Indigenous Steels for India's First CO_2 Battery

Indigenous Life-Cycle-Qualified Pressure-Vessel Steels for India's First CO_2 Battery Energy Storage System

ASME SA 517 Gr B and SA 533 Gr B Cl 3, quenched & tempered plate for the 160 MWh CO_2 Battery at NTPC Kudgi (Energy Dome technology) · Jindal Steel, Angul Plate Mill



PRESENTING TEAM

Sankhadip Mandal
General Manager

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Manager

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Jindal Steel Limited — integrated route to Angul plate

9.25 MT
CRUDE STEEL PRODUCED, FY26

8.68 MT
STEEL SOLD, FY26

₹ 62,412 Cr
ANNUAL TURNOVER

1979
YEAR OF ESTABLISHMENT

INTEGRATED WORKS
BF 1&2 (3.85 + 4.2 MTPA), SMS-1 &2,slab caster, twin slab caster, ultra-clean secondary metallurgy.

PLATE MILL & HEAT TREATMENT
Plate Mill 1.2 MTPA (8–150 mm) + Heat Treatment Complex, (AF1 , AF2 , TF1 , TF2)

Steel Plate / Plate Mill Process Flow

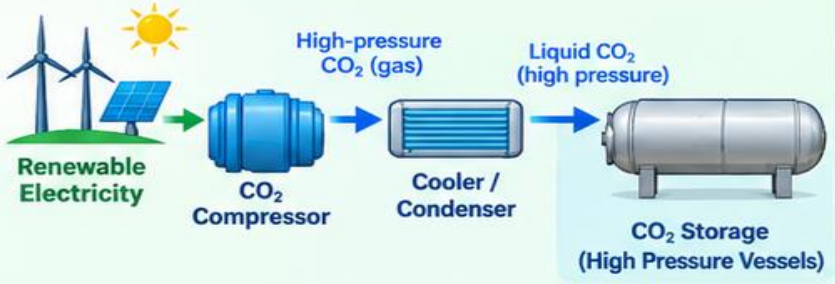


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India's first CO_2 battery steels

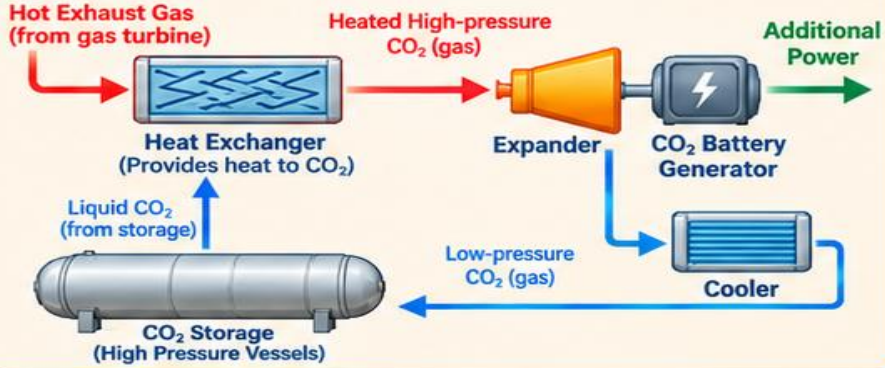
1 Charge Mode (Store Energy)

During low-demand hours or excess renewable production, power is used to compress CO_2, which is then stored as a liquid in high-pressure vessels.



2 Discharge Mode (SuperBoost)

During peak-demand hours, the liquid CO_2 is evaporated and heated using heat from the gas turbine's exhaust(s), driving an expander and thereby running the CO_2 Battery turbine, providing additional power comparable to that of an additional gas turbine (>100%).



