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Review

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

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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 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. A structured narrative method is used because the evidence base combines peer-reviewed papers, SAE Technical Papers, patents, trade literature, government reports and supplier disclosures. 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 strongest public evidence supports peen and particle-impact routes for directional or inflected lower-cover geometry, CAF for large smooth heat-treatable covers, laser peen forming for specialised thick or stiff panels, and hybrid routes where no single mechanism closes the full contour.

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

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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 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 five periods: process origins before routine aircraft use; industrial establishment (approximately 1950–1972); widebody scale challenge (1972–1990); CAF and integral-panel/property-management maturity (1990–2010); and specialisation/composite transition (2010–present). These period 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. [18], 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 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. A PRISMA-style systematic review is not appropriate because the relevant evidence includes patents, SAE Technical Papers, trade articles, official supplier disclosures 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 structured method used here is therefore designed to make source selection, evidence grading and claim attribution auditable rather than to aggregate comparable experimental results. Searches were updated through April 2026.

Searches combined aircraft-family names, manufacturer names, and process terms such as shot peen forming, stress peen forming, ball forming, laser peen forming, creep age forming, stretch forming, integral panel, wing skin, wing cover, and residual stress. Scholarly searching was undertaken across Google Scholar, SAE Mobilus, ScienceDirect, SpringerLink and publisher-hosted journal platforms represented in the bibliography. Patent searching used public patent-family databases including Google Patents and Espacenet. Industrial searching was restricted to official manufacturer or supplier sources, laboratory disclosures, and archived industrial papers with identifiable provenance. A structured summary of source domains, query families, and retention rules is provided in Supplementary Table S1.

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, 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 Table 3A and 3B, upper and lower evidence are recorded separately.

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; and Dev. patents claim compensation, control, residual-stress management, microstructural control, or analysis-enabled process design. Patents are used to establish capability and development logic, not as proof of serial production without corroborating programme or supplier evidence.

Table 2A synthesises the principal contour-forming routes, Table 2B isolates upstream stock-state conditions, Table 3A and 3B capture the aircraft-level attributions retained in the main manuscript, and Appendix A provides the corresponding aircraft-manufacturer lineage map. Lower-evidence boundary cases, extended catalogues, source-status notes, and cross-source observations are retained in the supplementary material to preserve traceability without overloading the main article.

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Where the literature is conflicting or does not unambiguously separate upper and lower covers, the more conservative attribution has been retained and the limitation is stated explicitly in the relevant aircraft table. Source-type convergence is used as supporting context only: claims supported by independent combinations of patents, academic papers, supplier disclosures and programme histories are treated as more robust than claims supported within a single source class alone.

Grey literature declaration. Commercial supplier pages and institutional communications are used only for application lineage, stated supplier capability or facility context where no stable technical publication is available. Core mechanics claims are anchored in peer-reviewed papers, SAE Technical Papers, patents, standards, or government/committee reports. Detailed source-status notes are provided in the supplementary material.

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 straddles 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.

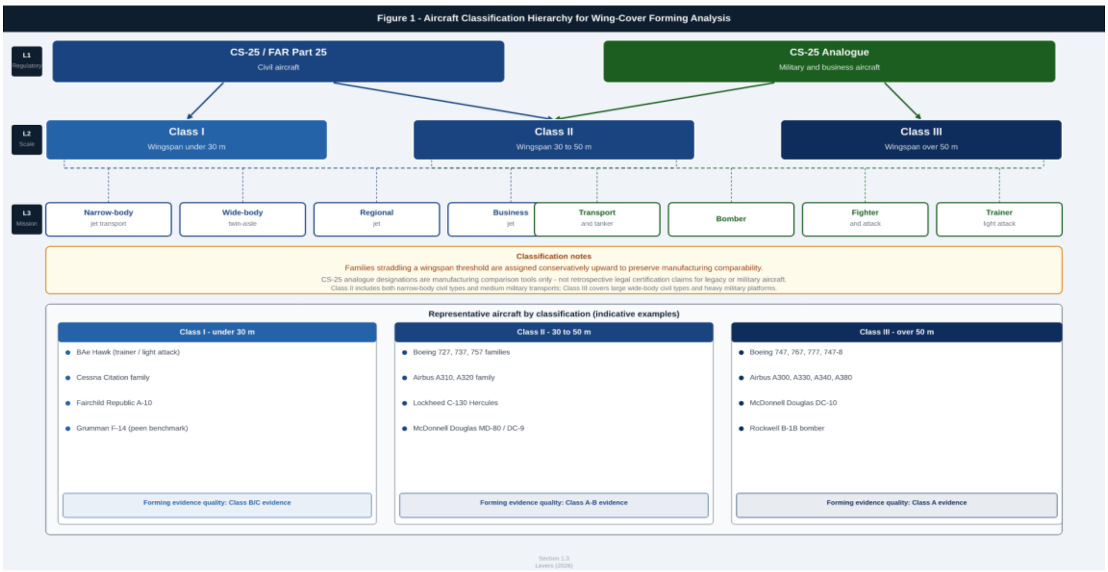

Figure 1 - Aircraft Classification Hierarchy for Wing-Cover Forming Analysis

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Figure 1. Hierarchical classification framework for aircraft considered in the wing-cover forming analysis. Scale classes are assigned conservatively upward for families straddling thresholds. CS-25 analogue designations are used for manufacturing comparison only. 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 1 summarises these classes and their principal process implications.

Table 1. 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.
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.

Figure 2. Curvature taxonomy for metallic wing covers with indicative forming-route thickness operating ranges. Spanwise and chordwise profiles are schematic. Stretch forming is limited to single-curvature sheets to approximately 6 mm. CAF is restricted to precipitation-hardening alloys in smooth large-radius compound curvature. Section 2.2 and Table 1.

The five classes in Table 1 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 2A and the aircraft-level attributions of Tables 3A and 3B: the curvature class of a wing cover largely predetermines the feasible forming routes before any consideration of panel scale, alloy, or thickness.

Table 2. (A) part 1. Mechanical and peen-forming routes. (B) Upstream stock state and precursor manufacturing conditions that condition metallic wing-cover accuracy before dedicated contour forming.

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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; US5239456A (GE/Cincinnati Milacron —corrective shaping 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
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/aerobreak work, directional correction	Limits: Fixture complexity and preload qualification burden

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]
Laser peen forming	Laser-shock-induced plastic strain under confined plasma [45,65]	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

(B)

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]
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]

Note: Table 2A 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 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. Note: Table 2B is intentionally not a process-ranking table. It isolates inherited material state from deliberate contour generation.

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].

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 five historical periods: in the establishment era (Section 5.1), peen forming was applied to relatively thin, low-alloy skins where quench stress was modest; in the CAF maturation era (Section 5.3), 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 2B makes explicit [30,32–34].

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 [35].

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

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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 [4,36]. 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. [37] 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. 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 [38]. 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

Al-Li alloys (8090, 8150 in second generation; 2099, 2196, 2050, 2055 in third generation) offer density reduction of 8–10% and stiffness improvement. 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 [39]. 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/Constellium patent evidence on thick aluminium alloy products and edge-on stress relief illustrates the broader industrial effort to tailor residual-stress and ageing response in thick plate products for aircraft structural components [32,40].

3. Section Title

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 [1,2,41,42]. 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 [24,43,44].

A brief note on a Rockwell International patent (US4567743A, 1986) for a segmented forming die for compound-curvature aircraft panels: this patent, filed by the same company that applied CAF to the B-1B in the same decade, illustrates the industrial exploration of both mechanical and thermal forming routes in parallel during the 1980s, consistent with the view that CAF was not adopted as an obvious first choice but as the solution to a mechanical forming problem that had resisted resolution by die-based methods. The Northrop Corporation stretch forming machine patent (US3757557A, 1973) occupies a parallel position: filed during the period when peen forming was becoming the dominant contouring route, it represents the concurrent industrial investment in stretch forming infrastructure that the peen forming route was displacing on large compound-curvature panels but not on simpler single-curvature forms.

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 2A and captured instead in Table 2B, where their influence on residual-stress inheritance, anisotropy, machining distortion, and downstream compensation is made explicit. The Pechiney Rhenalu patent WO2004053181A1 (2004), companion to the WO2004053180A2 edge-on stress-relief patent already cited in Section 2.4, provides the most complete single-document treatment of the wing cover manufacturing route from a material-supplier perspective, covering the coupled sequence of stock preparation, stress relief, forming, and inspection as an integrated system. It is the patent-level equivalent of the Table 2B framework: a material producer's codification that rolling, stress relief, machining, and contour forming are not independent operations but a coupled chain in which each stage affects the inputs to the next. Additionally, the aluminium plate producer community has addressed the quench residual stress problem described in Section 2.4 through a series of patents: Alcan's US20030159759A1 (2003) covers production of aerospace plate with reduced residual stress, Pechiney/Constellium's EP1288317B1 (2005) covers thick 7xxx product specifically for aircraft structural ISPs, Aleris's US7449075B2 (2008) addresses high-strength damage-tolerant 7xxx for aerospace structures, and Arconic's US20180209009A1 (2018) represents the current state of the art in 7xxx alloy processing for aerospace ISP production. Together these patents show that the material-producer community was independently addressing the inherited stock state problem that Section 2.4 identifies as a key forming-process variable.

