NODiVEC

RHEONA™ — Finite Element Solver for Additive Manufacturing & Thermal Processing

Production-oriented simulation software for thermo-mechanical analysis, viscous sintering, and process-induced distortion in advanced manufacturing workflows.

www.nodivec.com

Executive Summary

RHEONA™ is a proprietary finite element solver that brings production-grade process simulation within reach of the shop floor. It models the physics that actually decide whether a build succeeds — thermal history, evolving material state, and geometry change — across three focused solution classes: thermo-mechanical stress and distortion, transient thermal analysis, and viscous sintering with density evolution. Instead of a sprawling, expensive general-purpose FEA suite, RHEONA™ delivers only the essential functionality metal-AM and sintering shops use every day — priced and packaged so a working engineer, not just a simulation specialist, can run it.

- **Affordable by design —** a focused solver core at a fraction of the cost of legacy FEA platforms, so simulation fits a shop's budget and pays back on the first avoided failed build.
- **Only the essentials —** the mechanical, thermal, and sintering capability shops actually need — no paid-for breadth that sits unused.
- **Runs where the work is —** practical on standard multi-core workstations; no HPC cluster, GPU farm, or specialist IT required.
- **Manufacturing-aware setup —** layer activation, deposition-aligned meshing, thermal boundary tracking, and process-specific constraints keep model prep fast and repeatable.
- **Fits your workflow —** command-line and service-oriented integration slot into existing design, MES, or digital-thread environments.

Why RHEONA™ Exists

Conventional finite element platforms are designed to support a wide range of physics, element families, contact formulations, and workflows. That generality is useful, but it often introduces computational overhead and model complexity for manufacturing problems with more regular structure. RHEONA™ takes a narrower approach: it concentrates on the subset of formulations, mesh types, and boundary-condition patterns that dominate additive manufacturing and sintering simulations.

The solver is optimized for recurring characteristics such as:

- Dense hexahedral meshes with consistent element quality
- Layer-by-layer deposition sequences
- Temperature-dependent viscous materials
- Density evolution during sintering
- High anisotropy in the deposition direction

By narrowing scope to these recurring manufacturing patterns, RHEONA™ reduces setup complexity and improves computational efficiency relative to broader solver stacks — an architecture better suited to repeated design iteration, parameter studies, and integration into automated manufacturing-analysis pipelines.

Core Technical Capabilities

1 · Multi-Physics Solver Suite

The mechanical, thermal, and sintering solvers are independent solution modes. They are not automatically coupled — each runs from its own inputs and boundary conditions.

a) Mechanical Solver — Inherent Strain & Stress

- Implicit static structural analysis
- Inherent-strain elastic solve, with pseudo-elastoplastic yield applied as a post-processing step
- Multi-step deposition with residual stress tracking
- Optional geometric nonlinearity (large-deformation) for high-strain processes
- Reduced-integration elements with hourglass-control stabilization for fast, locking-free assembly
- Mesh coarsening for efficient assembly and solve
- Inherent-strain prediction driven by the layer-by-layer deposition sequence

b) Thermal Solver — Transient Heat Transfer

- Full 3D transient heat diffusion during layer-by-layer deposition
- Temperature-dependent conductivity and heat capacity
- Convection and radiation heat loss, including dynamic top-surface tracking that follows the exposed build face layer by layer
- Exact constraint condensation for thermal tie interfaces (accurate coupling across dissimilar mesh regions)
- Built-in material database with sintering profiles
- Advanced moving-mesh capability for deposition tracking

c) Sintering Solver — Viscous Consolidation

- Specialized solver for powder compaction and sintering
- Skorokhod–Olevsky continuum viscous-sintering model with Arrhenius temperature-dependent viscosity
- Gravity-driven densification with particle rearrangement
- Time-stepping through furnace thermal profiles (ramp, soak, cool)
- Setter friction and tooling constraints
- Mass conservation with density-evolution tracking

2 · High-Performance Computing Architecture

JIT compilation & parallel assembly

- Element-level kernels compiled to native machine code at runtime to reduce overhead during assembly and update operations
- Loop-level parallelization distributes assembly work across available CPU cores for large element counts
- Single-pass assembly minimizes temporary memory allocation and improves cache behavior on large sparse systems
- Numerically intensive operations routed through optimized math libraries where beneficial

Dual-path assembly strategy

- **Standard path —** fast, parallelized assembly for non-constrained elements.
- **Constrained path —** specialized handling for multi-point constraints (hanging nodes, tied contacts).
- **Adaptive dispatch —** automatically selects the optimal assembly path based on mesh topology.

