

METALLAI

Materials Intelligence Platform

Comprehensive Analysis Report

4140

Fe alloy | C-0.42, Cr-1.05, Fe-97.28, Mn-0.80, Mo-0.20, Si-0.25

Yield Strength	937 MPa	Hardness	314 HV
Tensile Strength	1043 MPa	Elongation	14.5 %
Fatigue Life	167,925,363 cycles		

Report generated: September 24, 2026 at 11:53

Classification: Internal / Confidential

Executive Summary

Route assessed: 4140 — Hot Forging — QUENCH TEMPER

Yield strength	937 MPa
Tensile strength	1043 MPa
Hardness	314 HV
Elongation	14.5%
Fatigue life (at the loading entered)	167,925,363 cycles

Process-comparison tier: predictions are reliable enough to RANK alternative routes / heat treatments for this chemistry. NOT a substitute for measured property data when absolute values matter for engineering decisions.

Primary risk drivers: none flagged — input sits inside the training cloud and the standards engine found applicable references.

Recommended next step: Use this report alongside reports for alternative routes / heat treatments to RANK options for this chemistry. Validate the chosen route with the Validation Plan section below before any engineering commitment.

The following pages give the full technical breakdown — process physics, microstructure, strengthening decomposition, fatigue chain, sensitivity analysis, and the route-specific validation plan.

1. Alloy Overview

Metal Family	Fe (Steel)
Alloy Designation	4140
Process Route	Hot Forging
Heat Treatment	Quench Temper

Suitable for:

[x] Screening	[x] Process comparison	[] Pre-production	[] Certification
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Applicable standard found, but model uncertainty (+/-1.9% on yield) or physics quality is too uncertain for design-allowables use. Suitable for route comparison only.

Per-layer confidence:

● Feasibility Caution — some constraints near limits	● Microstructure Good	● Mechanical High — design-quality	● Fatigue Moderate — finite-life screening
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Feasibility layer is the weakest signal: feasibility check raised a warning. Use for process comparison; not for certification.

Domain check: Low extrapolation risk — the current input sits within the dense region of the training data — predictions interpolate rather than extrapolate.

Chemical Composition (wt%)

Fe	Cr	Mn	C	Si	Mo
97.28	1.05	0.800	0.420	0.250	0.200

2. Manufacturing Process

Process Category	Hot Forging
Process Temperature	870.0 C
Strain Rate	2.88 s ⁻¹
Total Strain	0.5
Reduction Ratio	5.689:1

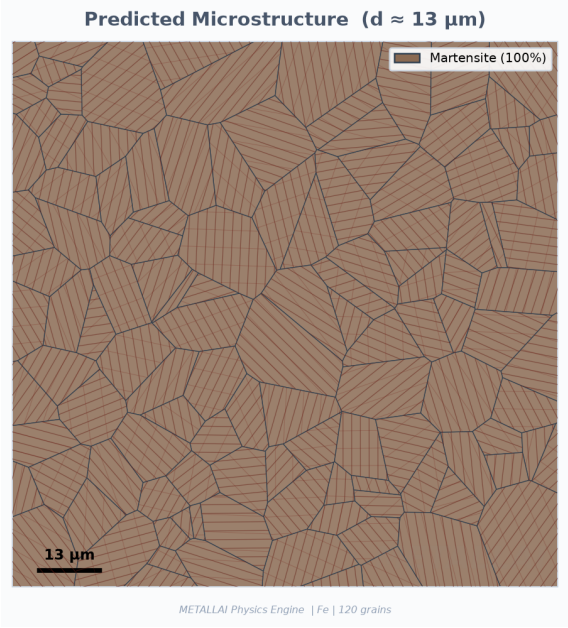
Heat Treatment

Type	Quench Temper
Austenitizing Temperature	850.0 C
HT Temperature	570.0 C
HT Time	2.0 hours
Cooling Method	Oil

Inferred Process Sequence: austenitize 850°C 1.0h → quench 20°C → temper 570°C 2.0h

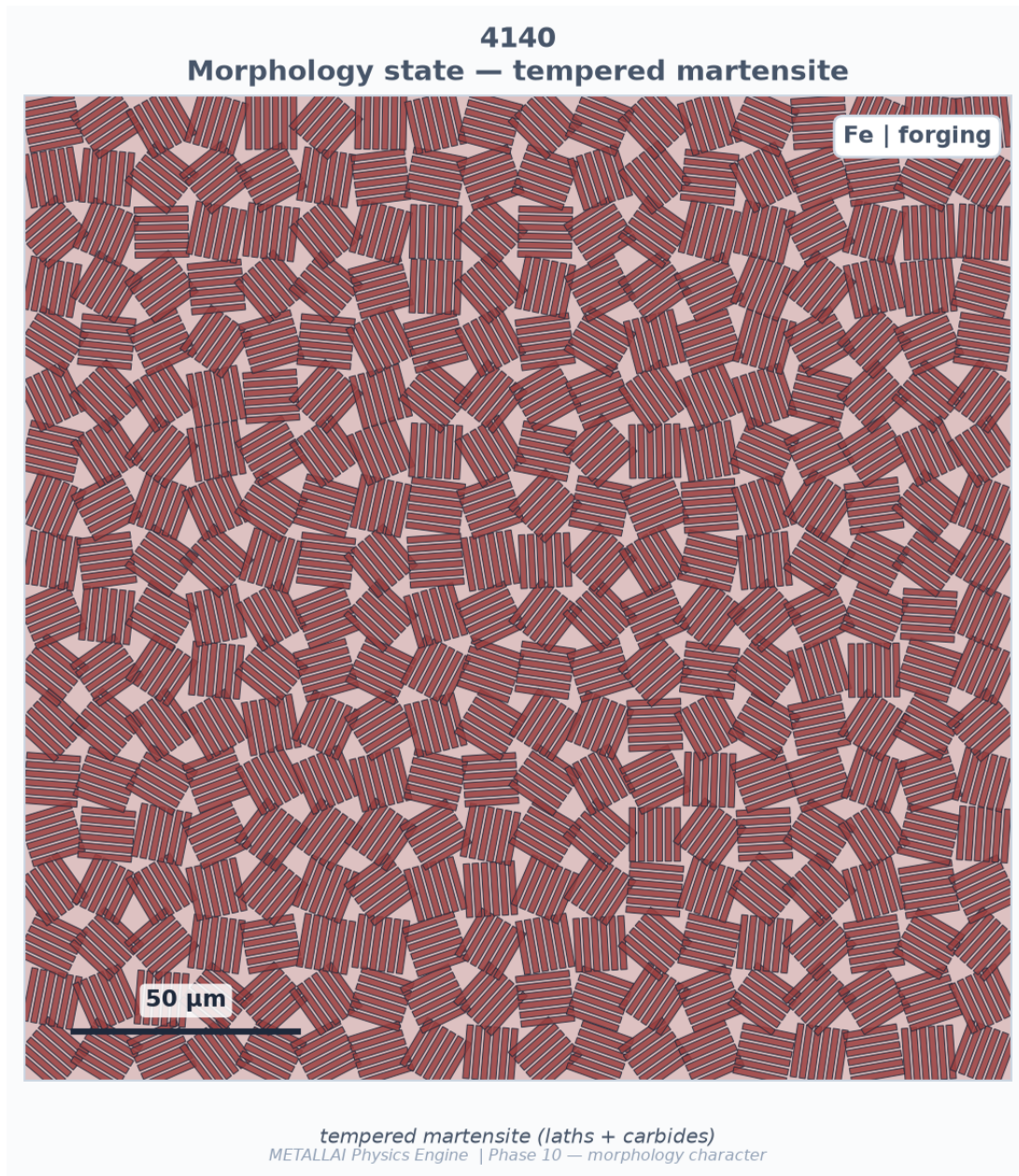
3. Microstructure

Grain Size	13.1 μm
Phase Type	Tempered Martensite
Grain size basis	the heat-treatment stage estimate (heat-treatment stage: austenitized 850 C, 1.0 h (kind default), plain/low-alloy, QT, forge (corpus-calibrated grain growth, leave-one-alloy-out x/÷ 1.38)); the Hall-Petch chart uses 2.6 um, the prior-austenite grain after heat treatment
Martensite	100.0%