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

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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 [5–7,9,10,45]. 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 [46,47].

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 [4,12,24,39,48,49]. 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 [4,50].

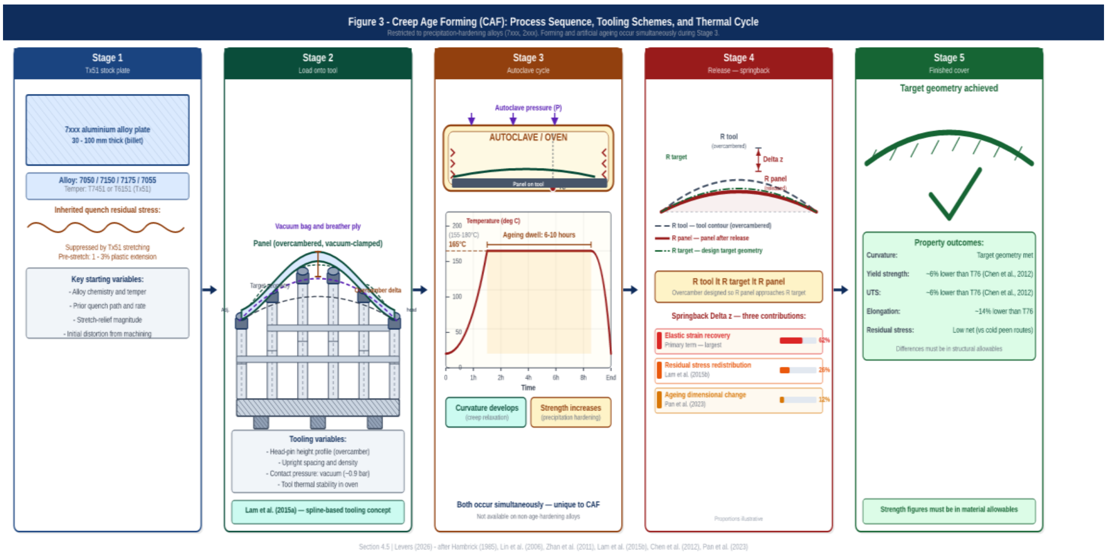

Figure 3. Creep age forming process sequence and springback compensation logic. The red dashed feedback loop from Stage 4 to Stage 2 represents iterative tool compensation. Concurrent ageing in Stage 3 raises yield strength simultaneously with curvature development. Section 4.5, after Hambrick [23], Lin et al. [12], and Zhan et al. [4].

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.

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 [14,29,51,52].

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 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 [56] and applied systematically to peening by Kang et al. [54] 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. [54] 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

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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 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 [53], on titanium aerospace panels (Schulze et al., 2006), on early ISP peening modelling [54], and by the most recent industrial patent from AVIC First Aircraft Institute (MHI JP2002361338A; CN113305176B, AVIC, 2022). The most recent industrial articulation of this spatially varying correction problem is CN113305176B (AVIC First Aircraft Institute, 2022), which explicitly addresses shot peen forming of large aircraft ISPs by controlling the curvature gradient across stiffness transitions, confirming that the ISP heterogeneity problem identified in the academic literature of the 2000s remains an active area of industrial development into the 2020s. From the Airbus perspective, EP2189228B1 [55] connects shot peening of structural aircraft components to both fatigue life management and panel contouring within a single industrial framework, consistent with the dual-purpose (forming + fatigue) interpretation of peen-based routes developed in Section 8.4. The Yamada et al. [53] work was conducted at Mitsubishi Heavy Industries and relates to shot peening of integral wing skins for Continental Business Jets; the companion MHI patent JP2002361338A provides the process protection context for the same ISP shot-peening work. The same manufacturing infrastructure at MHI is relevant to the Mitsubishi F-2 fighter programme, which is carried in Supplementary Table S3.

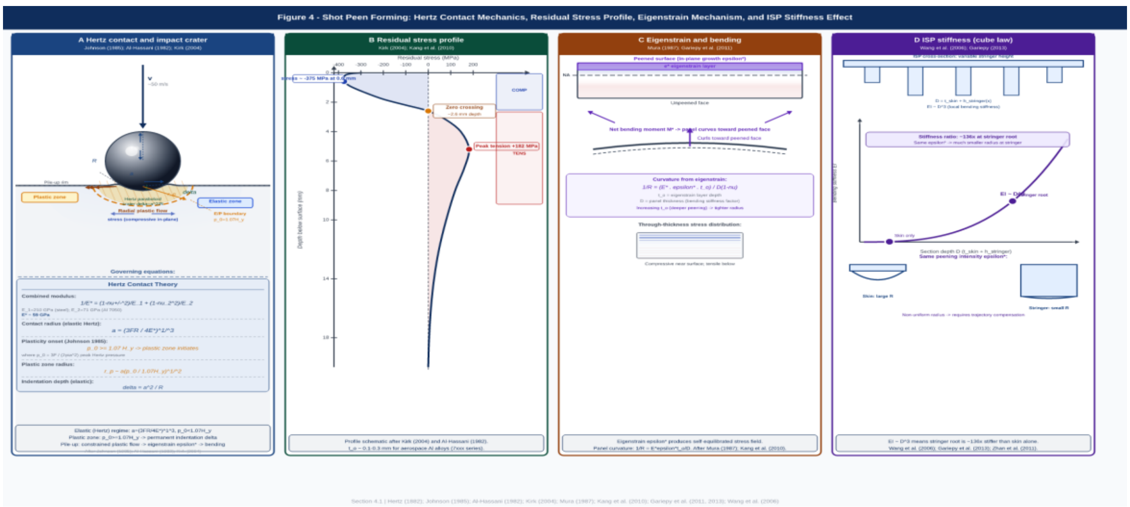

Figure 4. Eigenstrain mechanism in shot peen forming: (1) shot impact with radial plastic flow; (2) constrained eigenstrain layer formation; (3) self-equilibrated residual stress profile — compressive near the surface, balancing tension deeper; (4) net panel bending toward the peened face. The ISP stiffness note illustrates the cube-law reduction in curvature response at thicker stringer root regions. Section 4.1, after Mura [56], Al-Hassani [5], and Kang et al. [54].

Industrial control is therefore a problem of mapping required curvature onto a controlled combination of Almen intensity (SAE J442/J443), coverage, shot size, velocity, incidence angle, stand-off, pass count, and trajectory. Fathallah et al. [57] 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. [59] 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. [58] 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 [11,57,58]. 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 [7,46,47]. Industrial patent literature codifies the same conclusion: US5239456A (GE/Cincinnati Milacron, 1993) claims corrective shaping of metal parts by peening, formalising the measure-and-correct loop as a production process step, while US20080083265A1 [60] covers a closed-loop peen forming system with in-process measurement feedback, the patent 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]. Mylonas and Labeas [61] 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 [51]. Sonaca's US9114449B2 (2015) extends this work to sharper aerobreak transitions, wing geometry with more abrupt directional changes than the smooth V-zones of the original ISP patent, confirming that the directional peen forming approach remained an active area of industrial patent development into the current period. At the tooling level, US5826453A (General Dynamics/Lockheed Martin, 1998) claims a pre-loading fixture specifically designed for shot peen forming of metal parts, providing the production hardware context for the prestress concepts analysed here.

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. [62] 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

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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 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. [63], 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 in excess of the dynamic yield stress of aerospace aluminium alloys (typically 300–500 MPa at high strain rates for 7xxx alloys, see Ding and Ye [64], 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 [63,64]. 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 [45], US6410884B1, and Hackel, Halpin and Harris [65], US6670578B2, supplemented by the standard process monograph Ding and Ye [64], peer-reviewed characterisation by Clauer [66], and materials response studies by Peyre et al. [67].

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. [68] 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 [45,65,68].