Memory efficiency

- **Single-precision (float32) default —** 50% less memory vs. float64, near-identical accuracy.
- **CSR sparse format —** with pre-computed assembly topology.
- **Intelligent matrix caching —** topology changes detected automatically; stiffness reused when possible.

3 · Advanced Mesh & Geometry Handling

Voxel-based meshing with G-code reader

- Native G-code reader for direct CAM integration
- Automatic mesh generation from deposition sequences
- Multi-layer, multi-material build-path support
- Hex-dominant meshing from STL geometry

Mesh options

- **Structured hexahedral —** optimal for layer-by-layer deposition.
- **Unstructured tetrahedral conversion —** for complex geometries (automatic tet-to-hex available).
- **Voxel refinement —** density-aware refinement during sintering.
- **Deposition-aligned refinement —** finer mesh near the heat source, coarser away.

Mesh coarsening

- Automatic multi-level coarsening to reduce unknowns by 5–20×
- Hanging-node constraints enforced via Lagrange multipliers
- Typical 10–20% speedup on large simulations with coarsening enabled

4 · Solver Options

Direct solvers

- Intel Pardiso LU decomposition — fast for 100K–2M DOF, symmetric & unsymmetric matrices
- Factorization caching for reused topologies
- Automatic pivot selection for numerical stability

Iterative solvers

- Conjugate Gradient (CG) — symmetric positive-definite systems
- MINRES — indefinite symmetric systems
- GMRES — general unsymmetric systems
- Algebraic Multigrid (AMG) preconditioner — 5–10× faster convergence

Adaptive solver selection

- Small systems (<50K DOF) → Pardiso direct solver
- Medium systems (50K–500K DOF) → Pardiso with iterative fallback
- Large systems (>500K DOF) → AMG-preconditioned iterative solver

5 · Material Library

RHEONA™ includes a pre-characterized material library covering common alloys used in additive manufacturing and thermal-processing workflows.

- **Aluminum alloys —** AlSi10Mg, AlSi12, Scalmalloy
- **Titanium alloys —** Ti-6Al-4V, Ti-6Al-4V ELI, Pure Titanium
- **Nickel superalloys —** Inconel 718, Inconel 625, Hastelloy X, Haynes 25 / 188 / 230
- **Steel & iron —** 316L, 17-4 PH, 15-5 PH, D2 & H13 tool steel, 4140 low-alloy, Maraging MS1, Super Duplex
- **Specialty alloys —** Cobalt Chrome, Pure Copper, GRCop-42

All materials support temperature-dependent properties — including Arrhenius-based viscosity for sintering and temperature-dependent thermal and mechanical properties.

6 · Boundary Conditions & Constraints

Mechanical constraints

- Displacement BCs (fixed, prescribed motion)

- Point loads and distributed body forces (gravity, pressure)
- Inherent-strain specification applied per deposition step
- Setter friction with velocity-dependent behavior
- Multi-point constraints for element connectivity (hanging nodes)
- Nonlinear contact (tied surfaces, bilateral contact)

Thermal boundary conditions

- Fixed temperature (sink)
- Convective heat loss on side surfaces, with optional dynamic top-surface convection that tracks the exposed build face
- Radiative heat loss (Stefan–Boltzmann) on side and top surfaces, configurable emissivity
- Coupled convection (temperature-dependent heat-transfer coefficient)
- Per-material BC and property assignment within a single model
- Symmetry planes