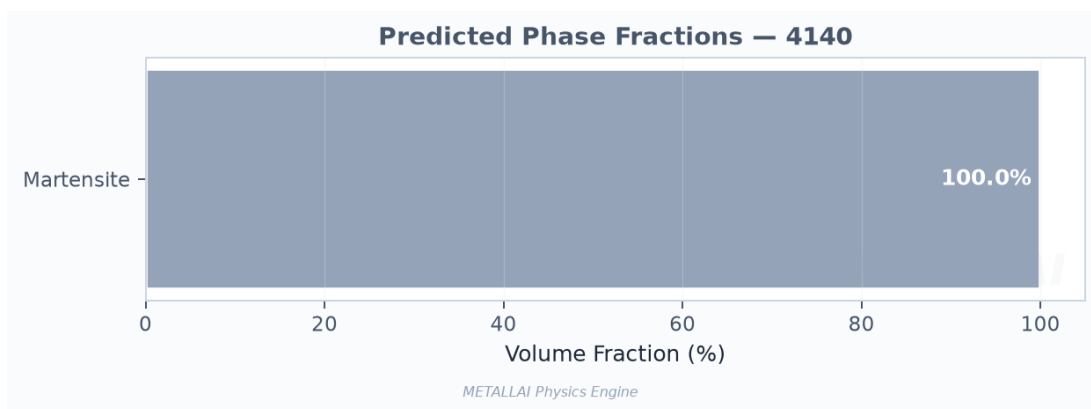


Predicted microstructure (Voronoi tessellation)

Morphology state — same chemistry but different manufacturing route produces different microstructure CHARACTER (dendritic vs equiaxed grains; acicular vs fragmented eutectic; β-AlFeSi plates vs broken fragments; banded vs uniform ferrite-pearlite). The figure below visualises that character schematically.

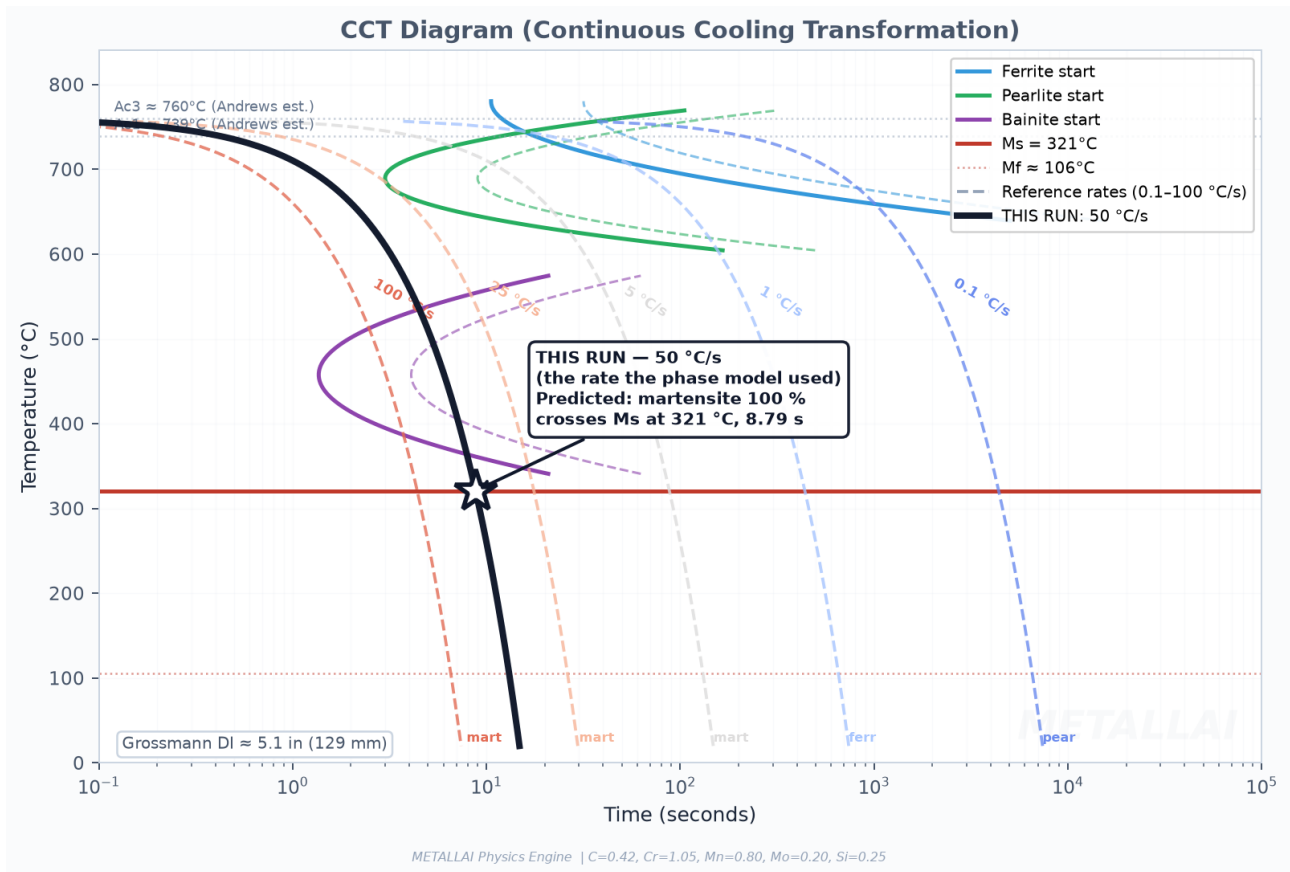


Morphology character: tempered martensite (laths + carbides)



Phase volume fraction distribution

Basis: Koistinen-Marburger leaves 3.6 % austenite untransformed at the quench; it decomposes on tempering at 570 C and is counted with the tempered martensite.



CCT diagram — the bold curve is this run's cooling path (50 °C/s, the rate the phase model used), the star marks where it meets the transformation. Predicted constitution: martensite 100 %. Dashed curves are generic reference rates.