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 has reached the same conclusion comes from two non-Boeing sources: GE Aviation's US10207306B2

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(2019) covers laser shock peening of curved aerospace workpieces, extending the process to the turbine and structural components context where GE operates; and Airbus Defence and Space's EP3354753B1 (2019) explicitly covers laser shock peening for forming metallic aeronautical structural panels, an Airbus programme-assignee patent that confirms European aerospace independent adoption of the LLNL/MIC technology, not derived from the Boeing lineage. The simultaneous filing of laser peen forming patents by Boeing (via Curtiss-Wright), GE Aviation, and Airbus D&S in the 2015–2021 window, with no visible cross-citation between the Airbus and Boeing streams, indicates that the process was being industrially developed in parallel rather than transferred linearly. The Chinese NPU patent CN110202062B (2020) adds a fourth independent stream, addressing laser peen forming of aircraft ISPs with complex curvature within the same period. 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 [21,45,65]. The material window extends beyond aluminium: US7321105B2 [69] covers processing of titanium alloys and other metals using laser shock peening, broadening the applicable alloy range. US8334477B2 [70] covers low-intensity laser pulse variants, which reduce surface roughness penalties and are relevant to clad skin and aerodynamic surface applications discussed in Section 8.4. 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 [71–73].

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 [30,39].

Structurally, CAF is a low-inelastic-strain bending process with strong time dependence. The through-thickness stress field begins approximately elastic, relaxes progressively during the dwell, and then partially recovers on unloading, which is why springback remains the central process problem. The constitutive framework for predicting this behaviour was established through material characterisation experiments [74] and the resulting constitutive model [36], who developed a unified creep-ageing constitutive law that couples power-law creep, precipitation kinetics, and changing yield strength into a single consistent set of differential equations, the foundational model that Lin, Ho and Dean [12] then applied to springback prediction in a bending context. Lin and co-workers showed that accurate springback prediction requires the simultaneous treatment of all three coupled phenomena (creep, ageing kinetics, changing modulus or strength) rather than any two in isolation, while Jeong et al. [76] provided further experimental validation of creep-springback coupling using 7xxx alloys, and Lam et al. [39] showed that initial distortion and machining-induced residual stress can materially bias springback if the blank is treated as stress-free. The full constitutive framework, covering creep, ageing kinetics, and springback compensation, is reviewed comprehensively by Zhang et al. [20]. These constitutive and tooling models were developed within the Age Form

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programme, a major EPSRC-funded collaborative research initiative between the University of Manchester (Dean, Lin and co-workers), Airbus UK, Textron Aerostructures, and BAE Systems, whose explicit industrial objective was to provide the scientific underpinning for large-ISP CAF at the scale required for the A380 upper cover (Dean and Lin, 2005; Zhan et al. [4]). The programme is important contextually because it confirms that CAF was an industrial production process (Avco/B-1B, Textron/A330–A340) for over a decade before the academic constitutive framework that is now used to predict its behaviour was formally established, the practical capability preceded the theoretical explanation. In industrial practice this means that tool compensation is not a single geometric overbend but a calibrated correction against the final unloaded part, usually combining empirical trials, constitutive modelling, and sparse-point or spline-based flexible tooling [39,49,75].

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 [77].

Stress-ageing studies on Al–Cu (2xxx) alloys show that applied stress can influence precipitation and yield response relative to stress-free ageing [38]. 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 [78]. 7xxx-specific age-forming work, including Chen et al. [37] 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 [78].

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 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 3B qualification note).

Table 3. (A) Core aircraft-level mapping of metallic wing-cover forming routes in commercial transport and business aircraft. (B) Core aircraft-level mapping of metallic wing-cover forming routes in military fixed-wing aircraft.

(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)
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)

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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)
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)
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)
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)

(A) part 2. Curvature/process route, patent anchor and qualification note.

Aircraft / programme	Curvature / process route	Patent anchor	Qualification / limitation
Lockheed Constellation	SuperSmooth transport large-radius curvature; shot peen forming of formed skin sheets	Nondirect	MIC/Champaigne [91] 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.
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.

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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 [45,71]	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 per Implementation 3 audit.
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.
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	US5168169A (Textron Aerostructures, Proc.); EP0689479B1 (BAe, Proc./Tool.) adjacent	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). Key patents: US5168169A (Textron), EP0689479B1.

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Airbus A340	Large smooth upper covers and stiff metallic lower panels; split CAF/peen route	US5168169A (Textron Aerostructures, Proc.); EP0689479B1 (BAe, Proc./Tool.) adjacent	Same upper/lower split as A330; upper covers formed at Textron Aerostructures Nashville (AERAC programme). Key patents: US5168169A, EP0689479B1.
Airbus A380	Very large smooth metallic covers; split CAF/peen route	US7195203B2; US20080042011A1 (Adj.)	Broughton skin-and-creep facilities [95] anchor the A380 upper-cover case. Distinct from A330/A340, which were formed at Textron Aerostructures Nashville under the AERAC programme.
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 [50] 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.); CN102974674B (NPU, Tool.); CN103962436B and CN108543866B (Tool. /Proc.); CN110202062B (laser peen, adjacent).	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.

(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)
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)

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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][23] primary source)	Named-aircraft SAE Technical Paper (A/B) — Hambrick primary production disclosure; NRC [50] secondary synthesis	Autoclave age-formed lower wing skins (Class A: Hambrick [23][23] primary source)	Named-aircraft SAE Technical Paper (A/B) — Hambrick primary production disclosure; NRC [50] 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)

(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 [92] 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.	US5649728A (Rockwell/Boeing, Proc.) — programme-lineage age-forming patent	Hambrick [23] provides direct panel geometry and autoclave age-forming route; NRC [50] is secondary. Key patent: US5649728A.
BAe Hawk family	Trainer/light-combat upper panel with smooth compound curvature; CAF	EP0689479B1 (British Aerospace / BAE Systems, Proc./Tool.) — programme-adjacent CAF patent	Hawk upper-panel CAF is repeatedly cited in modelling and review literature (Jeunechamps et al. Key patents: EP0689479B1.

Note: Tables 3A and 3B separate upper and lower evidence because public aircraft records are often asymmetric. Class A = direct serial-production or supplier/manufacturer disclosure. Class B = named-

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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. Note: Non-transport military aircraft retained only where they materially illuminate forming-process development or transfer. Antonov An-124/225 relocated to Supplementary Table S5 (see Implementation 10 note). Lower-evidence fighter and patrol comparators summarised in Supplementary Table S3.

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 [14,24,50].

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 [14,15,50].

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 [31,79].

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), 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 [80]. 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 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 (Curtiss-Wright Surface Technologies, n.d.-b). 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 [11,46], 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. (2011, 2013), Miao et al. (2010, 2011), and the industrial guidance of Curtiss-Wright Surface Technologies (n.d.-b, n.d.-c).

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 [39,77]. Support density affects the through-thickness pressure distribution

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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.

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 [37], 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. [39] 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. (2015a, 2015b), and Li et al. [75]. 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. [83] and Withers and Bhadeshia [84] 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 [81] 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 [82], 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 [81–83].

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. [85] 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 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 [82], 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 across five chronological periods. The periodisation is the analytical lens, not the subject: each sub-section asks what changed in the nature of the manufacturing problem in that period, and what the public evidence shows about how industry responded. The period 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 3A for commercial transport and business aircraft and Table 3B 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 2A and in the variable discussion of Section 4.7.

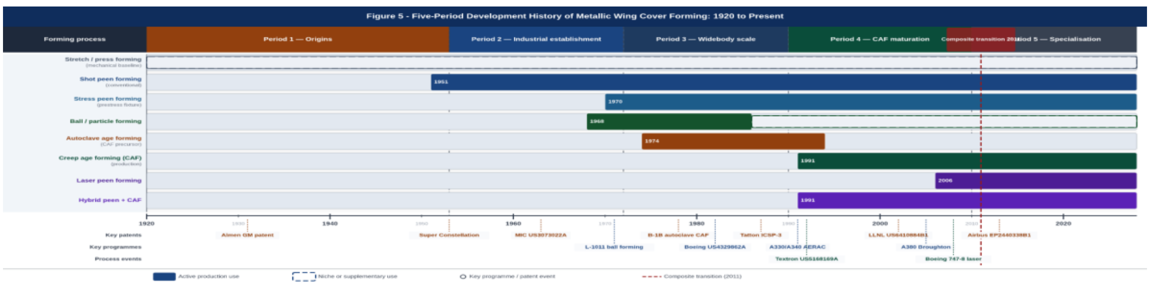

Figure 5. Five-period development history of metallic wing cover forming, 1920 to present. Process and patent events above the timeline; aircraft programme milestones below. The vertical dashed red line marks the composite transition point (2011). Sections 5.0 to 5.4a and Section 8.1.

5.1. Origins and Pre-Industrial Context (1920S to ~1953)

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 [86]. 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 [87] 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 identifiable patent for aircraft skin contouring is US1872384A [88], which describes stretch forming of aircraft sheet panels over wooden bucks; a contemporaneous Budd Manufacturing patent (US2014799A, 1935) covers stretch-press forming of curved aircraft panels. By 1938, Curtiss-Wright had patented multi-hit bump forming for compound-curvature aircraft skins (US2132002A), the method that would become the principal wartime contouring technique. Lockheed's US2366164A (1945) represents the last major purely mechanical contouring patent before peen forming adoption; it describes controlled tensile stretch forming of aircraft sheets, the immediate precursor to the Cyril Bath and Lockheed production machines (US3238753A, 1966) already cited in Section 3.1. 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 [90], 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 [89].