Pressure Vessel Steels for CO_2 Battery

ASME SA 517 (Gr B) & ASME SA 533 (Gr B, Cl 3)

ASME SA 517 — Gr B

High Strength • Q&T • Pressure Vessels

Tensile Strength (UTS): ≥ 690 MPa	Impact Energy (CVN): ≥ 28 J individual; ≥ 40 J average @ –29 °C
Yield Strength (YS): ≥ 450 MPa	Min. PWHT: 620–680 °C (as per TDC)
Elongation (EL): ≥ 16% (t ≥ 22 mm)	Microstructure: Tempered Martensite
	Key Chemistry: C 0.12–0.20 | Mn 0.70–1.30 | P ≤ 0.025 | S ≤ 0.010

CO_2 STORAGE PRESSURE VESSEL

Application: High-pressure liquid CO_2 storage

ASME SA 533 — Gr B, Cl 3

High Toughness • Pressure Vessels

Tensile Strength (UTS): ≥ 585 MPa	Impact Energy (CVN): ≥ 60 J average @ –20 °C and –29 °C
Yield Strength (YS): ≥ 415 MPa	Min. PWHT: 620–690 °C (as per TDC)
Elongation (EL): ≥ 18% (t ≥ 22 mm)	Microstructure: Tempered Bainite / Martensite
	Key Chemistry: C 0.15–0.25 | Mn 0.60–1.20 | P ≤ 0.025 | S ≤ 0.010

Where SA 517 & SA 533 Are Used

The CO_2 is stored in high-pressure, liquid form in pressure vessels. These vessels are fabricated using high-strength pressure vessel steels such as SA 517 and SA 533 (as per vessel designer's code and specification).

Key Role

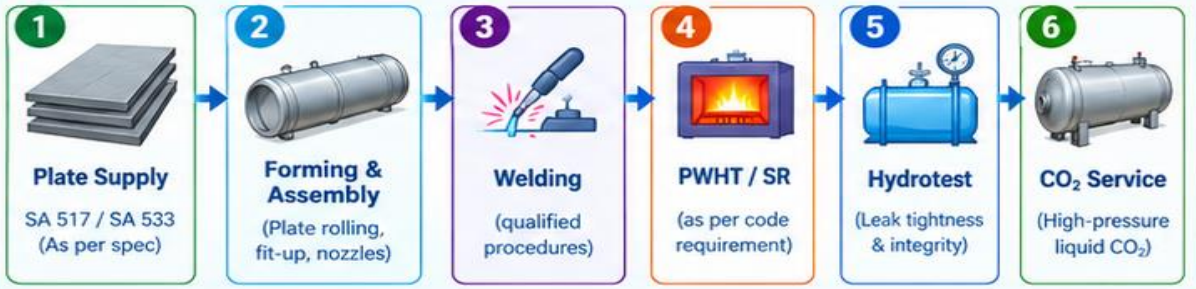
- High pressure containment
- High strength & toughness
- Reduced vessel wall thickness
- Long service life in CO_2 environment



Typical Operating Condition

Pressure: High (as per design) | Temperature: Ambient (liquid CO_2)

Pressure Vessel Fabrication Process



Why It Matters

Enables Renewable Integration
Stores excess renewable energy as clean CO_2.

Higher Output
>100% additional power in SuperBoost mode (+ up to 25% in Boost mode).

Reliable & Safe
Uses proven pressure vessel technology and high-strength steels (SA 517 / SA 533).

Supports Net Zero
Low carbon, long-duration energy storage for a cleaner future.

Proving the Plate in the Fabricator's Thermal History

Material Receipt & Traceability



Receipt of ASME SA 517 & ASME SA 533 steel plates with MTC review and traceability check.

Plate Marking & Cutting



Marking, nesting and cutting of circular blanks from ASME SA 517 and ASME SA 533 plates.

Edge Preparation & Blank Inspection



Edge beveling as per drawing and inspection of blank diameter, thickness and edge profile.

Dishing & Knuckle Forming



Trim, Bevel & Dimensional Check



Trimming to final size, edge bevel (if required) and dimensional inspection (diameter, depth, profile and thickness).

PWHT Preparation



Claaning, thermocouples installation and preparation for PWHT furnace loading.

PWHT: Controlled Heating, Soaking & Cooling



CRITICAL PWHT STAGE

PWHT of ASME SA 517 and ASME SA 533 dish ends in controlled furnace cycle (heating, soaking and cooling) as per approved procedure.

