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Residual Stress Control in Hybrid Manufacturing Processes

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Abstract

Hybrid manufacturing combines two or more complementary processing mechanisms—commonly additive deposition with milling, turning, grinding, rolling, heat treatment, or other secondary operations—to exploit the geometrical flexibility of additive manufacturing while achieving improved dimensional accuracy, surface integrity, and material performance. A central challenge is the development and redistribution of residual stress. Rapid localized heating and cooling during metallic additive manufacturing generate steep thermal gradients, constrained shrinkage, and repeated thermal cycling, while subsequent machining introduces additional mechanical and thermal loads at the near-surface region. Residual tensile stresses may promote distortion, dimensional instability, cracking, delamination, or reduced fatigue resistance, whereas deliberately introduced compressive surface stresses can be beneficial in selected applications.

This conceptual–methodological paper develops an integrated residual-stress-control framework for hybrid manufacturing based on thermal-gradient reduction, deposition-path planning, interpass temperature management, sequencing of additive and subtractive operations, controlled material removal, mechanical deformation, stress-relief treatment, and measurement-informed process adaptation. Published research shows that substrate preheating and scan-strategy control can reduce additive-manufacturing thermal gradients, while hybrid wire-arc additive–milling studies demonstrate that suitable machining conditions can substantially alter surface residual stress. Interpass and post-build rolling provide an additional mechanical pathway for reducing distortion in suitable wire-based additive systems.

A simulated analysis compares three progressive control strategies using hypothetical residual-stress distributions. Because no experimental manufacturing dataset was supplied, all quantitative values are explicitly illustrative. The study concludes that residual stress should be treated as a process-history variable that evolves throughout deposition, cooling, machining, mechanical treatment, unclamping, and final heat treatment rather than as a defect addressed only after manufacturing.

Keywords**:** residual stress, hybrid manufacturing, additive–subtractive manufacturing, directed energy deposition, machining, stress relief, distortion control, process planning.

1. Introduction

Hybrid manufacturing has emerged as a means of combining the strengths of manufacturing processes that are individually subject to important limitations. Additive manufacturing can produce near-net-shape metallic components with high geometrical freedom and efficient material utilization, but deposited parts may exhibit rough surfaces, dimensional deviation, porosity, anisotropic microstructures, residual stress, and distortion. Subtractive processes such as milling or grinding can subsequently improve surface finish and dimensional accuracy. When additive and subtractive operations are integrated within a coordinated process chain, material can be deposited only where required and critical surfaces can be finished before they become inaccessible. Research on hybrid additive manufacturing accordingly emphasizes that the final material state reflects the interaction among several physical mechanisms rather than the effect of one isolated operation.

Residual stress is particularly important because it remains in a component after the external processing forces or thermal loads responsible for its formation have been removed. Metallic additive manufacturing repeatedly heats small material volumes to high temperatures while adjacent material remains significantly cooler. The associated expansion is mechanically constrained, followed by rapid cooling and contraction. Repetition across layers can generate substantial tensile and compressive stress fields, sometimes accompanied by component bending or distortion after removal from the substrate. Mercelis and Kruth demonstrated that residual stresses in laser-based metallic additive processing can reach considerable magnitudes, while subsequent research has linked accurate prediction of stress and distortion directly to reconstruction of the thermal history.

The subtractive stage introduces a second stress-generating mechanism. Machining produces severe localized mechanical deformation, frictional heating, and material removal at the surface. Depending on cutting parameters, tool geometry, material behavior, cooling, and the pre-existing stress state, machining can produce either tensile or compressive near-surface residual stresses. These stresses form part of surface integrity and can influence fatigue performance, dimensional stability, and corrosion-related behavior. Hybrid manufacturing therefore cannot be understood by assuming that machining simply removes an additive-manufactured surface layer without changing the stress field.

Experimental evidence illustrates that interaction clearly. Zhang and colleagues investigated a hybrid wire-arc additive and milling process and reported that selected milling conditions substantially reduced mean surface residual stress relative to the additive-only condition. Their work also demonstrated that machining parameters influenced tensile-property anisotropy, confirming that interleaving the two processes affects more than dimensional accuracy. Similarly, rolling integrated with wire-arc additive manufacturing has been shown to modify residual stress and substantially reduce distortion, although its effectiveness depends on alloy, geometry, rolling location, roller design, and applied load.