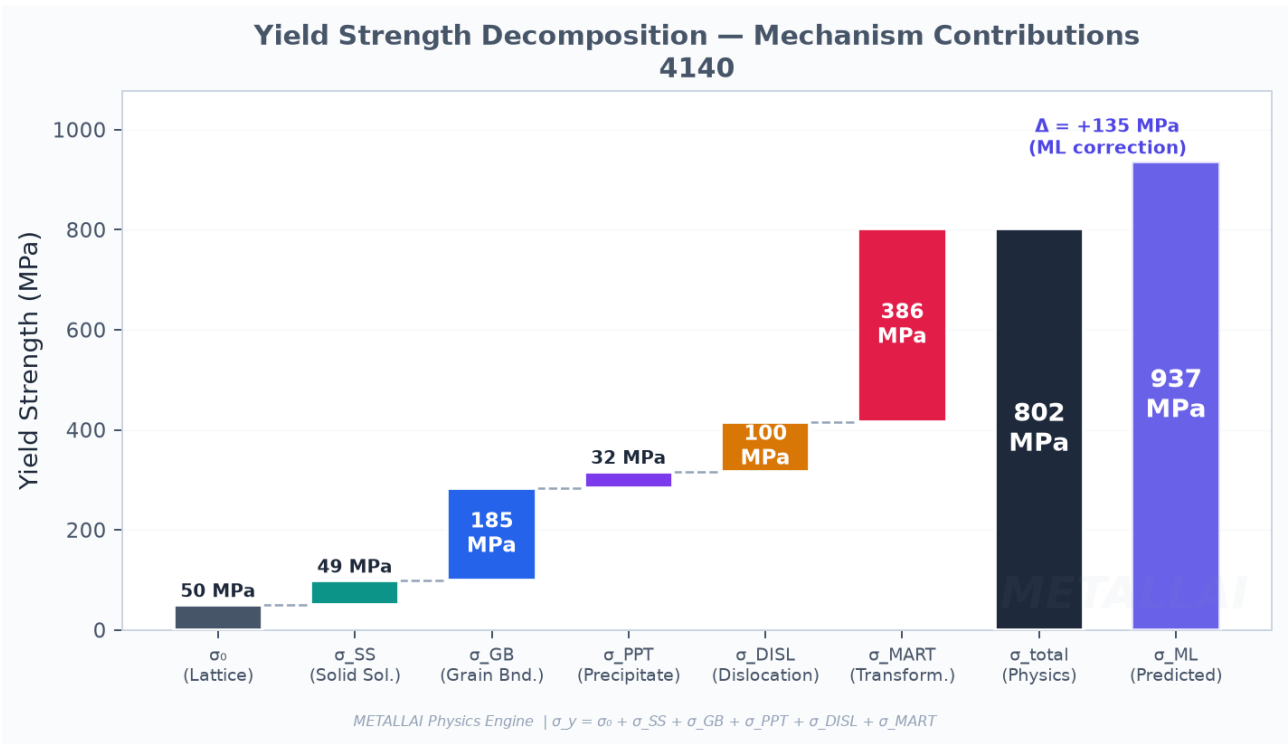
4. Mechanical Property Predictions

Property	Predicted Value	Model spread ($\pm 1\sigma$)	$\pm 1\sigma$ range
Yield Strength	937.2 MPa	+/- 17.9	[919.3, 955.1]
Tensile Strength	1043.1 MPa	+/- 11.2	[1031.9, 1054.3]
Hardness	313.7 HV	+/- 8.1	[305.6, 321.8]
Elongation	14.5 %	+/- 0.7	[13.8, 15.2]
Quality Index (YS x EI)	13,589		

5. Strengthening Decomposition

Mechanism	Contribution
Lattice Friction (sigma_0)	50.0 MPa
Solid Solution (sigma_SS)	48.6 MPa
Grain Boundary (sigma_GB)	185.3 MPa
Precipitation (sigma_PPT)	32.4 MPa
Dislocation (sigma_DISL)	100.0 MPa

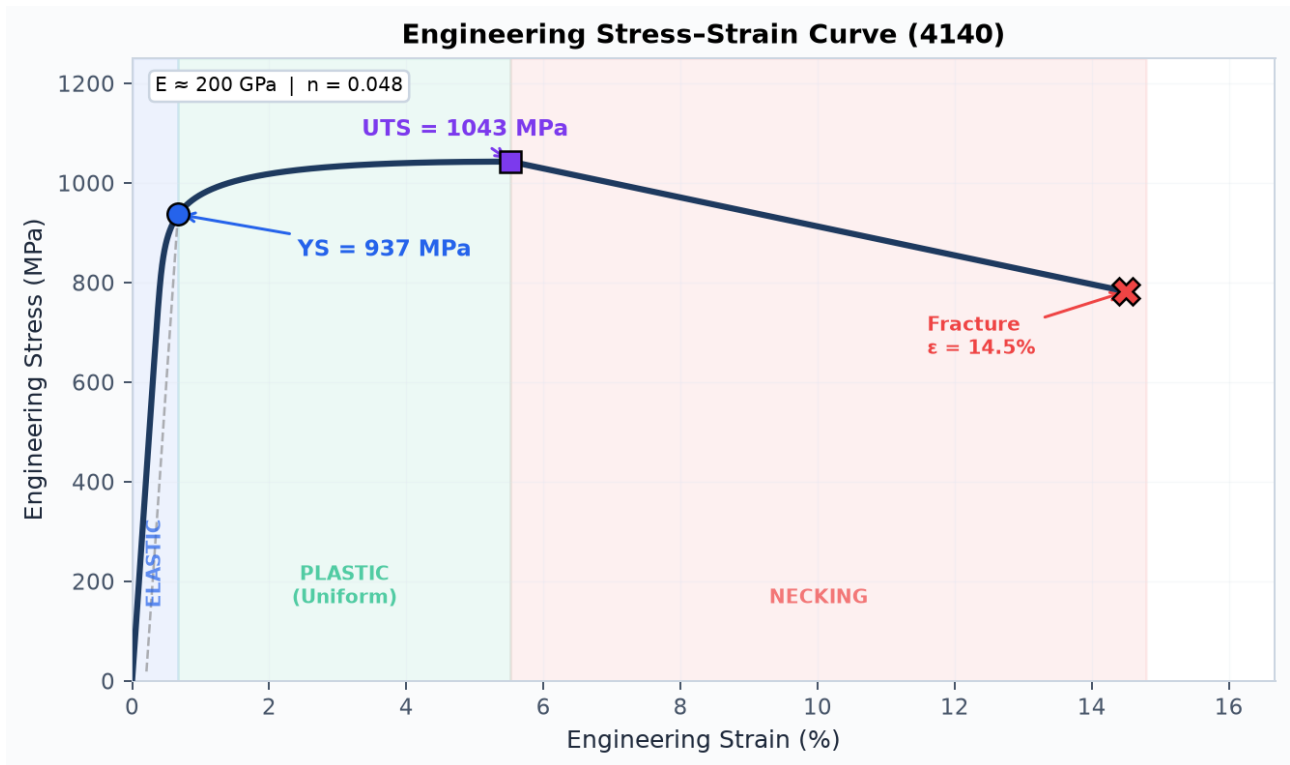
Mechanism	Contribution
Martensite (sigma_MART)	385.9 MPa
Total (Physics)	802.2 MPa
ML Predicted YS	937.2 MPa
Delta (ML correction)	+135.0 MPa



Yield strength mechanism decomposition

Process Sequence: austenitize 850°C 1.0h → quench 20°C → temper 570°C 2.0h

6. Stress-Strain Curve



Synthetic engineering curve — not experimental tensile-test data. Reconstructed from $YS=937$, $UTS=1043$, $EI=14.5\%$ (Ramberg-Osgood / Hollomon $n=0.048$, $K=1275 \text{ MPa}$ true stress, $E=200 \text{ GPa}$). Uniform elongation 5.5% is where the curve's own maximum falls (Considère), not an input.

7. Fatigue Life Analysis

Verdict: Close to the endurance limit — the life is uncertain.

The amplitude is 0.313 of the endurance estimate. Treat the predicted life as a screening estimate, use the conservative design bound (Nf design P10) and confirm by test.

Loading Conditions

Stress Amplitude	100.0 MPa
R-ratio	-1.0
Mean Stress	0.0 MPa
Surface Finish	machined

Fatigue Life Prediction

Predicted Life (Nf)	167,925,363 cycles
log10(Nf)	8.23
Model spread, lower ($\pm 1.96\sigma$)	36,159,916 cycles
Model spread, upper ($\pm 1.96\sigma$)	779,839,401 cycles
Uncertainty	+/- 0.34 decades
Basquin Baseline	10,000,736 cycles
ML Correction	+1.23 decades
Design Life P10 ($\geq 90\%$ survival)	2,074,036 cycles

Model spread is not a confidence interval. On S-N curves the model never saw, this range held 47 % of the measured steel lives and 30 % of them fell BELOW it, so read it as the scatter the model sees rather than a range the answer sits in. The number to design to is the P10 life: at least 90 % of measured lives exceed it.