Post-PWHT Inspection



Hardness testing and dimensional measurement

NDT



RT / PT / MT as per ITP

Final Acceptance, Preservation & Dispatch



Final inspection acceptance, stamping, preservation (anti-corrosion) and packing for dispatch.

HEAT TREATMENT COMPLEX



Austenitizing Furnace



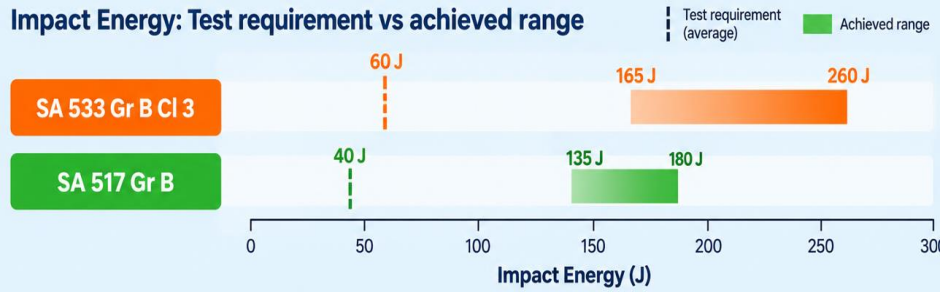
Quenching System



Tempering Furnace

(water quench after austenitizing)

VALUES REACHED AGAINST THE APPROVED TDC



SA 533 GR B CL 3 — ANUP ENGINEERING, thickness 8–40 mm

N1 Hot forming	N2 (Austenitize + Q)	SR3 Tempering	SR1 ×2 cycles	SR2 ×4 cycles	Re-test
900±10°C, 1.2min/mm 40mm only	900±10°C, , 1.2min/mm 40mm only	585°C min, 20min minimum 40mm only	555±10°C, 150min / cycle 20mm & 34mm only	555±10°C, 150min / cycle 20mm & 34mm only	tensile, impact, hardness, microstructure

SA 517 GR B — TEMA INDIA / INOX INDIA, thickness 10–30 mm

N1 Hot forming	N2 (Austenitize+Q)	SR1 Temper	Re-test
910±10°C, 1.4 min/mm 30mm only	910±10°C, 1.4 min/mm 30mm only	620°C minimum, 20min minimum 30mm only	tensile, impact, hardness, microstructure

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SIMULATION HEAT TREATMENT



N1 cycle sample — furnace, red-hot



SR cycle — stress-relief loading

Tangible and Intangible Benefits

TANGIBLE

2000 MT
640 MT - SA 533 Gr B Cl 3 delivered
1360 MT - ASME SA 517 Gr B delivered

100%
import substitution of the contracted requirement

8
thicknesses industrialized, 8–40 mm across both grades

160 MWh
India's first CO_2 battery enabled at NTPC Kudgi

~41,000 t
CO_2 a year displaced (CEA 0.71 t/MWh)

~₹162 Cr
potential annual EBITDA, both grades



INTANGIBLE

People and society

- A strategic material capability created inside India for a national clean energy asset.
- Shorter, traceable supply chain between mill, fabricator and end user.

Morale and motivation

- A first-in-nation grade development gave the team visible national purpose.
- Genuinely cross-functional: SMS, mill, HTC, laboratory and marketing on one charter.

Skill upgradation

- Simulation-heat-treatment design and execution is now an in-house competence.
- Through-thickness sampling and quantitative metallography discipline

Attitude shift

- From meeting a specification to guaranteeing service behaviour.
- The fabricator's furnace cycle is now our own test condition.

ACHIEVED Carbon — import logistics avoided

2000 MT no longer shipped from overseas mills; Carbon, logistics: 2000 MT × ~10,000 km ≈ 20 million t-km of sea freight avoided; 80–90 t CO_2e saved over ~10,000 km sea freight (estimated).