The patent record provides a finer-grained account of the transition. John O. Almen's first GM patent (US1828869A, 1931) established shot peening as a controlled industrial process with defined media and velocity parameters; his second (US2028874A, 1936) introduced the concept of controlled shot blast parameters as process variables, the conceptual ancestor of the Almen intensity system.

Pangborn Corporation, the industrial peening equipment manufacturer whose later patent US4694672A (1987) is already cited in Section 4.1, patented shot peening for surface stress improvement in 1944 (US2350440A), establishing the wartime industrial infrastructure. Metal Improvement Company's first identifiable patent for aircraft components (US2619820A, 1952), filed in the same year as the likely Lockheed Super Constellation production adoption, establishes MIC's institutional presence in aircraft peening. MIC's subsequent US2702951A (1955) is the first patent explicitly for shot peening of aircraft wing skins, providing the patent-level anchor for the Lockheed production account. The earliest confirmed application of shot peen forming to aircraft wing covers is at Lockheed in the early 1950s, documented retrospectively by MIC/Curtiss-Wright supplier literature (Champaigne [91]; US2702951A) and treated by Moore [3] as the industrial origin point. The significance of this transition, from peening as a fatigue treatment to peening as a contouring mechanism, should not be understated. It transformed a metallurgical surface process into a structural manufacturing route, and in doing so created the industrial foundation on which all subsequent wing-cover forming technology described in this review rests.

The industrial adoption of shot peen forming in production aerospace programmes from the early 1950s is described in Section 5.1.

5.2. Industrial Establishment and Early Programme Adoption (~1950–1972)

The period from the early 1950s to approximately 1972 is defined by the transformation of peen forming from an experimental curiosity 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 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 period 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 patent record marks this transition precisely: MIC's US3073022A (1963) is the first apparatus patent specifically for using peening to form (contour) a curved surface rather than to treat a flat one, the institutional and intellectual separation of peen forming from peen treating, codified in IP a decade before it appears in the open technical literature. US3475945A (1969) covers a general shot-peening apparatus that formed the production hardware basis for early contouring applications. MIC's subsequent US3668912A (1972) covers trajectory-controlled contouring apparatus for aircraft panels, contemporaneous with the Troka [92] trade account of F-15, 747, and L-1011 wing-skin peening that represents the first published evidence of the industrial breadth of the route. Metal Improvement Company documentation, archived in ICSP proceedings and supplier literature, traces shot peen forming of wing skins to the Lockheed Super Constellation in the early 1950s, and the wider peen-forming literature treats early Lockheed practice as the industrial origin point [3,87,91]. In this phase the decisive innovation was the recognition that intentionally induced residual stress could function as a forming mechanism; the process mechanics were not yet understood analytically in the way Al-Hassani [5] and Kirk [6] would later formalise them, but the industrial result was reliable enough to commit to production.

Evidence from this first period 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 the 1970s programmes could adopt an already industrial, rather than merely experimental, process family [3,91]. 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 S2 as transitional-era comparators for which no separate forming-route disclosure has been located.

An important control case in this first period 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 S2 rather than a core Table 3A programme. This distinction matters methodologically: temporal proximity to a known process adoption is not the same as evidence of that adoption [93]. 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 and retained in Supplementary Table S2. 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 S2 as mechanically formed and machined boundary cases; available sources support their construction methods but do not confirm serial shot peen forming or CAF for the upper or lower covers.

5.3. Widebody Scale Challenge and Process Diversification (~1972–1990)

The widebody era, beginning with the DC-10 first flight in 1970, the L-1011 in 1970, and the 747 entering service in January 1970 (first flight February 1969), transformed the scale of the wing-cover forming problem and, in doing so, sharpened the public record considerably. Where the establishment period (Section 5.1) normalised peen forming, this third period 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, is less detailed. The DC-10 evidence class has accordingly been separated in Table 3A, with Class A for the lower cover (where Moore provides the most explicit production evidence) and Class B for the upper cover. The same production lineage also supports later continuity into the DC-9-80 / Super 80 family, although the public record is less explicit in separating upper and lower covers there [3].

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 process route; the L-1011 entries in Table 3A 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 [92] 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 Table S3, while the core military transport and benchmark cases remain in Table 3B [13,92]. The aircraft named in Troka's account, the Grumman F-14 Tomcat (NC shot-peening of centre section), Grumman A-6 Intruder (MIC peen-formed centre-section covers), Northrop F-5 Freedom Fighter (wing skins), and Lockheed S-3 Viking (anti-submarine patrol wing skins), are all carried in Supplementary Table S3 with Class B or C attributions reflecting their trade-source provenance. The Grumman F-14 merits brief separate note: its variable-geometry wing box required shot peening of a structurally complex centre-section carry-through structure rather than conventional wing-skin contouring, which explains why the forming evidence is cited at the component rather than cover level.

5.4. Integral Panel and Property Management: CAF Maturation (~1990–2010)

The fourth period, running from approximately 1990 to 2010, is the era in which integrally stiffened panels and high-strength aluminium alloys imposed property-management constraints alongside geometry constraints for the first time. Where the widebody period asked whether peen forming could produce the required shape, this period asked whether the resulting material state, residual stress, surface integrity, and precipitate structure, was 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 period 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 changes, and the National Research Council [50] subsequently summarised production experience on both upper and lower B-1B skin panels in a committee review report (treated here as a secondary synthesis corroborating Hambrick's primary data). Airbus A330/A340 upper covers are the clearest public civil CAF benchmark: Vogeli et al. [16], a Textron Aerostructures SAE Technical Paper describing the AERAC programme (the acronym expansion is not reproduced here as it could not be verified from the abstract alone; the programme is an autoclave age-forming facility at Nashville), which directly discloses upper-cover age forming for these types, and the companion patent US5168169A [94] provides the programme-assignee process protection for the same autoclave forming methodology, while the lower covers remain within the shot-peen family. The A380 extends the same process split to a larger scale: lower covers remain associated with shot peen forming, whereas the upper covers, which are large conventional built-up panels with mechanically attached stringers rather than integrally machined ISPs, are creep-age-formed: the A380 upper covers at the dedicated Airbus UK Broughton facility [26,95], and the earlier A330/A340 upper covers at Textron Aerostructures in Nashville under the AERAC programme (Vogeli et al. [16]; US5168169A). The relationship between these two programmes is not one of technology transfer but of parallel independent development: Airbus built the Broughton A380 capability independently from 1998 (LOCOMAMS DTI programme, QinetiQ constitutive modelling,

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Aeroform autoclave concept) and reached production in 2003 without acquiring Textron's process knowledge [26]. The fact that Airbus needed a four-year engineering programme and bespoke capital infrastructure to achieve what Textron had done at Nashville for the A330/A340 is itself a confirmation that CAF production knowledge is not transferable in the conventional sense. Sources: Hambrick [23]; National Research Council, 1996; Zhan et al. [4]; Vogeli et al. [16]; Levers [26]; Airbus [95]).

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 [12,49,96].

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. Specialisation and Composite Transition (~2010–Present)

The fifth period 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 review period.

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 [71–73]. 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 S4 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 [97,98]. 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 reverse pattern (academic institution patents preceding industrial patents) identified in Section 8.7.

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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 five-period span from pre-1950 origins to the current era. 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 S5 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 F/A-18 Hornet/Super Hornet, Northrop B-2 Spirit, Boeing B-52 Stratofortress, Lockheed C-141 Starlifter, Lockheed C-5 Galaxy, McDonnell Douglas C-9, Lockheed P-3 Orion, Boeing P-8 Poseidon; British/European types, Panavia Tornado, BAC/BAe Jaguar, Eurofighter Typhoon, Dassault Mirage family, Dassault Rafale, BAe Nimrod; Soviet/Russian types, Sukhoi Su-27/30 family, Tupolev Tu-95/142, Tupolev Tu-22M/Tu-160, Ilyushin Il-76/78; and selected other national programmes, Embraer AMX/A-1 (Brazil), HAL Tejas LCA (India), Mitsubishi F-2 (Japan), KAI T-50/FA-50 (Korea). Concorde and Tupolev Tu-144 are retained in Supplementary Table S2 as mechanical-forming and machined-panel boundary cases.

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 S5 as a lineage comparator. The result is an intentionally tiered treatment: direct process cases stay in Table 3B; lower-evidence military comparator rows are shifted to Supplementary Table S3; broader transport families remain in Supplementary Table S5 unless the process route can be defended [13,50].