Fatigue life decomposition — breaks the predicted Nf into an explicit log10(Nf) chain: ideal Basquin baseline (from heat-treatment lookup), process and porosity knockdowns (castings only), the surface finish, the mean stress of this loading, and the residual ML correction. Every step is computed from the parameters the fatigue engine itself used, so the steps sum to the predicted life; a remainder appears only where the engine's baseline stops at its 10^7 -cycle knee.

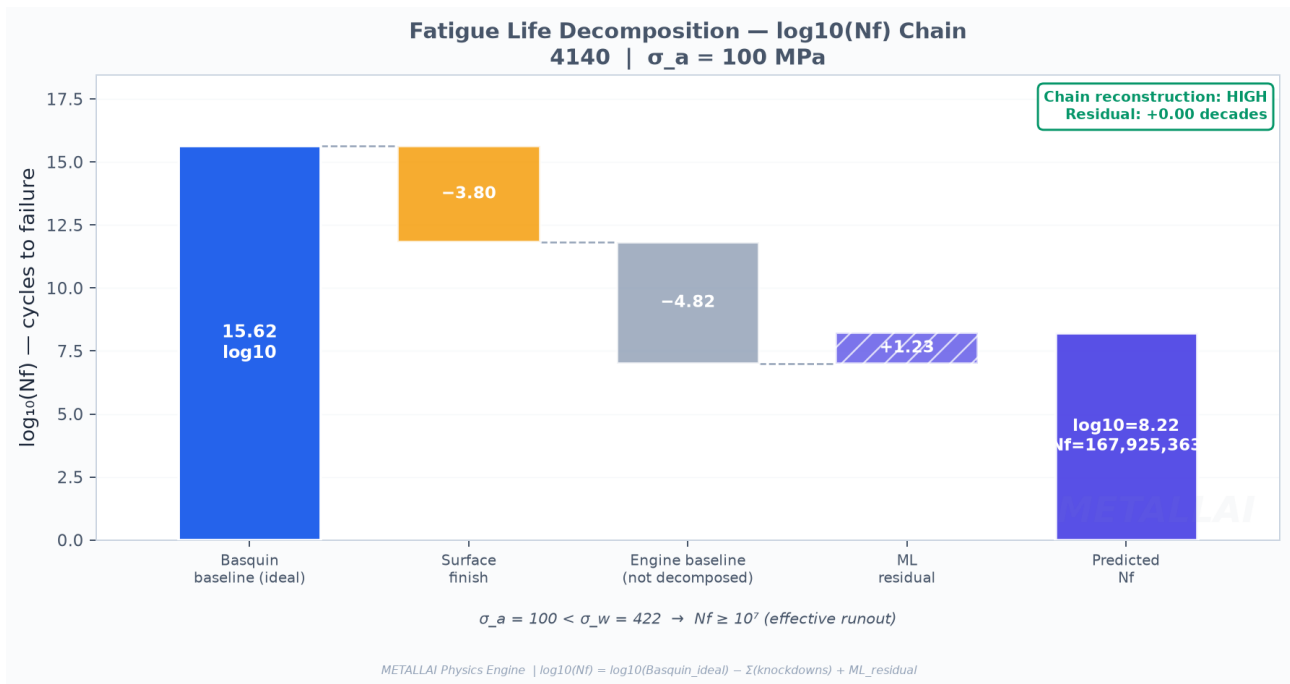
Chain step	Δ contribution
Basquin baseline (ideal $\sigma_f = 1565$ MPa)	+15.62 decades (running: 15.62)
– Surface finish ($k_a = 0.80$)	-3.80 decades (running: 11.82)
– Engine baseline (not decomposed here)	-4.82 decades (running: 7.00)
ML residual correction	+1.23 decades (running: 8.22)
Predicted log10(Nf) / Nf	8.22 (167,925,363 cycles)

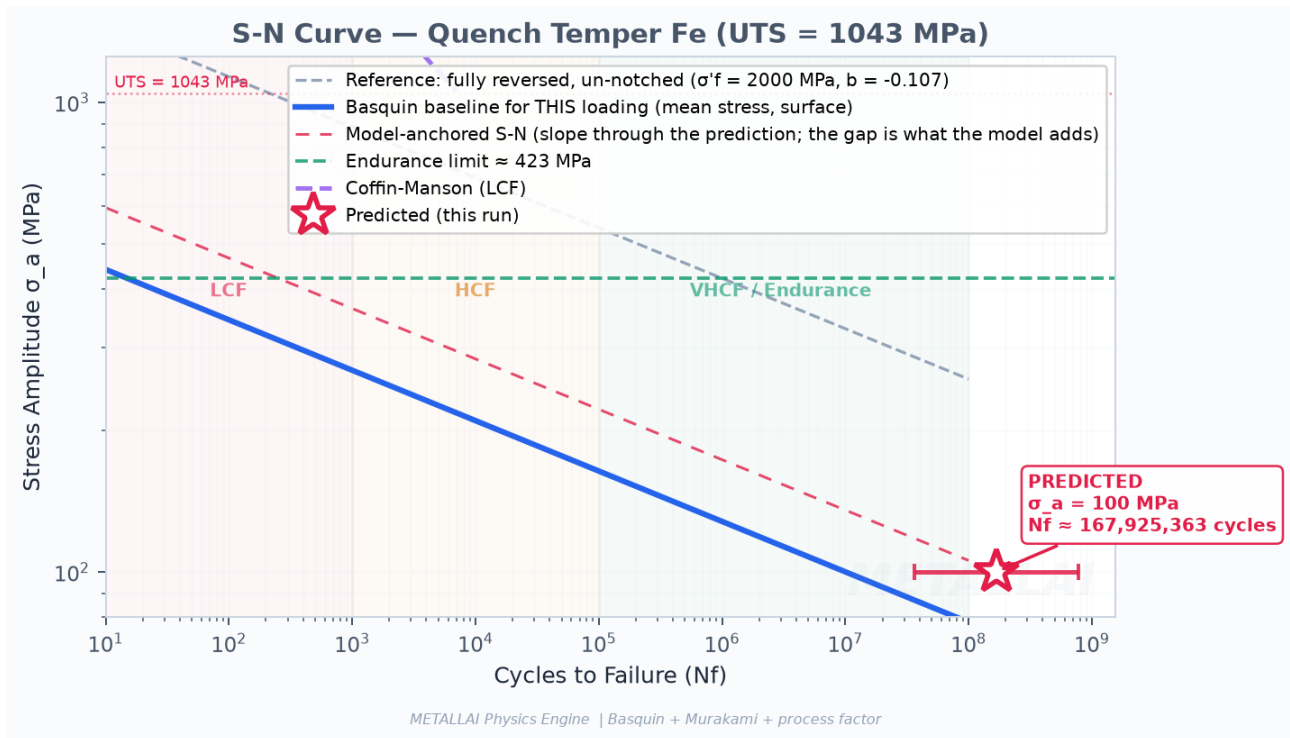
Chain reconstruction: **HIGH** (residual +0.00 decades — physical chain reproduces engine output cleanly).

Defect-size chain — porosity $\rightarrow \sqrt{\text{area}} \rightarrow \text{Murakami } \sigma_w \rightarrow \text{endurance check}$. This is the parallel physical narrative for fatigue: smaller defects raise σ_w and push the safe-life threshold up.