[1] Smart Freight Centre (SFC), GLEC Framework for Logistics Emissions Accounting and Reporting, Global Logistics Emissions Council.[2] UK Department for Energy Security and Net Zero (DESNZ) / DEFRA, Greenhouse Gas Conversion Factors for Company Reporting, Freight Transport Emission Factors.[3] ISO, ISO 14083:2023 — Greenhouse gases — Quantification and reporting of greenhouse gas emissions arising from transport chain operations

ENABLED Carbon — renewable energy made dispatchable

160 MWh/cycle; at one cycle a day, of the order of 41,000 t CO_2 a year of coal generation displaced (CEA grid factor 0.71 t/MWh). Accrues at NTPC.

[1]Central Electricity Authority (CEA) — *CO_2 Baseline Database for the Indian Power Sector, Version 19.0*.

The replicable part is the method, not the tonnage

Evidence of Assimilation, and Where It Goes Next

THE METHOD

Work backwards from service and fabrication conditions into chemistry, cleanliness, rolling and heat treatment.

ASSIMILATED IN THE PLANT

- Q&T route standard
- AF1 • AF2 • TF1 • TF2
- Simulation HT: routine qualification
- Ultra-clean practice

WHAT NEXT

- Extend qualified band beyond 40 mm
- Share TDC + simulation model
- CO_2 storage & CCUS enquiries

SECTOR TRACTION

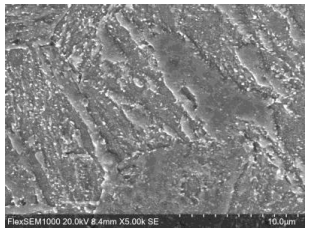
- PO Repeat order
- 3 fabricators qualified
- Anup Engineering • FEMA India • INOX India
- ~11,000 MT/yr per grade

WHERE THE STEEL GOES

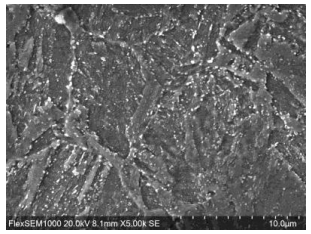
- CO_2 storage & LDES
- H_2 CCUS & hydrogen
- Boiler drums & heat exchangers
- Reactor vessels
- SA 533 Gr B: reactor-vessel reference grade

EVIDENCE — MICROSTRUCTURE HOLDS THROUGH THE CYCLE

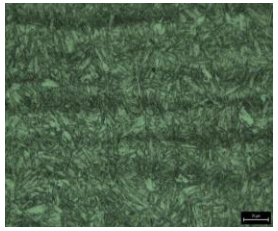
SA 517 Gr B



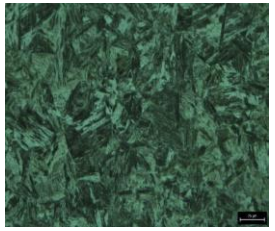
AS QUENCHED



TEMPERED



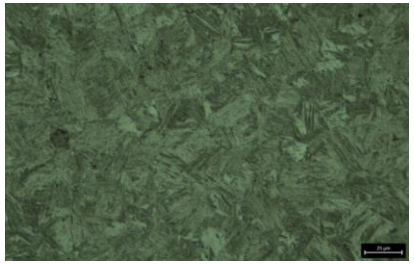
INDUSTRIAL Q&T



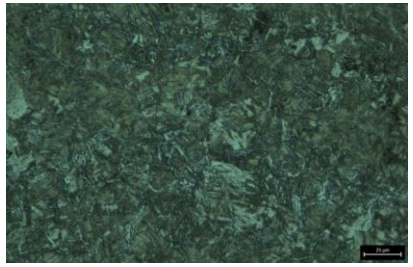
INDUSTRIAL(Q&T)+ Lab Simulation (N1+N2+Q+SR1)

SEM 5,000×, SA 517 Gr B. The TDC calls for tempered martensite by direct microstructure check — this pair shows exactly that transformation, uniform through the section.