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 five-period span. 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 S4 catalogue. Regional transport and commuter aircraft with metallic wing covers are also carried in Supplementary Table S4, 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 metallic wing-cover manufacturing challenge in a smaller structural class and are included for completeness, but their public forming-route disclosures are either absent or insufficient for Table 3A attribution. In the main aircraft-process mapping, however, only analytically useful benchmark or boundary cases are retained. Gulfstream IV remains the strongest business-jet hybrid benchmark; HondaJet is valuable because the manufacturer discloses a machined one-piece aluminium-alloy wing skin backed by alloy ribs, but not a named contour-forming route; and the Hawker 125 remains an important long-running business-jet lineage without a disclosed serial cover-forming route.

6. Comparative Process Capability

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The aircraft-level evidence in Section 5, spanning five periods from the pre-industrial origins of peen forming through to the current composite-transition era, 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 2A compares the contour-forming routes themselves. Table 2B 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.

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

The process mechanics of Section 4, the five-period 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 3A and 3B. Aircraft-level process attribution is summarised in Table 3A for commercial transport and business aircraft and in Table 3B 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.

8. Thematic Analysis

The evidence assembled in Sections 5–7 is now interpreted thematically. Eight analytical threads are examined: the five-period 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 8.6a); and cross-source patterns in the knowledge infrastructure (Section 8.7). Section 8.8 states the principal limitations of the evidence base.

8.1. Five-Period Evolution

The evidence assembled in Sections 5 through 7 supports a five-period rather than two-period periodisation of metallic wing-cover forming: origins and pre-industrial context (pre-1950s); industrial establishment (~1950–1972); widebody scale challenge (~1972–1990); integral panel and property management (~1990–2010); and specialisation and composite transition (~2010–present). Each period is defined by a change in the manufacturing problem rather than merely a change in programme chronology. In the origins period, the decisive innovation was the recognition that induced residual stress could function as a forming resource; in the establishment period, this was industrialised across multiple manufacturers; in the widebody period, scale exposed the limits of isotropic peening and drove process diversification; in the CAF maturation period, property-management constraints were added to geometry constraints; and in the current period, the metallic wing-cover manufacturing domain is contracting while the technical demands on the remaining metallic structures are increasing. This five-period framing better explains why the later literature is richer in FE modelling, springback compensation, autoclave tooling, and hybrid process chains, these tools were developed in response to specific period-by-period manufacturing challenges, not as a steady progression [3,4,7,9,12,39].

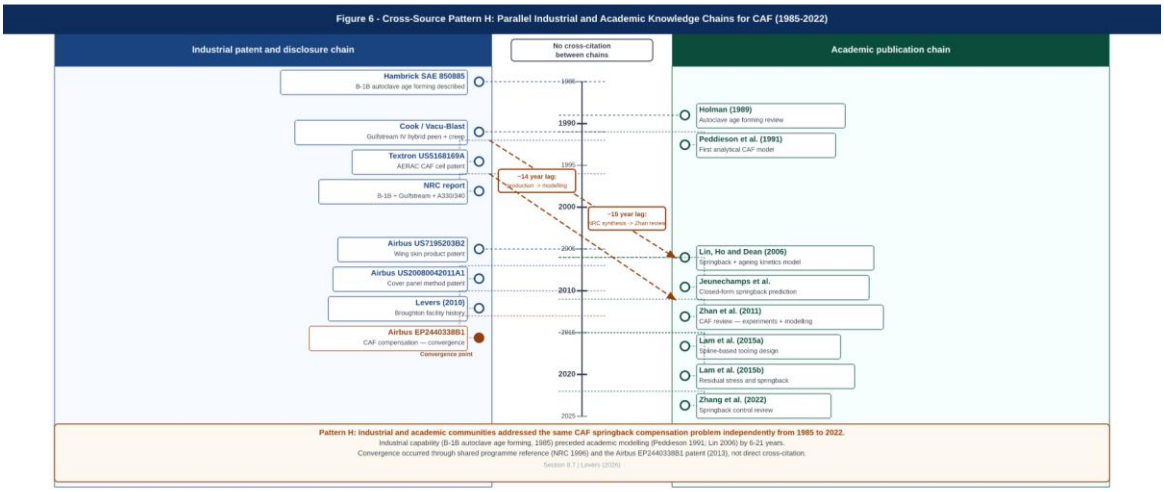

Figure 6. Cross-source Pattern H illustrated as two overlapping knowledge communities. The left circle (industrial patent chain) and right circle (academic publication chain) addressed the same CAF springback compensation problem independently from 1991 to 2015 without cross-citation. The amber overlap zone represents convergence at Airbus EP2440338B1 (2013). Section 8.7.

8.2. Upper Vs Lower Divergence

The analytical distinction between upper and lower covers introduced in Section 2.1 is confirmed by the aircraft-level evidence in Section 5. The review supports a substantive manufacturing divergence between the two covers rather than a merely semantic one. The structural architecture of the two covers reinforces this divergence. Upper covers for large transports are most consistently manufactured as large ISPs, monolithic machined plates with integral stringers running the full span, where the combination of smooth compound curvature and high bending stiffness makes CAF the natural process choice. Lower covers, even for the same aircraft, are more often partially built-up or semi-ISP in form, with heavier local machining at discrete pad and rib-attachment regions but a less uniformly stiffened skin between them; this architecture is more compatible with peen forming because the stiffness discontinuities are less severe, and the inflected lower-surface geometry requires the directional forming control that stress peen forming provides. Lower covers are therefore more often linked publicly to shot peen forming, stress-assisted peen forming, ball forming, or rolled-and-machined routes combined with mechanical preforming. Upper covers in large civil transport programmes, where ISP architecture predominates, are the clearest public domain of CAF. This association is not solely a consequence of upper cover loading but of the combination of ISP architecture, large panel scale, and the precipitation-hardening alloys (primarily 7xxx series) that are simultaneously required for upper surface fatigue and compression performance. Built-up upper covers, where they occur in smaller aircraft or military programmes, do not generate the same forming demand, and are typically handled by peen-based or mechanical routes. Airbus provides the cleanest public family-level expression of that divergence: A300/A310 and A320 lower covers remain in the peen-plus-mechanical lineage, whereas A330/A340 and A380 upper covers move decisively into the CAF lineage [13,14,16,26,50]. It should however be noted that this divergence is empirically supported primarily by Airbus and Gulfstream programme evidence; the Boeing family, which accounts for the majority of Class III transports in Table 3A, does not separately disclose upper and lower cover routes for any aircraft, so the claim about upper/lower divergence as a general principle rests on mechanistic reasoning for the Boeing cases rather than on direct production evidence.

8.3. Process Selection Logic

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

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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 the upper and lower covers, between the early and late periods of aircraft development, 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 upper 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. Shen et al. [100] explicitly frame this as a scale and curvature threshold: below a critical combination of panel size and curvature demand, peen forming remains viable and cost-effective; above it, the capital and qualification cost of CAF is justified by the inability of peen forming to achieve the required contour accuracy without unacceptable residual stress heterogeneity or stiffness-related curvature error. The Airbus A330/A340 and A380 upper-cover cases in the present review sit above that threshold; the Airbus A320 lower-cover cases sit below it. Mechanical forming remains attractive for simple single-curvature preforms or local corrections, but not as a universal answer for double-curvature integral covers. A cross-route perspective on springback, one of the principal practical differences between these methods, is provided by Wagoner, Lim and Lee [99], who show that springback magnitude and sensitivity to process variables differ fundamentally between ambient-temperature mechanical routes, stress-based routes, and thermal routes: cold mechanical routes accumulate elastic springback that scales with yield strength and bend radius; peen-based routes generate springback-like recovery governed by the eigenstrain field and elastic modulus of the substrate; CAF generates springback driven by the creep recovery during unloading, which is smaller in absolute terms but strongly dependent on temperature history and alloy kinetics. This cross-route comparison provides the mechanistic basis for the selection logic here. Across all routes, the decisive practical issue is rarely nominal curvature alone; it is whether the route can absorb upstream residual stress, machining distortion, springback, and any ageing-related dimensional change at acceptable cost and qualification burden [20,30,31,99]. A complementary selection screen, visible only when adjacent-industry transfer cases are examined, is throughput economics. The physical capability of laser peen forming is sufficient to contour automotive aluminium body panels, but the economics are not: stamping achieves equivalent curvature at automotive production rates for a fraction of the cost. This confirms that laser peen forming's selection domain is not only governed by geometric and material constraints but by a volume-economics screen that restricts it to low-volume, high-value, stiffness-critical applications. The geometric and material screens in Table 2A do not capture this economic screen explicitly; for completeness, throughput rate and capital cost should be read alongside Table 2A's formal capability columns.