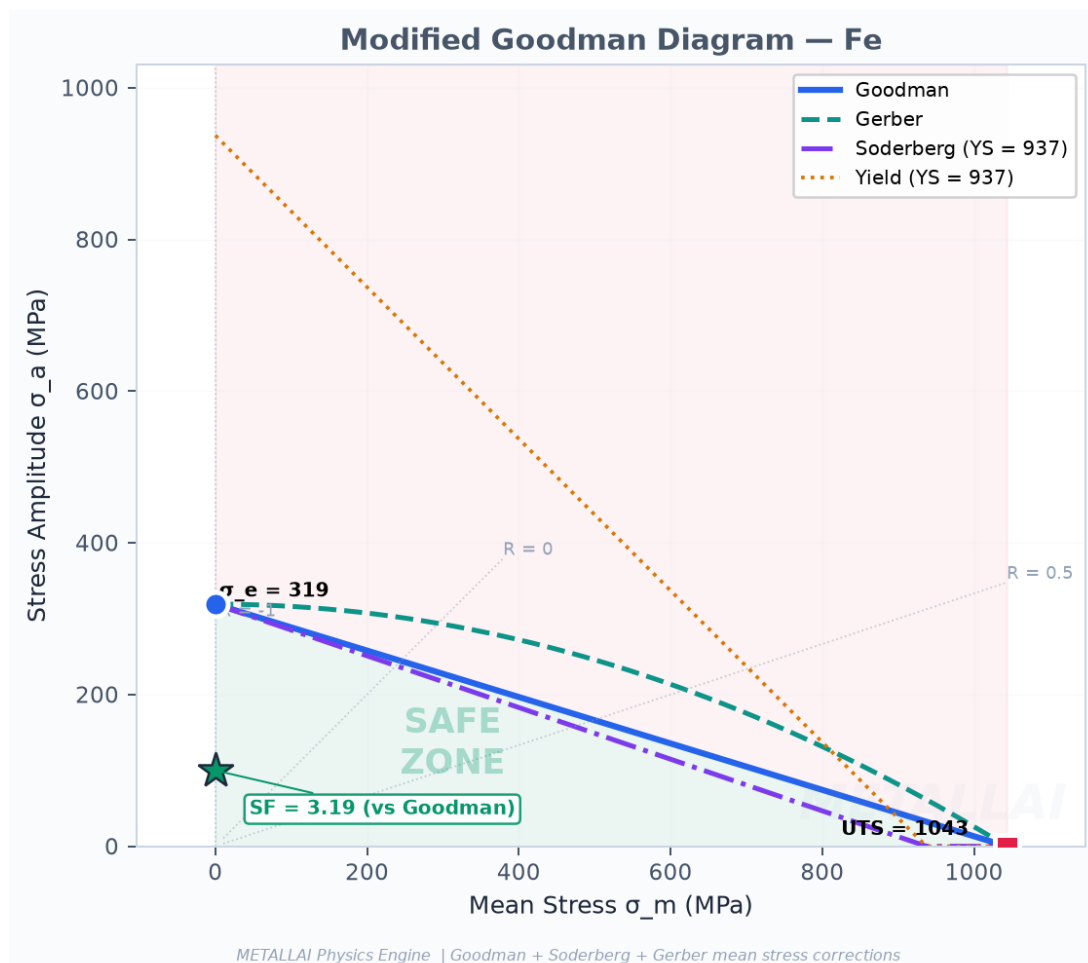
Quantity	Value	Note / source
Porosity	3.00 %	From explicit input
$\sqrt{\text{area_max}}$ (largest defect)	10.0 μm	via forging default (inclusion-only)
Murakami σ_w (endurance limit)	422.5 MPa	$\sigma_w = 1.43 \cdot (\text{HV} + 120) / (\sqrt{\text{area}})^{(1/6)}$, HV = 314, $\sqrt{\text{area}} = 10.0 \mu\text{m}$
Applied stress vs σ_w	-322.5 MPa	Mean-corrected amplitude $\sigma_{ar} = 100 \text{ MPa}$ ($\sigma_a = 100$) is BELOW $\sigma_w \rightarrow$ low defect-initiation risk; bulk S-N model still predicts finite life.

Note: Applied stress is below σ_w AND the predicted life exceeds 10^7 cycles — both the defect chain and the S-N life model agree on effective runout behaviour.

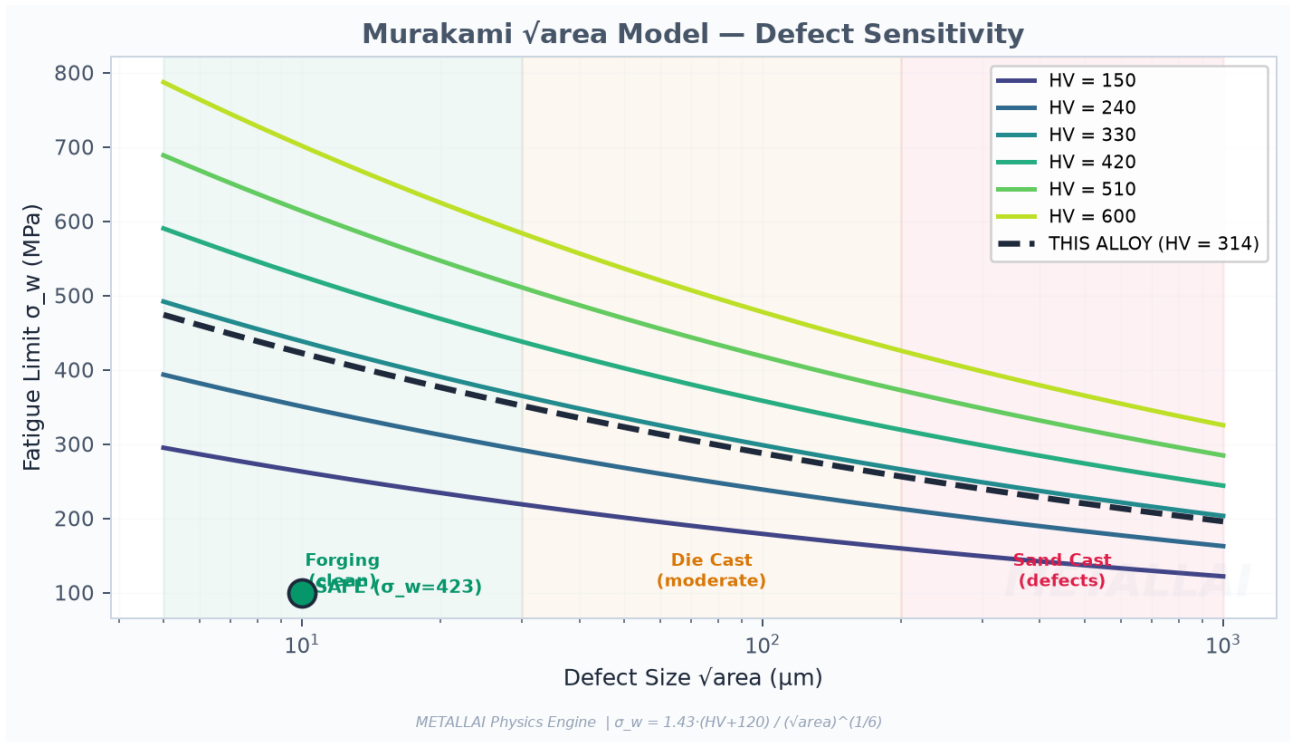




S-N curve — starred point is this run's prediction: $\sigma_a = 100$ MPa $\rightarrow N_f \approx 167,925,363$ cycles (model spread 36,159,916 – 779,839,401; design to N_f P10); Basquin line uses the fatigue model's own fit