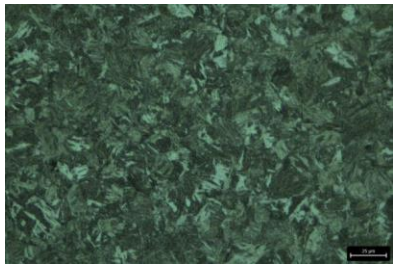
SA 533 Gr B



N1+N2+Q



N1+N2+Q+SR1



N1+N2+Q+SR1+SR2



CO2 Storage battery



Plates

ILLUSTRATIVE IMAGE ONLY

Technical

Two boron strategies, one campaign

SA 533: 10 ppm max (incidental)

≤10

SA 517: deliberate 5–50 ppm window

5 – 50 ppm

0 10 25 50 ppm

Both controlled to TDC ladle/product limits, heat by heat

One heat design across 8 mm to 40 mm

8 mm — 40 mm

Thin: distorts on quench — Thick: needs through-hardenability

Thickness-wise hold-and-resume rolling | **Slab selection**

Solved for adequate reduction ratio

Retention after repeated post-weld stress relief

SA 533 Gr B Cl 3 · 40 mm gauge

N1 | N2 | Q | T › SR × 2 or 4

555 ± 10 °C, 150 min each

SA 517 Gr B · 30 mm gauge

N1 | N2 | Q | T sim › SR1

T sim: 910 ± 10 °C, 1.4 min/mm · SR1: 620 °C, 20 min minimum

Head-to-tail uniformity of properties

Head	Body	Tail

Impact toughness | **Lateral expansion** | **Tensile strength**

Tempering tuned by thickness and length: ranges, charging, holding, discharging

Administrative

No domestic precedent

TDC-008518A | **TDC-008557A**

Negotiated with each fabricator. Goes beyond ASME, with SHT built into the acceptance criteria.

Two fabricators, two qualification scopes

SA 517	SA 533
30 mm only	20mm, 34mm & 40mm
Simulation Heat Treatment	Simulation Heat Treatment

Maintenance

± 10 °C

80 m furnace

Temperature uniformity, roller-hearth

Radiant-tube and burner condition monitoring, thermal survey, profile correction before each Q&T campaign.

8 / 4

bar zones

Quench header pressure stability

Nozzle and header cleaning schedule, with pressure logged plate by plate.

Flat

thin quenched plate

Flatness and distortion control

Leveller setting standards for Q&T gauges, plus a plate-wise flatness check.

Every cycle

logged

Traceability of lab simulation cycles

Calibrated lab furnaces; loading temperature, heating rate, soak and cooling recorded against TDC targets.

Benchmarked Grade by Grade Against the Approved TDC

SA 533 Gr B Cl 3 · 8–40 mm · ASTM A533/A533M - 24

Requirement	ASME code	TDC-008518A achieved
Sulphur / phosphorus	≤ 0.025% each	S ≤ 0.015%, P ≤ 0.015% (ladle & product)
Carbon equivalent	Not restricted	CE(IIW) ≤ 0.59
Boron	Not specified	≤ 0.0010% (10 ppm) — incidental only
Yield / tensile / elongation	YS ≥ 570 MPa (T&L); UTS 690–860 MPa; El ≥ 16%	YS ≥ 570 MPa (T&L); UTS 690–860 MPa; El ≥ 17%
Impact, –20 °C / –29 °C	Not specified	≥ 60 J average (T), both temperatures
Hot tensile, 425 °C	Rp0.2 ≥ 399 MPa (T)	Rp0.2 ≥ 399 MPa (T)
Hardness	Not specified	≤ 330 HV10
Grain size	ASTM A20/A20 M No. 5 or finer	No. 5 or finer, ASTM E112 (McQuaid–Ehn)
Ultrasonic testing	ASTM A578 L C + S1	EN 10160 S1E1 (8–9.99 mm) / ASTM A578 C+S1 (10–40 mm)

SA 517 Gr B · 10–30 mm · ASTM A517/517M – 17 (Reapproved 2023)