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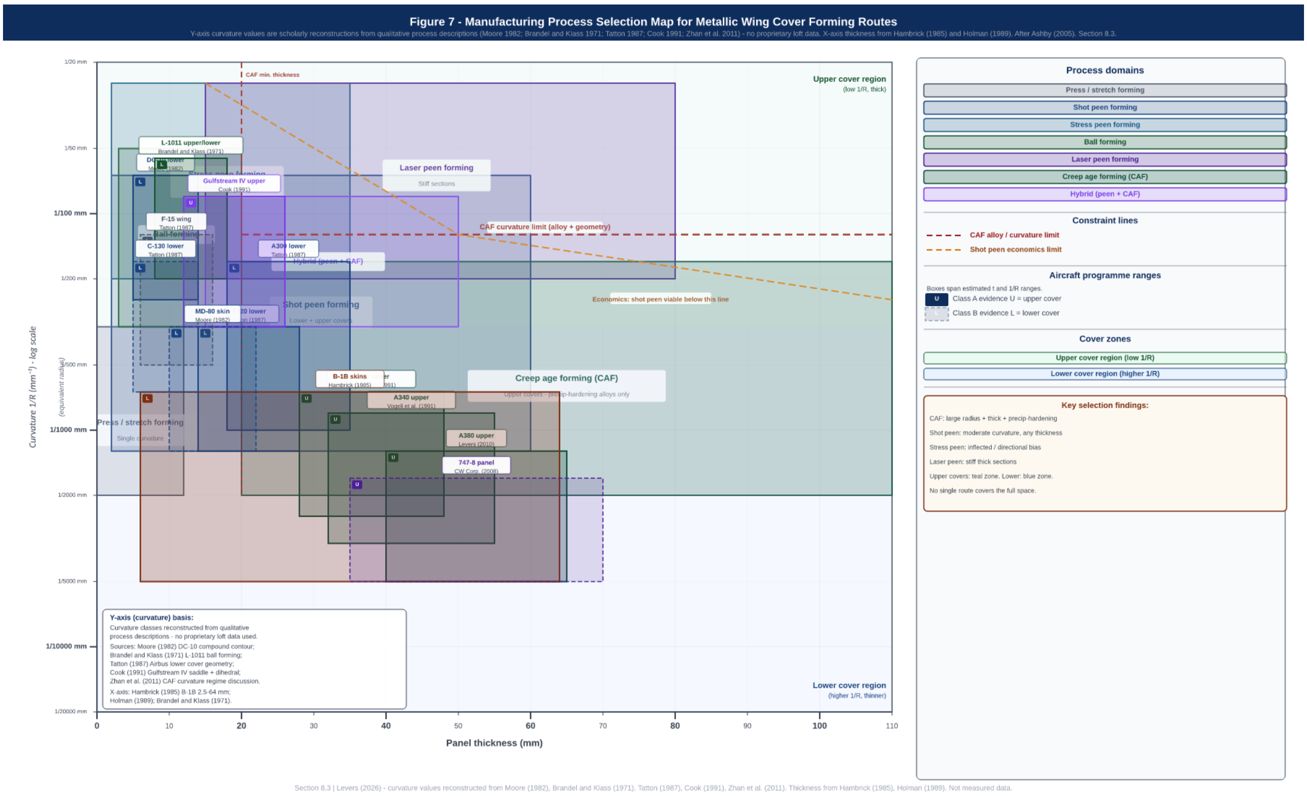

Figure 7. Manufacturing process selection map for metallic wing cover forming routes. Process domains are indicative based on production evidence reviewed. Constraint lines show T3 temper and non-age-hardening alloy exclusions (red dashed) and volume economics screen (amber dashed). Named aircraft programme cases are plotted as reference points (Class A/B evidence only). Section 8.3.

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

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 [101] 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 [101]. Surface roughness, work hardening, dislocation density, microstructural refinement, residual-stress depth, and potential surface damage are all process outputs. Huang et al. [102] 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. [80] 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. [103] further 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 [104] and Rodopoulos et al. [105] 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

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. [44] show how even a single bend in large-radius bumping alters the response of subsequent hits, while Coelho et al. [43] 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 [4,19,44].

8.6. Military-To-Civil Transfer of Forming Technologies

The discussion so far has been primarily analytical, about process mechanics and selection logic. The evidence base also supports a historical claim with practical implications that spans the five-period structure of Section 5: a selective but important transfer of forming technologies from military into civil manufacture, concentrated in the third and fourth periods (widebody era and CAF maturation) when the structural and geometric demands of civil aircraft for the first time 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 alongside Gulfstream IV compound-curvature upper wing panels and Airbus A330/A340 upper wing panels. Subsequent CAF review literature extends essentially the same lineage to the BAe Hawk and later to the A380. A second transfer pathway is visible in laser peening, where LLNL laboratory communications (2012, 2017) document defence-funded origins for the commercialised process, and Curtiss-Wright Corporation [71] records Boeing's adoption of a laser peen-forming cell for 747-8 wing sections, with the underlying process anchored in patents Hackel and Harris [45] and Hackel et al. [65].

8.7. Evidence Limitations

The analytical claims in Sections 8.1 through 8.7 are bounded by the quality of the underlying evidence. The principal limitation of the public record is asymmetry. One specific asymmetry deserves explicit discussion: the difference between the Douglas/McDonnell Douglas and Boeing traditions of programme-level publication. Moore [3], describing DC-10 wing-skin forming, and Tatton [13], describing Airbus lower-cover forming, are named-aircraft conference papers that provide the programme-level Class A evidence for their respective types. No equivalent named-aircraft wing-cover SAE or ICSP programme paper has been identified for any Boeing aircraft from the same era, despite Boeing manufacturing a greater total number of large civil aircraft over the review period. This asymmetry likely reflects a difference in corporate publication culture and IP strategy rather than a difference in manufacturing maturity: the Douglas organisation historically encouraged programme engineers to publish through the SAE; Boeing's approach has been more protective of wing-specific manufacturing data. If archived Boeing programme papers for the 707, 727, or 747 wing-skin forming processes exist in company or SAE Mobilus archives that were not accessible to this review, their recovery would significantly alter the strength of the Boeing attribution and potentially elevate the upper/lower divergence argument from mechanistically inferred to empirically demonstrated for the Boeing family. Legacy metal programmes are often better documented because supplier case studies and trade papers were historically more explicit about shop-floor practice. Contemporary manufacturers still patent wing architecture and process capability, but they publish complete shipset-level accounts of upper and lower metallic cover contouring far less readily. A second limitation is metrological asymmetry: many sources name a forming route without publishing the residual-stress measurement method, the spatial sampling density, or the final geometry-validation basis. A third is property asymmetry: process papers may report contour achievement without fully reporting the accompanying surface-integrity or durability consequences. A fourth, identified during revision, is the use of undated commercial web pages as primary capability evidence for multiple process claims; this has been addressed by grey-literature reclassification and substitution with patent and peer-reviewed sources where possible (see Section 1.2). A fourth limitation is the incomplete coverage of ICSP conference proceedings. ICSP-4 (1990, Tokyo) through ICSP-8 (2002, Garmisch) are represented in this review only through the papers that were subsequently published in peer-reviewed journals or that appeared in sources independently accessible through the search strategy described in Section 1.2. Papers presented at these conferences but not separately republished, including Baughman's Boeing shot peening work at ICSP-4, Eaton and Ebenau's aerospace peen forming papers at ICSP-5, and Ramati, Levasseur and Kennerknecht's Boeing advanced peen forming paper at ICSP-7, were identified through citation tracing but not independently accessed in full. Ramati et al. [106] is cited based on its description in Pashkov et al. [62] and its ICSP-7 proceedings listing.

A fifth limitation is the constraint on non-English source material: Chinese-language CAF and shot peen forming literature at NPU, CSU, and COMAC, and Russian-language forming literature at Sukhoi, Tupolev, and KNAAPO, was searched only to the extent of English abstracts and patent summaries. Chinese-language programme papers, if accessible, might upgrade the COMAC C919 evidence from Class C to Class B or Class A; Russian-language technical literature might similarly resolve the unattributed lineages of the Su-27/30 and Tu-22M/160 programmes. These represent specific research opportunities for researchers with the requisite language capability.

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.

10. Conclusions

The central 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 determine which routes remain feasible.

The strongest public aircraft-level evidence supports a differentiated process landscape. Shot peen and stress peen forming dominate large-radius and directional curvature problems; particle-impact forming is important where surface finish and controlled double curvature are critical; CAF is a high-accuracy route for precipitation-hardening alloys and smooth large covers; laser peen forming is a specialised route for thick or stiff panels; and hybrid routes are selected where no single mechanism can close the full contour.