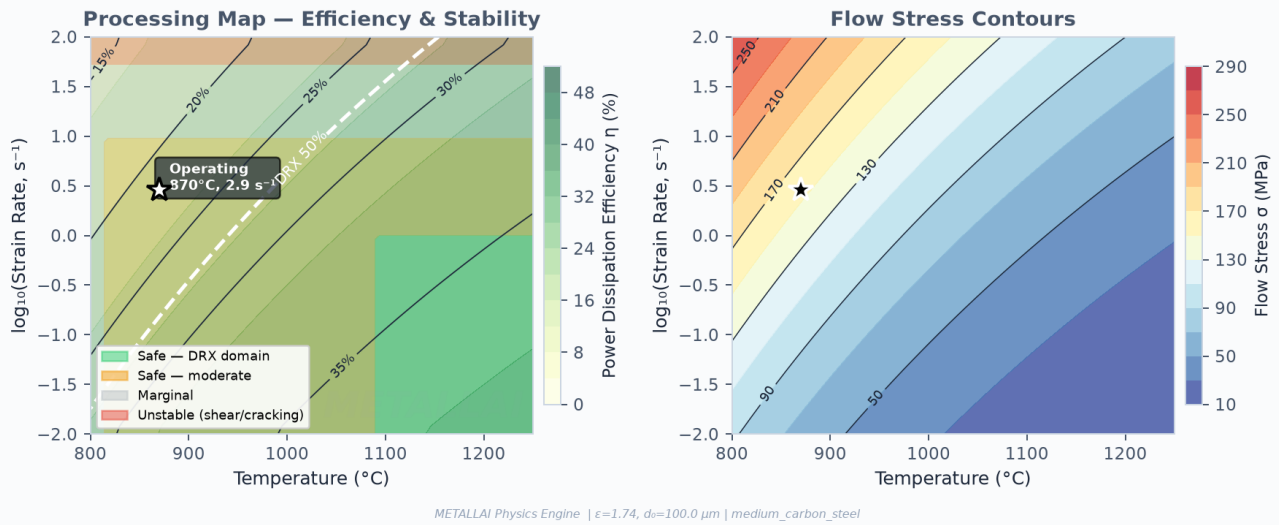
Goodman / Soderberg / Gerber diagram — operating point ($\sigma_m = 0$, $\sigma_a = 100$) MPa, $\sigma_{e,eff} = 319$ MPa, the limit derated for this part (surface, process and load factor; polished-specimen $\sigma_{e,raw} = 469$ MPa). The safety factor is a screening number against an infinite-life line; the predicted cycles and the P10 design life are the life answer.



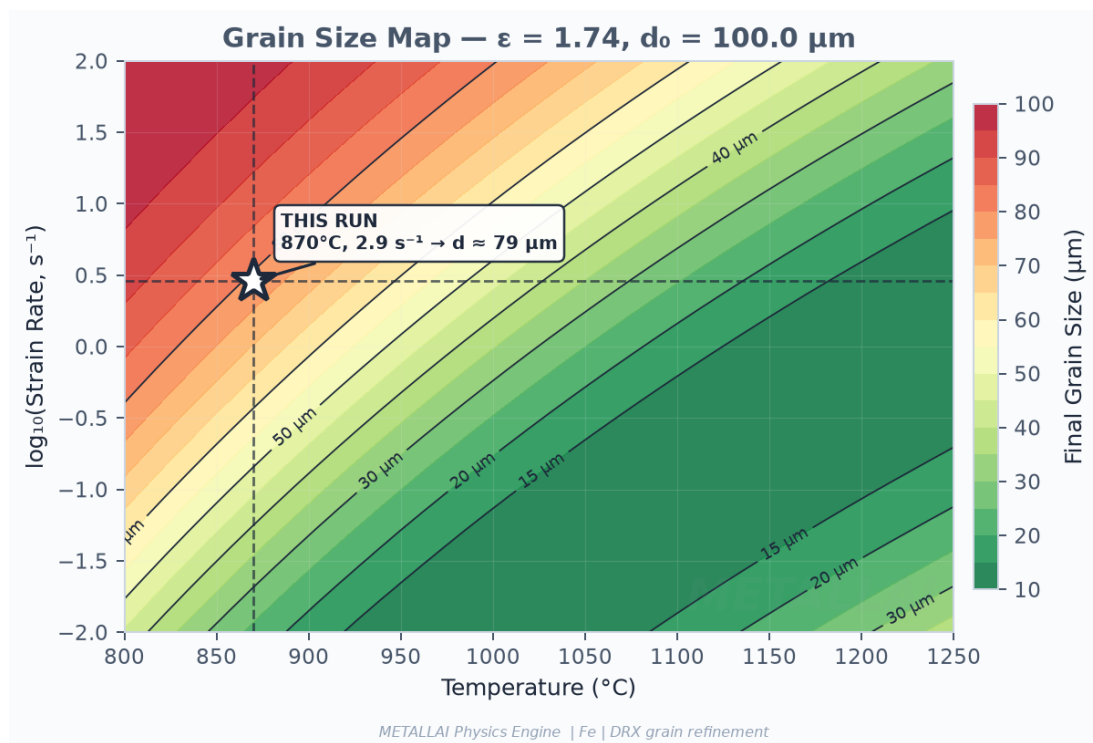
Murakami defect sensitivity — operating point at this run's predicted defect size $\sqrt{\text{area}} \approx 10 \mu\text{m}$, HV = 314, $\sigma_a = 100$ MPa

8. Process Physics

Hot Deformation Analysis — Medium Carbon Steel ($\epsilon = 1.74$)

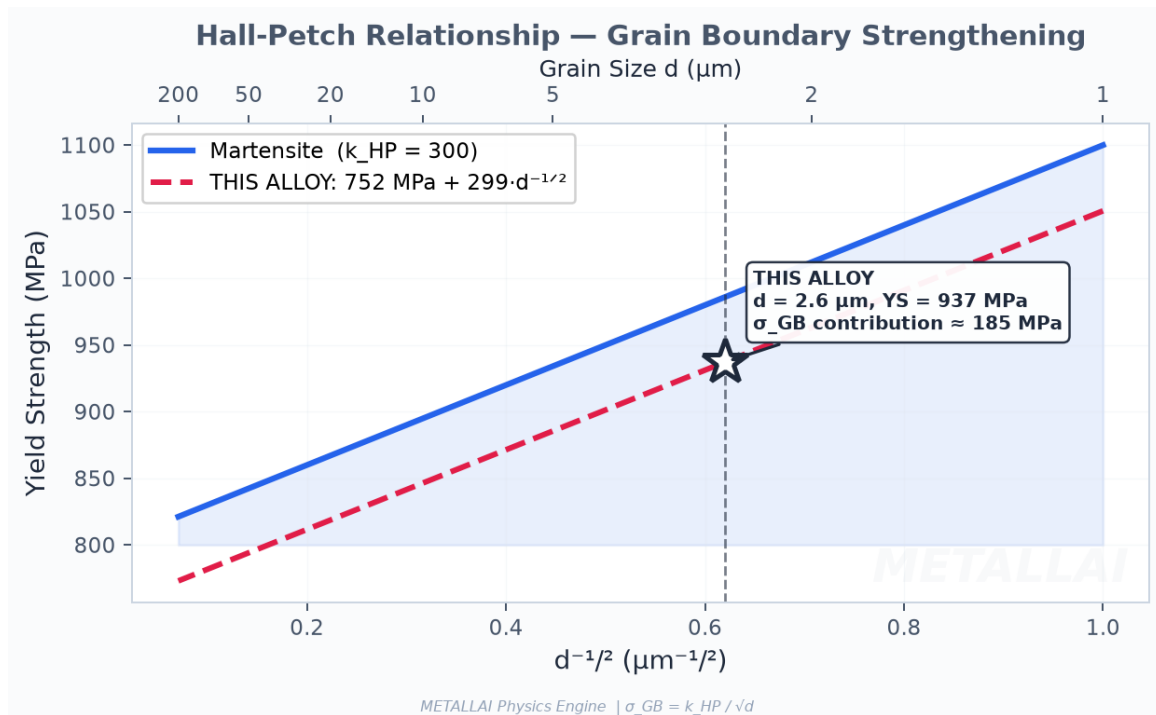


Processing map — this run operates at 870°C, 2.9 s⁻¹ (zone: safe moderate); efficiency, stability zones & flow stress contours. The surface is built from alloy-class hot-working constants, not from a measured processing map of this grade.