The present study develops an integrated approach to Residual Stress Control in Hybrid Manufacturing Processes. Rather than treating residual stress as an unavoidable additive-manufacturing defect followed by corrective stress relief, the framework considers prevention, redistribution, measurement, and final qualification throughout the hybrid process chain. Particular emphasis is placed on additive–subtractive manufacturing, while mechanical rolling and thermal stress relief are incorporated as complementary hybrid interventions. Since no physical manufacturing trial or measured residual-stress dataset has been supplied, the study is explicitly conceptual–methodological and its quantitative analysis uses transparent simulated distributions intended to support subsequent experimental validation.

2. Objectives of the Study

2.1 To Develop an Integrated Residual-Stress Control Architecture

The first objective is to develop a framework in which residual stress is managed from the beginning of process planning. The approach links heat-input control, deposition sequence, interpass temperature, substrate condition, dwell time, restraint, machining sequence, material-removal depth, and post-processing.

Residual stress is therefore considered a cumulative process-history variable. A parameter change intended to improve one stage must be evaluated according to how it influences subsequent operations. For example, greater substrate restraint may improve geometric stability during deposition but can also store elastic energy that becomes visible as distortion after unclamping.

2.2 To Examine the Interaction Between Additive and Subtractive Stress States

The second objective is to examine how machining can either mitigate or aggravate the stress field created by additive deposition. Subtractive removal changes component geometry and stiffness while simultaneously eliminating material that may be carrying residual stress. The remaining material then redistributes internal stresses to satisfy mechanical equilibrium.

Machining itself also creates a new near-surface stress state. Consequently, the optimum machining sequence is not determined only by dimensional tolerance. Material-removal depth, cutting temperature, tool condition, cutting direction, and the timing of machining relative to deposition should be incorporated into residual-stress-control planning.

2.3 To Establish Measurement-Informed Stress Mitigation

The third objective is to integrate stress measurement with process control. Residual stress cannot be evaluated reliably through distortion alone because a component may remain geometrically acceptable while containing significant self-equilibrating stresses.

The proposed methodology therefore combines residual-stress measurement or validated simulation with dimensional monitoring. X-ray diffraction, neutron diffraction, hole-drilling methods, contour methods, distortion measurements, or other appropriate techniques can be selected according to component size, required depth information, accessibility, and research purpose.

3. Review of Literature

3.1 Thermal Origin of Residual Stress in Additive Manufacturing

Metal additive-manufacturing processes are characterized by repeated localized thermal cycles. DebRoy and colleagues describe steep temperature gradients, rapid solidification, repeated reheating, and process-dependent metallurgical transformation as central characteristics distinguishing additively

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manufactured metallic components. Residual stress and distortion consequently emerge from coupled thermal, mechanical, and metallurgical phenomena rather than from cooling alone.

Mercelis and Kruth's investigation of laser-based manufacturing provides an important early description of residual-stress formation. The underlying thermal-gradient mechanism arises when a heated region attempts to expand but is constrained by surrounding colder material. On cooling, the plastically affected region contracts against adjacent material, leaving a self-equilibrated stress field. Modern reviews continue to identify residual stress as one of the major quality challenges associated with metal additive manufacturing because it can lead to distortion, cracking, delamination, and unfavorable service behavior.

Several process-level measures can reduce stress development. Preheating the substrate decreases the temperature difference between newly deposited or melted material and the underlying structure. Scan- or deposition-path planning changes the spatial and temporal distribution of heat, while dwell-time adjustment alters heat accumulation and stress relaxation. Reviews of metallic additive manufacturing identify preheating and scan-strategy control as common approaches for reducing thermal gradients and associated residual stresses.

3.2 Stress Redistribution Through Machining and Hybrid Sequencing

Machining introduces both mechanical deformation and heat into a comparatively shallow surface layer. The resulting residual-stress distribution depends on which mechanism dominates. Mechanically dominated cutting conditions may generate compressive effects, whereas excessive thermal loading may contribute to tensile near-surface stresses. Tool wear, feed, cutting speed, depth of cut, coolant strategy, workpiece microstructure, and material hardness can all alter the final state.

In hybrid additive–subtractive processing, machining interacts with pre-existing additive-manufacturing stresses. Zhang and colleagues examined wire-arc deposition combined with milling and reported a large decrease in mean surface residual stress at an appropriate milling width when compared with the wire-arc additive-only condition. This result is especially important because it demonstrates that subtractive processing can become an active stress-management operation rather than merely a geometric finishing step.

Hybrid-process monitoring is therefore essential. Additive deposition generates substantial heat that can affect both the component and machine structure, while the resulting thermal history, microstructure, and residual stress influence subsequent machining response. Research on the digital thread in hybrid manufacturing accordingly emphasizes stronger monitoring and closed-loop control when additive and subtractive operations are combined.