The upper/lower distinction is especially important. Airbus evidence directly supports a split between peen/mechanical lower-cover routes and CAF upper-cover routes for selected families, while Boeing evidence is stronger at supplier or family level and should be cited more cautiously. The distinction is therefore a robust Airbus finding and a mechanically coherent, but less directly evidenced, inference elsewhere.

Material state is a hard process gate. CAF cannot be assumed for non-age-hardening alloys or unsuitable tempers, whereas peen-based and mechanical routes remain metallurgically available but may be limited by surface integrity, residual-stress effects, or geometry. This distinction explains why process selection must begin with alloy/temper and stock pedigree rather than with target curvature alone.

The review also shows that public evidence is uneven. DC-10, L-1011, Boeing 747/747-8, Airbus A300/A310/A320 lower covers, Airbus A330/A340/A380 upper covers, Gulfstream IV and B-1B remain the strongest programme anchors. Embraer, COMAC, Russian, business-jet and many military examples remain important for context but should not be cited as equivalent in evidential strength unless aircraft-level forming routes are publicly disclosed.

Finally, manufacturing route choice has organisational consequences. Specialist capability, large tooling, metrology, compensation know-how and surface-restoration control can determine whether forming remains in-house or is assigned to a specialised supplier. The practical outcome is that wing-cover forming should be interpreted as a coupled technical and industrial decision: a process is viable only if it can deliver the required contour, material state, surface integrity, rate, and repeatability within the available supply-chain capability.

Supplementary Materials: The following supporting information can be downloaded at the website of this paper posted on Preprints.org, supplementary source-status notes, search and retention information, contextual aircraft-process mappings, and extended manufacturer catalogue tables.

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Abbreviations

The following abbreviations are used in this manuscript: CAF, creep age forming; ISP, integrally stiffened panel; MIC, Metal Improvement Company; SAE, SAE International.

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 3A together with their manufacturer lineage and classification field, while Table A2 does the same for the military fixed-wing aircraft retained in Table 3B. The Antonov An-124/225 has been removed from Table A2 and relocated to Supplementary Table S5 as a geometric scale comparator with no attributed forming route. See Section 5.5.

Table A1. Commercial transport and business-aircraft families retained in Table 3A.

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 3A
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
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 [45], Hackel et al. [65]

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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
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; see also Airbus Deutschland US20030150263A1 wing-cover patent as adjacent evidence.
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
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

Table A2. Military fixed-wing aircraft retained in Table 3B, with manufacturer lineage and classification fields. Note: Antonov An-124/225 has been relocated to Supplementary Table S5 (see Implementation 10 note in Section 5.4a). Aircraft mentioned in Section 5.2 narrative but not retained in Table 3B (Grumman F-14, Grumman A-6, Northrop F-5, Lockheed S-3) are carried in Supplementary Table S3 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 Tables S3 and S5.

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 [92] 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 [50] 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

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, 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. Alcoa Inc. (2001) Method for stress relieving metal bodies. US Patent US6318141B1. Published 16 October 2001.

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35. MMPDS (2012) Metallic Materials Properties Development and Standardization (MMPDS). Washington, DC: Federal Aviation Administration.
36. 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.2004.04.237.
37. 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.
38. 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.
39. 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.
40. Pechiney Rhenalu SAS and Constellium (2005) Thick aluminium alloy product and method for producing an aircraft structural component. European Patent EP1288317B1. Published 2 November 2005.
41. 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.
42. Cyril Bath Company (2003) Stretch forming apparatus for forming aircraft skins. US Patent US6551551B1. Published 22 April 2003.
43. 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.
44. 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.
45. Hackel, L.A. and Harris, F.B. (2002) Contour forming of metals by laser peening. US Patent US6410884B1. Published 25 June 2002.
46. 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.
47. 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.
48. 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.
49. 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.
50. 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.
51. Sonaca NMF Canada Inc. (2005) Shaped metal panels and forming same by shot peening. US Patent US6938448B2. Published 6 September 2005.
52. OAO Komsomolsk-on-Amur Aircraft Production Association named after Yu.A. Gagarin (2013) Method of forming parts. RU Patent RU2475322C1. Published 20 February 2013.
53. 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.

54. 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/10.1243/09544054JEM1706.
55. Airbus Operations SAS (2012) Method of shot-peening a structural aircraft component. European Patent EP2189228B1. Published 18 January 2012.
56. Mura, T. (1987) Micromechanics of Defects in Solids. 2nd edn. Dordrecht: Martinus Nijhoff.
57. Fathallah, R., Inglebert, G. and Castex, L. (2004) 'Prediction of plastic deformation and residual stresses induced in metallic parts by shot peening', Materials Science and Technology, 14(7), pp. 631–639.
58. 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.
59. 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.
60. MTS Systems Corporation (2008) Method for forming a contoured metal workpiece using peening. US Patent US20080083265A1. Published 10 April 2008.
61. 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.
62. 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.
63. 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.
64. Ding, K. and Ye, L. (2006) Laser Shock Peening: Performance and Process Simulation. Cambridge: Woodhead Publishing. ISBN 978-1845690526.
65. 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.
66. Clauer, A.H. (2019) 'Laser shock peening, the path to production', Metals, 9(6), 626. https://doi.org/10.3390/met9060626
67. 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.
68. Ocana, J.L., Morales, M., Molpeceres, C., Garcia, O., Porro, J.A. and Garcia-Ballesteros, J.J. (2007) '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/10.1117/12.726763.
69. Metal Improvement Company LLC (Curtiss-Wright) (2008) Processing of titanium and other metals using laser shock peening. US Patent US7321105B2. Published 22 January 2008.
70. Metal Improvement Company LLC (Curtiss-Wright) (2012) Laser shock peening using low intensity laser pulses. US Patent US8334477B2. Published 18 December 2012.
71. Curtiss-Wright Corporation (2008) Curtiss-Wright awarded laser peen contract from Boeing. Press release, 14 January 2008.
72. Lawrence Livermore National Laboratory (2012) Fifteen scientists, engineers to be inducted into LLNL Entrepreneurs Hall of Fame. News release, 11 October 2012.
73. Lawrence Livermore National Laboratory (2017) 'Ready, set, innovate! Entrepreneurship flourishes at the Laboratory', Science & Technology Review, June.
74. Luo, J. and Lin, J. (2004) 'A study on the determination of mechanical properties for the creep age-forming of an aluminium alloy', Key Engineering Materials, 274–276, pp. 69–74. Available at: https://doi.org/10.4028/www.scientific.net/KEM.274-276.69.

75. 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.
76. Jeong, W., Cho, J.H., Kim, D., Barlat, F. and Chung, K. (2016) 'Creep and spring-back analysis in creep age forming', Metals and Materials International, 22(6), pp. 1036–1045. Available at: https://doi.org/10.1007/s12540-016-6233-y.
77. 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.
78. 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.
79. 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.
80. 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.
81. 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.
82. 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.
83. 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.
84. 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.
85. 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). https://doi.org/10.1115/1.4066155.
86. Almen, J.O. and Black, P.H. (1963) Residual Stresses and Fatigue in Metals. New York: McGraw-Hill.
87. 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.
88. Curtiss Aeroplane and Motor Corporation (1932) Method of forming sheet metal. US Patent US1872384A. Published 16 August 1932.
89. Juvinall, R.C. (1967) Engineering Considerations of Stress, Strain, and Strength. New York: McGraw-Hill.
90. Waterhouse, R.B. (1972) Fretting Corrosion. Oxford: Pergamon Press.
91. Champaigne, J. (2001) Shot peening overview. Mishawaka, IN: Electronics Inc./The Shot Peener. Available at: https://www.shotpeener.com/library/pdf/2001012.pdf.
92. 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.
93. Pennell, M.L. (1954) 'Design considerations of the Boeing Model 707'. SAE Technical Paper 540137. https://doi.org/10.4271/540137.
94. Textron Aerostructures (1992) Autoclave forming process including preload and age forming of aircraft panels. US Patent US5168169A. Published 6 December 1992.
95. Airbus (2003) UK's biggest new factory opens at Airbus, Broughton. Press release.
96. 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.
97. Embraer S.A. (2020) Methods for producing creep age formed aircraft components. US Patent US20200222967A1. Published 16 July 2020.