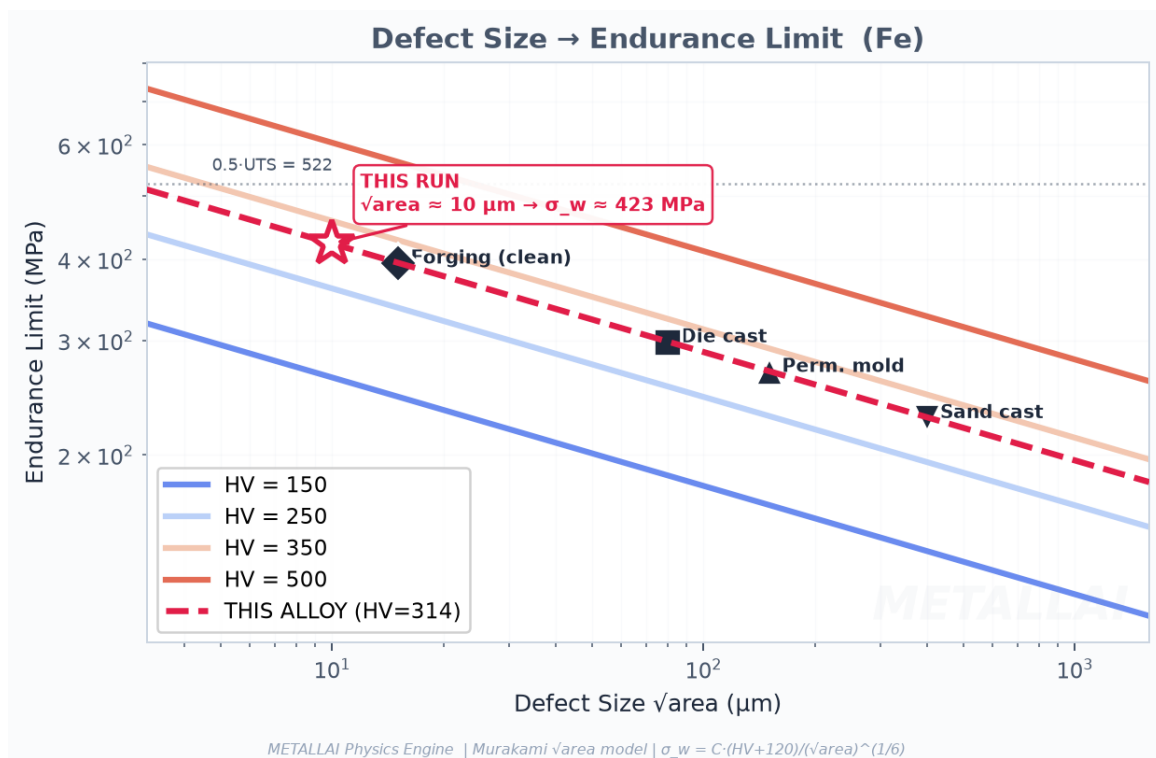
Grain size map — grain size right after hot working (partial DRX of the 100 μm starting grain), starred at this run's conditions. The final grain size reported for this run is 13 μm , after cooling and any heat treatment (re-austenitising resets a steel's grain), so it need not match the contour under the star

9. Additional Physics Charts



Hall-Petch relationship — this alloy started at $d = 2.6 \mu\text{m}$ (used by the strengthening model (post-HT)), predicted YS = 937 MPa; grain-boundary term contributes 185 MPa

Porosity vs fatigue life — not plotted for this run: the run reports 3.00 % porosity but no dendrite arm spacing, and this curve's porosity $\rightarrow \sqrt{\text{area}}$ step is built on one. The $\sqrt{\text{area}}$ the fatigue model did use is starred on the Murakami diagram in section 7.



Defect size vs endurance limit (Murakami model) — the dashed curve is this alloy (HV = 314), starred at the $\sqrt{\text{area}} \approx 10 \mu\text{m}$ the fatigue model used for this run. The labelled markers are typical defect sizes for other routes, shown for scale — they are not this run.

10. Sensitivity Analysis

Normalised effect coefficients showing the **direction and relative magnitude** of each input parameter's influence on the predicted properties. Values are dimensionless, scaled to roughly [-1, +1]: positive = parameter increase raises the property; negative = parameter increase reduces the property; magnitude indicates relative importance (≥ 0.6 strong, ≥ 0.3 moderate, < 0.3 weak). These are NOT absolute partial derivatives in MPa per wt% — use them for ranking and optimisation direction, not quantitative gradient estimates.

Parameter	YS MPa	UTS MPa	Hardness HV	Elongation pct	Fatigue
C content (wt%)	+0.8	+0.8	+0.9	-0.7	+0.3
Cr content (wt%)	+0.4	+0.4	+0.4	-0.2	+0.2
Mo content (wt%)	+0.4	+0.4	+0.4	-0.1	+0.2
Mn content (wt%)	+0.3	+0.3	+0.2	-0.1	+0.1
Si content (wt%)	+0.3	+0.2	+0.2	-0.2	+0.1
— Process and Heat-Treatment Parameters —					
tempering temp (°C)	-0.7	-0.6	-0.7	+0.6	-0.3
quench severity (H)	+0.5	+0.4	+0.6	-0.3	+0.1
surface finish					+0.6
DRX grain size (µm)	-0.5	-0.4	-0.4	+0.2	-0.3
grain size (µm)	-0.5	-0.3	-0.3	+0.2	-0.2
forging temperature (°C)	-0.3	-0.2	-0.2	+0.2	-0.2
strain rate (s ⁻¹)	+0.3	+0.2	+0.2	-0.1	+0.1
reduction ratio	+0.3	+0.3	+0.2	+0.2	+0.3
tempering time (h)	-0.3	-0.3	-0.3	+0.3	-0.1

Top levers for this prediction:

- **C content (wt%)** strongly raises hardness (+0.9)
- **tempering temp (°C)** strongly reduces yield strength (-0.7)
- **quench severity (H)** strongly raises hardness (+0.6)

How to read this table: for this steel hot forging route, the dominant levers for static strength are C content, hardenability elements (Cr / Mo / Mn / B) and tempering temperature + time (Hollomon-Jaffe). For

fatigue, forging temperature, strain rate, and reduction ratio set the recrystallised grain size, which controls fatigue performance through Hall-Petch and defect closure — these are the highest-leverage process levers for this route. Use the table to RANK candidate changes — not to estimate absolute MPa-per-unit-step gradients.

11b. Similar Alloys

Database alloys closest to this composition, ranked by weighted composition distance (lower = more similar; C and heavy alloying elements weigh most). ΔYS compares each benchmark against THIS prediction — use it to judge whether the predicted strength sits inside the envelope of known commercial grades. The **Class** column shows each benchmark's alloy type, so cross-class near-neighbours are visible, not just same-family grades.

Compared against **37** reference grades spanning 12 alloy classes; the 8 closest are shown below. top matches span: Carbon steel (low-C), Carbon steel (medium-C), Low-alloy steel. classifier placed this alloy in the low alloy steel family.

Alloy	Class	YS (MPa)	ΔYS	UTS (MPa)	HV	El (%)	Distance
» 4140 (this prediction)	(target)	937	—	1043	314	14.5	0 (self)
AISI 4140 Q&T	Low-alloy steel	900	-37	1050	320	15	0.14
AISI 4130 N	Low-alloy steel	460	-477	670	210	22	0.36
EN 25CrMo4	Low-alloy steel	700	-237	900	270	16	0.38
AISI 8620 Carb.	Low-alloy steel	360	-577	530	160	26	1.03
AISI 1040	Carbon steel (medium-C)	350	-587	570	167	25	1.31
AISI 1045	Carbon steel (medium-C)	415	-522	655	187	20	1.31
A36 Structural	Carbon steel (low-C)	250	-687	400	119	23	1.36
AISI 1060	Carbon steel (medium-C)	480	-457	750	229	13	1.37

Closest commercial benchmark: AISI 4140 Q&T (distance 0.14; predicted YS is +4% vs its 900 MPa). The composition is essentially within this grade's window — its published datasheets and standards are directly useful sanity anchors. Typical applications of AISI 4140 Q&T: Shafts, gears.