3.3 Mechanical and Thermal Stress-Relief Strategies

Mechanical deformation can intentionally alter additive-manufacturing residual stresses. Hönnige and colleagues investigated rolling applied to wire-arc additive aluminium components and found that interpass and side rolling substantially affected distortion and residual-stress distribution. Later modeling of post-build rolling confirmed that roller geometry and load influence the plastic-strain field responsible for stress mitigation.

The effect of rolling is material and process dependent. Research involving titanium wire-arc structures found that thermal stress relief could virtually eliminate measured residual stresses in the investigated configuration, whereas rolling provided additional benefits related to grain refinement even when its direct residual-stress effect was more limited. This distinction demonstrates why stress-control strategies should not be generalized across alloys.

Thermal stress relief remains important because elevated temperature can allow accumulated elastic and plastic incompatibilities to relax. However, heat treatment may also change precipitation state, microstructure, hardness, distortion, or subsequent machining response. Residual-stress mitigation must therefore be coordinated with the alloy's metallurgical requirements rather than treated as an independent final operation.

4. Research Methodology

4.1 Conceptual Hybrid Manufacturing Model

The proposed study architecture considers a metallic component produced through directed-energy deposition or wire-arc additive manufacturing followed by intermittent or final subtractive machining. Optional interpass rolling and thermal stress relief are incorporated as stress-control treatments.

The unit of analysis is the local residual-stress state after each manufacturing event. Each deposition pass, dwell period, machining operation, rolling pass, unclamping event, and thermal treatment is treated as capable of modifying the previous state.

4.2 Residual-Stress Control Variables

The methodology separates control variables into thermal, mechanical, geometric, and sequencing domains.

Table 1: Integrated Framework for Residual-Stress Control in Hybrid Manufacturing

Control Domain	Principal Residual-Stress Driver	Proposed Control Strategy	Expected Engineering Effect
Thermal input	High localized heat and steep gradients	Reduce excessive heat input and stabilize energy delivery	Lower thermally generated mismatch
Thermal baseline	Large temperature difference between deposition and substrate	Substrate/preform preheating where metallurgically suitable	Reduced temperature gradient
Deposition sequence	Uneven heat accumulation and directional stress buildup	Alternate paths, balanced deposition, controlled dwell	More uniform thermal history

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Control Domain	Principal Residual-Stress Driver	Proposed Control Strategy	Expected Engineering Effect
Additive–subtractive sequencing	Stress accumulation before finishing	Intermediate machining at planned build heights	Controlled stress redistribution
Machining conditions	Mechanical and thermal surface loading	Optimize cutting depth, tool condition, speed, feed, and cooling	Favorable surface-integrity state
Mechanical treatment	Tensile stress and distortion	Interpass or post-build rolling/peening where suitable	Plastic redistribution and possible compressive stress
Thermal post-treatment	Locked-in macro residual stress	Alloy-specific stress-relief cycle	Stress relaxation before final finishing
Measurement and prediction	Unknown evolving internal state	Diffraction, hole drilling, distortion monitoring, validated FE modeling	Feedback for process correction

4.3 Stress Metrics and Simulated Analytical Procedure

For conceptual comparison, the residual-stress state is represented by a normalized peak tensile residual stress:

These expressions are generic comparison metrics rather than constitutive models. Actual residual stress is three-dimensional, position dependent, and frequently influenced by temperature-dependent material properties, phase transformation, plasticity, geometry, clamping, and previous operations. Thermomechanical finite-element models should therefore be validated using suitable experimental measurements before they are used for process qualification. Mukherjee and colleagues demonstrate that accurate thermal-field prediction is central to reliable estimation of additive-manufacturing residual stress and distortion.\

5. Analysis

5.1 Residual Stress as a Process-History Quantity

The analysis indicates that the most effective control point generally occurs before high tensile stresses become fully embedded in the final component. A process that repeatedly deposits layers under severe thermal gradients and relies entirely on a final stress-relief treatment may succeed metallurgically, but it permits substantial distortion to develop during manufacturing.

Preventive control begins with heat distribution. Balanced deposition paths, lower unnecessary heat input, controlled interpass temperature, and suitable preheating reduce the thermal mismatch driving stress formation. Research on additively manufactured steels identifies substrate or feedstock preheating and scan-strategy adjustment as established residual-stress-reduction approaches.