Requirement	ASTM code	TDC-008557A achieved
Sulphur / phosphorus	≤ 0.025% each	S ≤ 0.025%, P ≤ 0.025% (as per TDC caps)
Carbon equivalent	Not restricted	Not computed under this TDC
Boron	0.0005–0.005% (5–50 ppm)	0.0005–0.005% (5–50 ppm) — hardenability agent
Yield / tensile / elongation	YS ≥ 690 MPa (T); UTS 795–930 MPa; El ≥ 16%	YS ≥ 690 MPa (T); UTS 795–930 MPa; El ≥ 16%
Impact, –29 °C	Lateral Expansion: 0.38 mm min Temp ≤ 0 °C	≥ 40 J average / ≥ 28 J individual (T) Lateral Expansion: For t ≤ 25 mm: 0.50 mm min For t > 25 mm: 0.58 mm min At -29 °C
Hardness	Not specified	≤ 225 BHN
Microstructure	Not specified	Tempered martensite, direct check per plate
Ultrasonic testing	ASME SA578	ASME SA578 Level C + S1

MEN · MATERIAL · METHOD · TECHNOLOGY · MEASUREMENT

Men A single cross-functional charter across SMS, mill, Heat Treatment Complex, laboratory and marketing.

Material Grade-specific ultra-clean practice: near-zero boron on SA 533, controlled 5–50 ppm boron on SA 517.

Method Hold-and-resume controlled rolling, then off-line austenitize, quench and temper to each plate..

Technology / Measurement MULPIC accelerated cooling, Q&T line; through-thickness sampling, 100% UT, microstructure analysis.

POSITION AGAINST DOMESTIC PEERS

As on date no other Indian mill has ever produced these grades in Q&T condition for this application; the benchmark above the project was the import itself.

NATIONAL PRIORITIES ADDRESSED

Make in India, Atmanirbhar Bharat, import substitution for critical infrastructure and a domestic supply chain for long-duration energy storage.

Year +1, Year +2, and the Ten Practices at Their Core

YEAR +1

- Widen the qualified band beyond 40 mm from the same heat design.
- Qualify further pressure-vessel fabricators on the existing TDC-plus-simulation template.
- Convert the repeat order into a standing supply position for SA 517 Gr B.
- Build the cost, forex and lead-time baseline into the mill's product P&L.

YEAR +2

- Extend the platform to adjacent pressure grades — SA 516, SA 387 and higher-alloy Q&T families.
- Target CCUS and hydrogen equipment enquiries as those programmes reach order stage.
- Pursue third-party and export code approvals for code-governed markets.
- Explore the highest integrity class for which SA 533 Gr B is the reference grade.

RESOURCES REQUIRED

- The **existing facility** is fully equipped to execute future plans

TOP TEN BEST PRACTICES — the core of the approach for year +1 and year +2

1. Application-led development — work backwards from service and fabrication conditions.
2. A Technical Delivery Condition agreed beyond code before the first heat.
3. Grade-specific boron strategy: near-zero on SA 533, controlled 5–50 ppm on SA 517.
4. Inclusion engineering by calcium treatment for isotropic through-thickness toughness.
5. Vacuum degassing as a rule for thick Q&T sections.
6. Hold-and-resume controlled rolling to condition austenite before heat treatment.
7. Off-line quench and temper under tight thermal control — properties made in the HTC.
8. Simulation heat treatment to the TDC's own N1/N2/SR parameters, not a generic cycle.

What the Project Taught Us

1

Specification compliance is not service confidence

A plate that meets the code as supplied can still fail the customer. The only meaningful test is the one that reproduces what the fabricator will do to it.

2

Import substitution is an engineering problem before it is a commercial one

The gap was never price. It was the simultaneous combination of strength, sub-zero toughness, a hardness cap and stability through fabrication heat treatment.

3

Two grades needed two different metallurgical strategies

SA 533 controls boron to near zero; SA 517 uses boron deliberately for hardenability. One heat design does not fit both TDCs.

4

The customer's process had to enter our test plan

Qualification improved the moment each fabricator's own N1/N2/SR cycle became a mill test condition instead of downstream risk.

5

Capability outlasts the order

2000 MT was the delivered scope. The lasting asset is a qualified Q&T platform, a documented simulation method, and a mill that can now be asked for the next hard grade.

2000 MT

DELIVERED SCOPE

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