock peening on the fatigue performance of 2024-T351 aluminum alloy', Journal of Materials Engineering and Performance, 12(4), pp. 414–419. Available at: https://doi.org/10.1361/105994903770342944.
98. Ramati, S., Levasseur, G. and Kennerknecht, S. (2000) 'Single piece wing skin utilization via advanced peen forming technology', in Proceedings of the 7th International Conference on Shot Peening (ICSP-7), Warsaw, Poland, 28-30 September 2000, pp. 1-17.
99. Airbus (2024) Airbus in the United Kingdom. Available at: https://www.airbus.com/en/about-us/our-worldwide-presence/airbus-in-europe/airbus-in-the-united-kingdom (Accessed: 23 April 2026).
100. Airbus Operations GmbH (2019) Method, use, system, and mobile laser shock treatment station for laser shock peening of metallic structures. US Patent Application US20190118302A1. Published 18 April 2019.
101. Alnan Aluminium Inc. (2021) Online regulation and control method and system for residual stress of aviation aluminum alloy pre-stretching plate. Chinese Patent CN109735780B. Published 12 February 2021.

102. Avco Corp. (1972) Low penetration ball forming process. US Patent US3705511A. Published 12 December 1972.
103. AVIC Beijing Aeronautical Manufacturing Technology Research Institute (2020) Die mechanism, apparatus, and method for shaping a component for creep-age forming. US Patent US10875074B2. Published 29 December 2020.
104. Central South University (2013) Forming plate-type mechanical-load creep age forming tool. Chinese Patent CN102266887B. Published 2013.
105. Central South University (2020) A creep age forming method for large thin-walled components. Chinese Patent CN111195677B. Published 2020.
106. Constellium SE (2013) Aluminium-lithium alloy with improved strength and low density for aerospace structural applications. US Patent US8366839B2. Published 5 February 2013.
107. Curtiss-Wright Surface Technologies (n.d.-a) Laser peening and laser peen forming. Capability pages. Accessed April 2026.
108. Curtiss-Wright Surface Technologies (n.d.-b) Shot peen forming. Capability page.
109. Curtiss-Wright Surface Technologies (n.d.-c) Shot peening applications. 10th edn. Technical applications guide. Accessed April 2026.
110. Dursun, T. and Soutis, C. (2014) 'Recent developments in advanced aircraft aluminium alloys', Materials and Design, 56, pp. 862–871. Available at: https://doi.org/10.1016/j.matdes.2013.12.002.
111. Shanghai Jiao Tong University (2015) Method and device for thermal-assisted laser peen forming. Chinese Patent CN105033462A. Published 2015.
112. Shanghai Aircraft Manufacturing Co., Ltd. (2026) Inverse simulation method for obtaining initial flattening model for shot peen forming. European Patent Application EP4703951A1. Published 4 March 2026.
113. Hu, Y., Gong, C., Yao, Z. and Hu, J. (2010) 'Investigation on the non-homogeneity of residual stress field induced by laser shock peening', Surface and Coatings Technology, 205(2), pp. 136–144. Available at: https://doi.org/10.1016/j.surfcoat.2009.04.029.
114. Lam, A.C.L., Shi, Z., Lin, J., Huang, X., Zeng, Y., and Dean, T.A. (2015a) 'A method for designing lightweight and flexible creep-age forming tools using mechanical splines and sparse controlling points', International Journal of Advanced Manufacturing Technology, 80, pp. 361–372. https://doi.org/10.1007/s00170-015-6982-9.
115. Lockheed Aircraft Corp. (1966) Stretch forming apparatus and method. US Patent US3238753A. Published 8 March 1966.
116. McMurray, R.J., Leacock, A.G. and Brown, D. (2011) 'The Influence of Through-Thickness Material Property Variation on Stretch Forming Springback', Key Engineering Materials, 473, pp. 436–443. https://doi.org/10.4028/www.scientific.net/KEM.473.436.
117. AVIC Beijing Aeronautical Manufacturing Technology Research Institute (2016) Shot peen forming method realizing torsional deformation of high-rib integral panel. Chinese Patent CN105598851A. Published 25 May 2016.
118. AVIC Beijing Aeronautical Manufacturing Technology Research Institute (2015) Wallboard creep age forming method based on finite element. Chinese Patent CN102930115B. Published 2015.
119. Jilin University (2016) Aluminium alloy aircraft integral panel multi-point forming method. Chinese Patent CN104646475B. Published 2016.
120. Northwestern Polytechnical University (2017) Positioner and method for wall-panel parts. Chinese Patent CN106955930A. Published 2017.
121. Pangborn Corp. (1987) Method and apparatus for imparting a simple contour to a workpiece. US Patent US4694672A. Published 22 September 1987.
122. Polmear, I.J., StJohn, D., Nie, J.-F. and Qian, M. (2017) Light Alloys: Metallurgy of the Light Metals. 5th edn. Oxford: Butterworth-Heinemann. ISBN 978-0080994314.
123. Rohr Inc. (2008) Stretch forming method for a sheet metal skin segment having compound curvatures. US Patent US7340933B2. Published 11 March 2008.
124. SAE International (2022) *SAE AMS2432E: Shot Peening, Computer Monitored*. Warrendale, PA: SAE International.

125. SAE International (2012) *SAE AMS2430S: Shot Peening, Automatic*. Warrendale, PA: SAE International.
126. SAE International (2022) Test Strip, Holder, and Gage for Shot Peening. SAE Standard J442_202205. Warrendale, PA: SAE International. https://doi.org/10.4271/J442_202205.
127. SAE International (2025) *Procedures for Determining and Verifying Peening Intensity*. SAE Standard J443_202512. Warrendale, PA: SAE International.
128. Schwarzer, J., Schulze, V. and Vöhringer, O. (2003) 'Finite element simulation of shot peening: a method to evaluate the influence of peening parameters on surface characteristics', in Wagner, L. (ed.) Shot Peening: Proceedings of the 8th International Conference on Shot Peening. Weinheim: Wiley-VCH, pp. 508–515. https://doi.org/10.1002/3527606580.ch65.
129. Zheng, K., Politis, D.J., Wang, L. and Lin, J. (2018) 'A review on forming techniques for manufacturing lightweight complex-shaped aluminium panel components', International Journal of Lightweight Materials and Manufacture, 1(2), pp. 55–80. https://doi.org/10.1016/j.ijlmm.2018.03.006.