Sintering-specific

- Zero-penetration constraint on the setter plate
- Friction model: $\tau = \mu \cdot N$ where $\mu = \mu_0(1 + \beta \cdot v)$

Operational & Engineering Value

1 · Faster iteration cycles

- Shorter simulation turnaround enables more design and process iterations within a fixed engineering schedule
- Batch execution supports parameter sweeps, calibration studies, and scenario comparison without manual model rebuilds
- Near-process-time analysis is feasible for selected reduced-order or repeated-solve workflows

2 · Lower process-development cost

- Fewer physical trial runs when distortion, thermal gradients, and densification can be evaluated in simulation first
- Residual stress and deformation assessed before support removal, machining, or furnace processing
- Thermal-profile optimization reduces scrap, rework, and energy consumption during development

3 · Improved predictive quality control

- Predict porosity, density gradients, and mechanical properties
- Identify high-stress regions vulnerable to failure
- Correlate simulated properties with mechanical testing

4 · Competitive differentiation

- Embedded simulation extends an existing software stack with process-specific analysis, not generic post-processing
- Direct ingestion of geometry and deposition instructions reduces workflow fragmentation
- Output supports downstream analytics, surrogate modeling, and process-parameter studies

5 · Ease of integration

- Command-line interface (CI/CD, cloud jobs, MES systems)
- REST-ready architecture (expose via microservices)
- Minimal external dependencies (self-contained solver)
- Windows-native deployment (exe distribution ready)

Integration Pathways

Option 1 · Command-Line Interface

A command-line interface suitable for batch execution, workflow orchestration, and integration with manufacturing or engineering automation systems.

```
# Mesh generation from STL + G-code deposition sequence
rheona.exe ^
  --part_stl turbine_blade.stl ^
  --gcode deposition.gcode ^
  --out ./results --mesh_only

# Thermal analysis (layer-by-layer build)
rheona.exe --inp mesh.inp --out ./results --mode thermal ^
  --T_ambient 300 --T_melt 1500 --layer_time 45 --threads 16

# Sintering (with custom furnace profile)
rheona.exe --inp mesh.inp --out ./results --mode sintering ^
  --furnace_csv furnace_profile.csv --threads 32

# Inherent strain (residual stress)
rheona.exe --inp mesh.inp --out ./results --mode strain ^
  --E 105e9 --nu 0.33 --yield_stress 900e6 --coarsening 2 --threads 24
```

Integration points:

- Call from manufacturing execution systems (MES)
- Trigger from CAM software post-processing
- Integrate with CI/CD pipelines for automated validation
- Submit to HPC clusters for batch processing

Option 2 · REST API / Microservices

RHEONA™ can be wrapped as a service and exposed through HTTP endpoints when centralized job submission, queuing, and results retrieval are required.

```python
from fastapi import FastAPI, File, UploadFile, BackgroundTasks
from subprocess import run
import uuid

app = FastAPI()

@app.post('/sintering/')
async def run_sintering(mesh_file: UploadFile = File(...),
                        params: dict = {}, background_tasks=None):
    job_id = str(uuid.uuid4())
    with open(f'jobs/{job_id}/mesh.inp', 'wb') as f:
        f.write(mesh_file.file.read())
    background_tasks.add_task(run, [
        'rheona.exe', '--inp', f'jobs/{job_id}/mesh.inp',
        '--out', f'jobs/{job_id}/results', '--mode', 'sintering', **params])
    return {'job_id': job_id, 'status': 'queued',
            'poll_url': f'/results/{job_id}'}
```

Deploy in Docker or Kubernetes for elastic scaling:

```
FROM python:3.10
RUN pip install fastapi uvicorn
COPY rheona.exe /usr/local/bin/
COPY api.py .
EXPOSE 8000
CMD ["uvicorn", "api:app", "--host", "0.0.0.0", "--port", "8000"]
```

Option 3 · Standalone Executable

For Windows-based deployments, RHEONA™ can be distributed as a self-contained executable for direct execution within existing engineering or manufacturing IT environments.

```
C:\Program Files\Rheona\rheona.exe `
  --inp mesh.inp --out results --mode sintering --threads 16

# Result: VTU files in ./results/ ready for visualization & analysis
```