Intermediate subtractive operations provide a second control opportunity. Material removal changes section stiffness and the equilibrium stress distribution, while finishing surfaces earlier in the process may reduce the amount of final machining performed on a heavily stressed finished structure.

5.2 Simulated Performance of Progressive Stress-Control Strategies

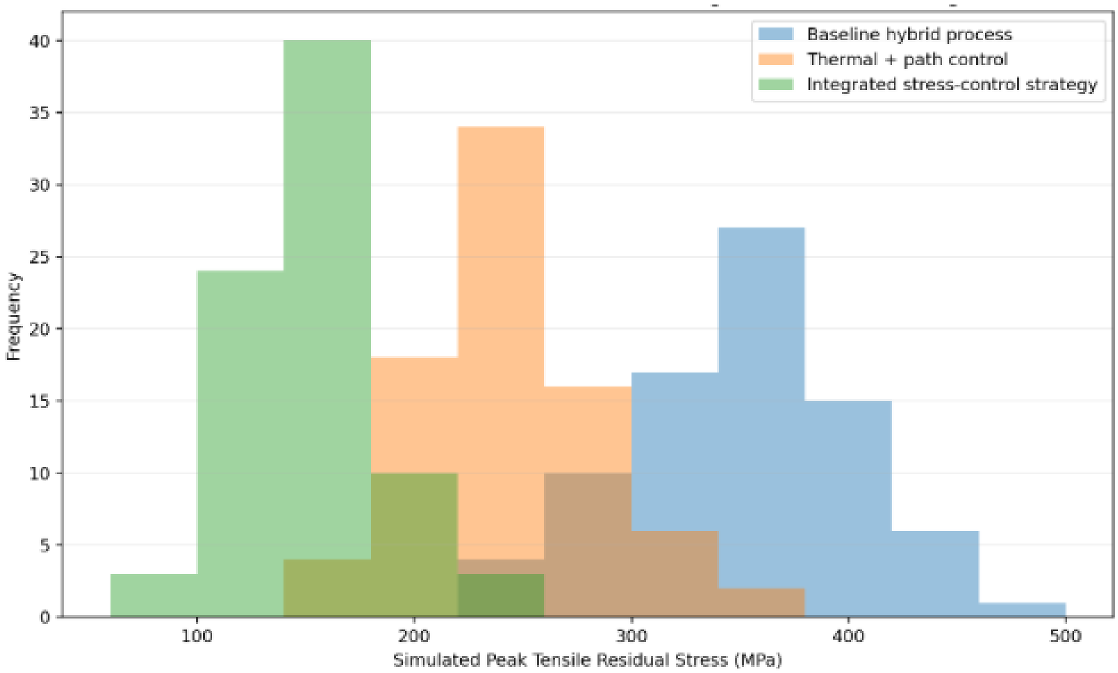
The scenario analysis compares a baseline hybrid process, a thermally and path-controlled process, and an integrated strategy combining thermal control, sequencing, machining optimization, and stress-relief intervention.

Table 2: Simulated Residual-Stress Response of Hybrid Manufacturing Strategies

Process Strategy	Simulated Mean Peak Tensile Stress (MPa)	Simulated Distortion Index	Stress-Control Interpretation
Baseline deposition + final machining	360	1.00	High thermal accumulation; correction occurs late
Thermal management + balanced path planning	245	0.68	Reduced stress generation before machining
Integrated hybrid stress control	150	0.39	Prevention, redistribution, and relief used jointly

The baseline scenario exhibits the highest residual-stress magnitude because additive deposition proceeds without dedicated thermal or sequencing control. Introducing thermal management and balanced deposition lowers the simulated mean peak stress by reducing the driving thermal gradient before the subtractive stage.

Graph 1: Illustrative Residual-Stress Distributions Under Progressive Control Strategi



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Interpretation: The histogram demonstrates a conceptual shift in the residual-stress population toward lower tensile values as process controls are progressively integrated. The distributions are illustrative rather than measured and should be interpreted as a visualization of the proposed framework, not as predicted performance for a particular manufacturing system.

5.3 Machining Can Be Used as an Active Stress-Control Operation

A major analytical finding is that machining should not automatically be postponed until deposition is complete. In suitable geometries, intermediate machining can remove highly stressed surface material, restore reference surfaces, control geometric accumulation, and alter section stiffness before further deposition.

Experimental hybrid wire-arc/milling research provides direct evidence that milling conditions can materially alter surface residual stress. An appropriate milling width produced a pronounced reduction relative to the additive-only process in the investigated aluminium alloy. The practical implication is not that greater material removal always reduces stress, but that material removal must be deliberately coordinated with the pre-existing stress field.