12. Standards Compliance

Applicable standards — composition and route both within the standard's design scope. PASS/FAIL verdicts are meaningful.

AISI 4140 — YS_MPa: **PASS** (predicted 937.2, required ≥ 655.0 / ≤ 1100.0 , margin +43% vs min)

EN 10083-3 42CrMo4 — YS_MPa: **PASS** (predicted 937.2, required ≥ 650.0 / ≤ 1100.0 , margin +44% vs min)

Certification grade. European Q&T alloy steels with cert-grade properties.

Considered but not applicable — these standards were checked but their composition envelope does not cover this alloy. Listed for transparency.

AISI 4340 — Composition outside 4340 Ni-Cr-Mo low-alloy steel (Q&T) envelope (Cr=1.050% > required max 0.9%).

AISI 8620 — Composition outside 8620 Ni-Cr-Mo carburizing steel envelope (Cr=1.050% > required max 0.6%).

Decision rationale — why each suitability level on the cover is checked or unchecked.

[x] **Screening**: Feasibility OK. Acceptable for concept exploration and "is this direction plausible" triage.

[x] **Process Comparison**: Strengthening quality is NORMAL; model uncertainty $\approx \pm 1.9\%$ on yield (self-reported spread, not measured error). Suitable for ranking alternative routes.

[] **Pre Production**: Blocked by: feasibility status is WARNING (need VALID); strengthening quality is NORMAL (need HIGH).

[] **Certification**: Blocked by: pre-production criteria not met; fatigue uncertainty ± 0.34 decades > ± 0.2 threshold.

13. Metallurgical Warnings & Advisories

5 finding(s): 0 critical, 3 warning, 2 advisory. Critical findings are listed first.

WARNING [Weldability] — If this part is welded: carbon equivalent CE(IIW) = 0.80 — hydrogen-induced HAZ cold cracking becomes likely above 0.45 without precautions.

→ Preheat $\approx 250^\circ\text{C}$ (section-dependent), low-hydrogen consumables, and slow cooling; qualify the procedure per ISO 15614.

WARNING [Feasibility] — Temperature 870°C is below typical Fe forging window ($900\text{--}1250^\circ\text{C}$). Flow stresses will be high; cracking risk.

→ Consider raising to $\geq 900^\circ\text{C}$ for cleaner deformation.

WARNING [Loading below the endurance limit] — **BELOW THE ESTIMATED ENDURANCE LIMIT**: the applied amplitude is 0.31 of the engine's textbook endurance-limit estimate, where classical S-N would call the loading run-out. In the Fe training corpus, of the 315 tests loaded below this estimate 280 FAILED, at a median of $10^{6.52}$ cycles, and only 36 % reached $1e7$ -- so the estimate is not a limit the data respects. The finite life shown therefore has a data basis: the Basquin term is saturated at $1e7$ here and the number comes from the ML residual fitted on those rows. Treat it as less certain than a life above the limit -- it is not monotonic in stress or mean stress across this region -- and do not present it or Nf_design_P10 as a design life. The endurance-limit estimate itself is the weaker of the two numbers.

→ Treat the part as run-out at this amplitude. If a finite number is required, use the P10 design bound rather than the point estimate, and raise the amplitude above σ_e if you need a calibrated life.

ADVISORY [Microstructure] — Grain size 13.1 μm was not measured: it is the heat-treatment stage estimate (heat-treatment stage: austenitized 850°C , 1.0 h (kind default), plain/low-alloy, QT, forge (corpus-calibrated grain growth, leave-one-alloy-out $\times/\div 1.38$)). It enters the model through the strengthening decomposition; the model's own grain column is left at its 'grain not stated' value (79.0 μm), which the alloy-disjoint measurement showed predicts an unseen alloy better than an estimate. Strength is little affected -- across 5-60 μm the yield moves about 5 % on steel and 11 % on aluminium, inside the model's own accuracy -- but the layer-4 fatigue limit is sized from the grain and moves by roughly half over the same range, so treat the endurance limit as the number this assumption reaches.

→ Supply a measured grain size (grain_size_um together with grain_size_measured=true) if one is available; it is then used as entered. Where no measurement can be obtained from the supplier, treat the fatigue limit as the number most exposed to this assumption and confirm it by test.

ADVISORY [Feasibility] — Austenitize temperature 850°C exceeds A_{c3} (760°C) by 90°C . Some prior-austenite grain growth expected but within normal industrial range.

→ For finest-grained Q&T, lower toward 790°C.

14. Validation Plan

Recommended lab measurements to validate this prediction before any engineering commitment. The baseline programme applies to every prediction; the route-specific section adds measurements that capture risk drivers unique to hot forging.

Baseline programme:

- **Tensile test (per ASTM E8/E8M or equivalent)** — YS, UTS, elongation, reduction-of-area on at least 3 specimens to anchor the static-strength predictions.
- **Hardness test (per ASTM E18 Rockwell or E92 Vickers)** — Confirms the predicted hardness and serves as a quick process-consistency check across batches.
- **Optical microscopy (per ASTM E3 / E407 etched section)** — Verify the predicted phase distribution and grain size / SDAS visually before relying on the multi-phase decomposition for design decisions.

Route-specific add-ons (forging):

- **Macroetch and flow-line inspection (per ASTM E381)** — Confirm uniform deformation and absence of laps, folds, or unreacted die-fill — the typical forging defects that bypass the model.
- **Texture / anisotropy check (longitudinal vs transverse tensile)** — Forging produces directional properties; the prediction is for the dominant loading direction. Measure both orientations if loading direction is uncertain.
- **Grain-size measurement (per ASTM E112)** — Verify the DRX-recrystallised grain size used by the strengthening decomposition.
- **1 fatigue point at the design stress amplitude** — Wrought forging fatigue is normally defect-tolerant; one measured point is enough to anchor the S-N curve.

Steel-specific add-ons:

- **Through-thickness hardness traverse (Jominy-informed)** — Confirms the section actually through-hardened; the prediction assumes the stated microstructure at the evaluation location.
- **Charpy V-notch at minimum service temperature (ASTM E23)** — Tempered martensite embrittlement and low-T toughness are not captured by static-strength predictions — mandatory for impact-loaded or sub-zero service.
- **Weldability qualification (if welding is foreseen)** — Carbon equivalent is elevated ($CE_{IIW} \approx 0.55$ from C+Mn/6 alone) — preheat / PWHT procedure qualification per ISO 15614 advised before production welding.

Acceptance anchors — each prediction with its model uncertainty ($\pm 1\sigma$). Use the range as a guide, not a pass/fail limit: a measured value far outside it means the model is extrapolating for this material state and needs recalibration:

Property	Predicted	Model uncertainty ($\pm 1\sigma$)
Yield strength	937 MPa	919 – 955 MPa
Tensile strength	1043 MPa	1032 – 1054 MPa

Property	Predicted	Model uncertainty ($\pm 1\sigma$)
Hardness	314 HV	306 - 322 HV
Elongation	14.5 %	13.8 - 15.2 %
Fatigue life (at entered loading)	167,925,363 cycles	36,159,916 - 779,839,401 cycles

These measurements are NOT a substitute for the applicable design code's acceptance plan when one exists. They are a pragmatic minimum set for converting this report's screening or process-comparison output into an engineering decision with quantified risk.

Disclaimer: This report is generated by METALLAI v2.0, a hybrid physics-ML prediction system. Predictions are estimates based on trained models and established metallurgical equations. Actual material properties may vary. All predictions should be validated against experimental measurements before use in critical engineering decisions.