Technical Specifications

System Requirements

Requirement	Specification
CPU	8+ cores required (16+ recommended)
Memory	16 GB minimum (64 GB+ for 2M+ element models)
Storage	2 GB (solver + cache)
OS	Windows 10 / 11 (64-bit)
Graphics	Standard — no GPU acceleration required

Solver Capabilities

Feature	Details
Max elements	3,000,000 (3M nodes accordingly)
Element types	Hexahedral (C3D8), optional reduced integration (C3D8R) with hourglass control
Heat-loss models	Convection (side + dynamic top surface), radiation (side + top, configurable emissivity)
Time-stepping	Explicit (forward Euler), implicit (backward Euler), adaptive step control
Nonlinear solvers	Newton–Raphson with line search, adaptive tolerance
Direct solver	Intel Pardiso (LU, symmetric & unsymmetric)
Iterative solvers	CG, MINRES, GMRES with AMG preconditioner
Material models	Elasticity (inherent strain), pseudo-elastoplastic post-processing, viscous flow, density-dependent
Constraints	Point loads, displacement / inherent-strain BCs, multi-point constraints, contact
Output format	VTU (ParaView / Gmsh compatible)

G-code reader capability

- **Direct CAM integration —** parse multi-axis G-code tool paths.
- **Automatic mesh generation —** voxel discretization from deposition sequence.
- **Multi-layer tracking —** layer-by-layer mesh activation for AM simulation.
- **Tool-path visualization —** pre-processing validation before simulation.

Technical differentiators

- Focused physics stack aligned with additive manufacturing and furnace-processing use cases
- Manufacturing-native inputs: direct process-derived meshing and layer activation
- Scalable execution: adaptive solver selection and sparse-system optimization across model sizes
- Integration readiness: CLI and service-based deployment for enterprise workflows
- Open downstream use: result formats suited to analytics, validation, and automation pipelines

Getting Started

Step 1 — Request a demo (30 min)

- See RHEONA™ on your example geometry

- Compare speed against your current workflow
- Q&A with the technical team

Step 2 — Proof of concept (1–2 weeks)

- Run your production workflows with RHEONA™
- Validate against experimental data or existing simulations
- Document performance gains and ROI

Step 3 — Integration planning (2–4 weeks)

- Assess deployment architecture (CLI vs. REST vs. distributed)
- Plan data pipelines (CAD/CAM → mesh → RHEONA™ → visualization)
- Identify bottlenecks and optimization opportunities

Step 4 — Production deployment (4–8 weeks)

- Full integration into your application stack
- User training and documentation
- Ongoing support and optimization

Why RHEONA™ Is Different

Academic heritage + industrial focus

- Built by researchers who understand both the physics and the software engineering required for production use
- Every optimization validated against experimental data
- No vaporware — proven, deployed code

Specialization = speed

- We don't try to solve everything — we solve your problem exceptionally well
- Focused optimization for AM, powder metallurgy, and sintering
- Beating general-purpose solvers at their own game on the relevant physics

Your data, your insights

- Open integration with your CAD, CAM, MES, and reporting systems
- Full access to simulation data for ML, process optimization, and digital twins
- Standard formats (VTU, JSON) — no vendor lock-in

Partnership, not transaction

- Dedicated support team for integration and optimization
- Regular updates with new physics models and performance improvements
- Collaborative roadmap — your use cases shape new features

Contact & Next Steps

- **Email —** info@nodivec.com
- **Website —** www.nodivec.com

What happens next

- **15-minute discovery call —** understand your use case
- **Custom demo —** run RHEONA™ on your geometry
- **ROI estimate —** quantify savings from faster simulation

- **Technical deep-dive —** architecture and integration options

Appendix — Advanced Features

A1 · Mesh Generation & Refinement Strategies

Structured meshing

- Layer-aligned hexahedral grids — optimal for AM deposition sequences
- Element aspect-ratio control for accurate physics near heated regions
- Automatic density-based refinement where gradients are higher