Machining parameters themselves require optimization. Excessive cutting temperature, a worn tool, or unsuitable process parameters can generate undesirable tensile surface stresses even if material removal temporarily releases deeper additive-manufacturing stresses. The hybrid objective should therefore minimize the net detrimental stress state after redistribution and machining-induced modification.

6. Discussion

6.1 Residual-Stress Control Should Begin During Deposition

The first major implication is that residual-stress management should be preventive before it becomes corrective. Thermal-gradient mechanisms are fundamental to stress formation in metallic additive manufacturing, so controlling heat input, path distribution, preheating, and dwell provides an opportunity to reduce the source rather than only its consequences.

This principle also improves geometric control. Once large residual stresses have accumulated, removing clamps or machining asymmetric material volumes can release them as macroscopic distortion. A part can therefore satisfy dimensional tolerances while restrained and move outside tolerance later.

Process planning should consequently predict not only the stress state during clamping but also the distortion expected after fixture release. Measurement after unclamping is particularly important because redistribution may reveal stresses that were mechanically balanced by the substrate or fixture during manufacturing.

6.2 Hybrid Processing Can Be Used to Engineer Rather Than Merely Remove Stress

The second implication is that hybridization offers an opportunity for intentional stress-state engineering. Milling can redistribute pre-existing stresses and generate new near-surface stresses, while rolling can impose plastic deformation that counters additive-manufacturing strain incompatibility. In aluminium wire-arc additive manufacturing, rolling has demonstrated strong capability for controlling distortion, while hybrid milling has shown substantial surface-stress modification.

Residual stress is not inherently harmful in every form. Compressive surface residual stress may improve resistance to fatigue-crack initiation in certain applications. The engineering objective should therefore not necessarily be zero residual stress throughout the component.

A more appropriate target is a stable and application-compatible stress distribution. High tensile stresses near fatigue-critical surfaces, abrupt stress gradients, or stresses capable of causing distortion during subsequent machining should receive priority for control.

6.3 Closed-Loop Monitoring Can Improve Hybrid Stress Management

The third implication concerns digital process integration. Hybrid manufacturing produces a particularly complex history because thermal deposition, cooling, cutting, reheating, and possible mechanical treatment occur sequentially. The state entering one operation therefore depends strongly on everything that occurred previously.

Research on hybrid manufacturing's digital thread highlights the importance of monitoring because residual stress, microstructure, and thermal history generated during additive processing influence subsequent cutting performance, while deposition heat can alter machine and part geometry. A closed-loop system could consequently combine temperature sensing, geometry measurement, force monitoring, distortion sensing, and validated simulation.

Future hybrid systems may use these data to change deposition order, dwell time, machining depth, or stress-relief intervention dynamically. Such capability would move residual-stress management from fixed parameter selection toward state-aware manufacturing.

7. Conclusion

Residual stress is one of the central mechanical challenges in metallic hybrid manufacturing because it evolves continuously across deposition, cooling, restraint, machining, mechanical treatment, fixture release, and thermal post-processing. Treating it solely as an additive-manufacturing defect addressed by a final heat treatment overlooks the opportunity to prevent and redistribute stresses earlier in the manufacturing sequence.

The framework developed in this study integrates thermal-gradient reduction, balanced deposition paths, interpass-temperature management, additive–subtractive sequencing, controlled machining, mechanical deformation, stress-relief treatment, and measurement-informed process adaptation. Published evidence demonstrates that preheating and path control can reduce stress-generating thermal gradients, that milling can substantially modify residual stresses in hybrid wire-arc processing, and that rolling or thermal stress relief can be effective under appropriate alloy and geometric conditions.

The simulated analysis illustrates the potential advantage of combining these interventions. The integrated conceptual strategy reduces the hypothetical mean peak tensile residual stress from 360 MPa to 150 MPa relative to the uncontrolled baseline. These values are not experimental findings and should not be transferred to real materials. Experimental validation should evaluate stress fields before and after deposition, machining, unclamping, rolling, and heat treatment while also measuring distortion, microstructure, hardness, surface integrity, and mechanical performance.

The broader conclusion is that residual-stress control in hybrid manufacturing should be formulated as an optimization of the complete thermo-mechanical process history. The most effective process is not necessarily the one that produces the lowest as-built stress or the lowest final stress in isolation, but the one that delivers stable dimensions, acceptable surface integrity, reliable mechanical performance, and a controlled residual-stress state throughout manufacture and subsequent service.

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