98. 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.
99. 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.
100. 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.
101. Schijve, J. (2009) Fatigue of Structures and Materials. 2nd edn. Dordrecht: Springer. ISBN 978-1402068072.
102. 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.
103. 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.
104. 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.
105. 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/10.1361/105994903770343383.
106. 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.
107. 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).
108. Airbus Defence and Space GmbH (2019) Device and method for laser shock peening of metallic aeronautical structural panels. European Patent EP3354753B1. Published 3 April 2019.
109. Airbus Operations GmbH and Airbus SAS (2013) Method for producing a curved section piece of large dimensions from a composite material. European Patent EP2440338B1. Published 22 May 2013.
110. Airbus SAS (2021) Method for manufacturing a structural component by creep-age forming and associated tooling. US Patent US20210114078A1. Published 22 April 2021.
111. Alcan International Ltd. (1984) Aluminium alloy composition and process. British Patent GB2133050B. Published 3 October 1984.
112. Alcan International Ltd. (2003) Process for producing aluminium alloy plate with reduced residual stress for aerospace structural applications. US Patent US20030159759A1. Published 21 August 2003.
113. Alcoa Inc. (1986) Production of aluminium-lithium alloy sheet. US Patent US4603029A. Published 29 July 1986.
114. Aleris Aluminum Koblenz GmbH (2008) High strength and damage tolerant aluminium alloy product for aerospace structural applications. US Patent US7449075B2. Published 11 November 2008.
115. 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.
116. Arconic Inc. (2018) Processing methods and alloys for manufacturing 7xxx series aluminium alloy products for aerospace applications. US Patent US20180209009A1. Published 26 July 2018.
117. Avco Corp. (1972) Low penetration ball forming process. US Patent US3705511A. Published 12 December 1972.
118. 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.
119. Boeing Company (2001) Reconfigurable tooling and method for creep age forming of metal panels. US Patent US6264771B1. Published 24 July 2001.

120. Boeing Company (2004) Flexible tooling for forming wing skins using multi-point discrete dies. US Patent Application US20040177666A1. Published 16 September 2004.
121. Boeing Company (2012) Methods and apparatus for peen forming aircraft panels. US Patent US8091406B2. Published 10 January 2012.
122. British Aerospace plc (1998) Method and apparatus for creep age forming. European Patent EP0689479B1. Published 2 September 1998.
123. Budd Manufacturing Company (1935) Method of forming sheet metal panels for aircraft. US Patent US2014799A. Published 17 September 1935.
124. Central South University (2019) Shot peen forming method for large integral wing panel of civil aircraft. Chinese Patent CN108543866B. Published 23 April 2019.
125. Central South University (2019) Springback prediction and compensation method for creep age forming of aluminium alloy integral panel. Chinese Patent CN107138583B. Published 28 May 2019.
126. Constellium SE (2013) Aluminium-lithium alloy with improved strength and low density for aerospace structural applications. US Patent US8366839B2. Published 5 February 2013.
127. Curtiss-Wright Corporation (1938) Forming method for aircraft skin panels. US Patent US2132002A. Published 11 October 1938.
128. Curtiss-Wright Surface Technologies (n.d.-a) Laser peening and laser peen forming. Capability pages. Accessed April 2026.
129. Curtiss-Wright Surface Technologies (n.d.-b) Shot peen forming. Capability page.
130. Curtiss-Wright Surface Technologies (n.d.-c) Shot peening applications. 10th edn. Technical applications guide. Accessed April 2026. Accessed April 2026.
131. 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.
132. Electroimpact Inc. (2019) Flexible multi-point tooling for large aerospace panel forming and assembly. US Patent US10518311B2. Published 31 December 2019.
133. Galatolo, R. and Lazzeri, R. (1999) 'A comparison between two failure criteria for notched aerospace aluminium alloys', International Journal of Fatigue, 21(8), pp. 785–794. https://doi.org/10.1016/S0142-1123(99)00046-3.
134. General Dynamics Corporation and Lockheed Martin Corporation (1998) Pre-loading fixture for shot peen forming of metal parts. US Patent US5826453A. Published 27 October 1998.
135. General Electric Company (Aviation) (2019) Method for laser shock peening of curved metal workpieces. US Patent US10207306B2. Published 19 February 2019.
136. General Electric Company and Cincinnati Milacron Inc. (1993) Method and apparatus for correctively shaping a part by peening. US Patent US5239456A. Published 24 August 1993.
137. Harbin Institute of Technology (2018) Laser shock peening forming for aircraft wing panel. Chinese Patent CN105414351B. Published 30 January 2018.
138. 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.2010.06.023.
139. 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.
140. Lockheed Aircraft Corp. (1966) Stretch forming apparatus and method. US Patent US3238753A. Published 8 March 1966.
141. Lockheed Aircraft Corporation (1945) Method of forming metal sheets. US Patent US2366164A. Published 2 January 1945.
142. 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.

 doi:10.20944/preprints202605.1979.v1

143. Metal Improvement Company (1952) Shot peening apparatus for aircraft parts. US Patent US2619820A. Published 2 December 1952.
144. Metal Improvement Company (1955) Method of shot peening aircraft wing skins. US Patent US2702951A. Published 22 February 1955.
145. Metal Improvement Company (1963) Shot peening apparatus for forming curved surfaces. US Patent US3073022A. Published 15 January 1963.
146. Metal Improvement Company (1972) Shot peening method and apparatus for contouring aircraft panels. US Patent US3668912A. Published 13 June 1972.
147. Metal Improvement Company (1987) Method and apparatus for shot peening wing skins. US Patent US4709457A. Published 1 December 1987.
148. Metal Improvement Company (1997) Shot peening of metal parts with computer controlled process. US Patent US5591313A. Published 7 January 1997.
149. Metal Improvement Company Inc. (1969) Apparatus for shot peening articles. US Patent US3475945A. Published 4 November 1969.
150. Mitsubishi Heavy Industries Ltd. (2002) Shot peening method for integrally stiffened panel. Japanese Patent JP2002361338A. Published 13 December 2002.
151. Northrop Corporation (1973) Stretch forming machine. US Patent US3757557A. Published 11 September 1973.
152. Northwestern Polytechnical University (2014) Creep age forming mould for large integral wing panel. Chinese Patent CN102974674B. Published 7 January 2015.
153. Northwestern Polytechnical University (2015) Multi-point flexible die for creep age forming of large integral panel. Chinese Patent CN103962436B. Published 11 March 2015.
154. Northwestern Polytechnical University (2020) Laser peen forming method for aircraft integral wing panel with complex curvature. Chinese Patent CN110202062B. Published 7 August 2020.
155. Pangborn Corp. (1987) Method and apparatus for imparting a simple contour to a workpiece. US Patent US4694672A. Published 22 September 1987.
156. Pangborn Corporation (1944) Method of treating metal by shot blasting. US Patent US2350440A. Published 2 January 1944.
157. Pechiney Rhenalu SAS (2000) Aluminium-lithium alloy products for aerospace structural applications. US Patent US6113711A. Published 5 September 2000.
158. Pechiney Rhenalu SAS (2004) Method for manufacturing a wing cover panel. WO Patent WO2004053181A1. Published 24 June 2004.
159. Pechiney SA and Alcan International (1992) Aluminium-lithium alloy product for aircraft structural applications. European Patent EP0260588B1. Published 26 August 1992.
160. 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.
161. Premium AEROTEC GmbH and Airbus SE (2020) Method for forming a metallic structural component of an aircraft by measuring and correcting distortion. European Patent EP3689491A1. Published 5 August 2020.
162. Rockwell International Corporation (1986) Forming die for compound-curvature aircraft panels. US Patent US4567743A. Published 4 February 1986.
163. Rockwell International Corporation (1997) Method of age forming for aircraft wing structures. US Patent US5649728A. Published 22 July 1997.
164. Rohr Inc. (2008) Stretch forming method for a sheet metal skin segment having compound curvatures. US Patent US7340933B2. Published 11 March 2008.
165. SAE International (2012) SAE AMS2432: Shot Peening, Computer Monitored. Warrendale, PA: SAE International.
166. SAE International (2012) Shot Peening, Automatic. SAE Standard AMS2430. Warrendale, PA: SAE International.
167. 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.

doi:10.20944/preprints202605.1979.v1

168. SAE International (2025) Procedures for Determining and Verifying Peening Intensity. SAE Standard J443_202512. Warrendale, PA: SAE International.
169. Safran SA (2019) Method for forming a metallic component for aircraft with distortion compensation using iterative simulation and tooling correction. WO Patent WO2019141929A1. Published 25 July 2019.
170. 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.
171. Sonaca S.A. (2015) Method for forming a metal part with sharp transitions. US Patent US9114449B2. Published 25 August 2015.
172. Southwest Aluminium (Group) Co. Ltd. (2016) Aluminium-lithium alloy sheet for civil aircraft wing skin applications. Chinese Patent CN104711499B. Published 2 March 2016.
173. Spirit AeroSystems Inc. (2013) Reconfigurable forming tool for skin panel contouring. US Patent US8539807B2. Published 24 September 2013.
174. 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.
175. Declaration of self-citation
176. The author is a co-author of Wang, Platts and Levers (2006), Kang et al. (2010), and Levers (2010). These sources are used only with independent corroborating literature or as programme-history context, and not as sole support for any core process-mechanics claim.