Unstructured mesh support

- Hanging-node handling via Lagrange multipliers (no remeshing required)
- Multi-material region support with discontinuous property fields

Adaptive coarsening algorithm

```
Fine mesh (800k elements)
   ↓ analyze element contributions to error
   ↓ mark elements with low energy content
   ↓ merge elements into coarse neighbors
Coarse mesh (200k elements, 75% reduction)
   ↓ hanging-node constraints auto-generated
   ↓ solve on coarse system — cost reduction 10–20%
```

- Automatic DOF reduction without manual coarsening
- Reuse coarse-mesh topology across multiple time steps
- Hanging-node enforcement via constraint equations (exact, no approximation)

A2 · Solver Selection & Convergence Control

Intel Pardiso direct solver

- Best for small-to-medium systems (100K–2M DOF), multiple RHS vectors
- Factorization cost ~O(N^2.3) for 3D FEM; solve cost O(N) per RHS
- Dense factor storage; recommended max ~2M unknowns
- Automatic pivot selection — accurate even for ill-conditioned systems

Iterative solvers with AMG

- Best for large systems (>500K DOF), single solve per iteration
- Algebraic Multigrid preconditioner — 5–10× acceleration
- O(N) memory — scales to 10M+ DOF
- Less sensitive to ill-conditioning than direct solve

```
Problem size < 100K DOF    → Pardiso direct
100K ≤ DOF < 1M            → Pardiso with iterative fallback
DOF ≥ 1M                   → AMG-preconditioned GMRES
```

Convergence acceleration

- Line search — prevent divergence in Newton iterations (backtracking)
- Adaptive tolerance — loosen inner solver tolerance as Newton converges
- Preconditioner reuse — recycle across load steps if topology unchanged

A3 · Post-Processing & Results Export

RHEONA™ exports all results in VTU (ParaView-native) format.

- **Nodal fields —** displacement, velocity, temperature, strain, stress, relative density
- **Element fields —** von Mises stress, strain-energy density, heat flux, material properties
- **Time-series —** full transient history with automatic time-step control

Visualization & monitoring

- Open .vtu directly, animate transient results
- Python post-processing — read VTU, compute custom metrics
- Mesh-quality analysis — aspect ratio, distortion metrics
- Property correlation — density → hardness, stress → fatigue life
- Per-step export for real-time monitoring, ML feature extraction, and adaptive-refinement decisions

A4 · Multi-Level Coarsening with Hanging Nodes

```
Fine level (0):   800,000 hex elements  →  K₀ (2.4M × 2.4M)
Coarse level 1:   merge 8 fine → 1 coarse  →  100,000 elements
                  hanging-node constraints: 1.2M slave DOFs
Coarse level 2:   further merge  →  12,500 elements
                  cascaded constraints: solve with 0.3M unknowns
Refinement:       solve L2 → interpolate to L1 → correct residuals → repeat
```

Mathematical framework

- Slave-DOF values computed from master nodes via Lagrange multipliers
- Constraint equations enforced exactly (not approximate)
- Standard Galerkin FEM — numerically identical to the refined mesh

Performance impact

- Assembly on coarse mesh: 5–10× faster (fewer elements)
- Solve on coarse system: 50–100× faster (100× fewer unknowns)
- Total step: 10–20% faster after constraint-assembly overhead

A5 · Transient Simulation with Adaptive Time-Stepping

RHEONA™ adjusts the time step automatically based on solution behavior:

```
Step 1:  dt = 1.0 s   → compute error estimate
         if error > tol   → halve dt and retry
         if error < tol/10 → increase dt next step
Step 2:  dt = 1.2 s   (increased, steady region)
Step 3:  dt = 0.6 s   (decreased, high thermal gradient)
Step N:  dt → automatic;   total time = Σ dt_i
```

- No user tuning of time-step size
- Coarse steps during steady regions (soak), fine steps during transients
- Automatic restart if divergence is detected

RHEONA™ is designed for teams that need process-specific simulation fidelity, repeatable execution, and integration into real manufacturing workflows.