CONFERENCE PRE-PRINT

A MATERIAL DATABASE OF SS316L(N)-IG FOR ITER BLANKET SHIELD BLOCKS

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Abstract

The ITER project requires reliable structural materials capable of withstanding high neutron flux, thermal stresses, and irradiation conditions. SS316L(N)-IG, a nitrogen-controlled ITER-grade austenitic stainless steel, has been adopted as the primary material for the Blanket Shield Block (BSB). This study presents a comprehensive database of its chemical, physical, and mechanical properties based on procurement and fabrication of more than two hundred forged blocks. The database integrates chemical composition, microstructural characteristics, tensile strength, yield strength, and elongation data, enabling robust design margins and predictive modelling of material performance for current and future fusion systems

1. INTRODUCTION

The ITER represents a key milestone in demonstrating fusion energy as a sustainable source. Among major components in ITER, the Blanket System plays a role; shielding the vacuum vessel and external structures from neutron and thermal loads, while serving as the primary plasma-facing interface in certain operational modes [1]. The Blanket Shield Block (BSB), in particular, ensures neutron attenuation and mechanical integrity under severe fusion environments. The Blanket System consists of 440 Blanket Modules (BMs) covering ~ 600 m² of the vacuum vessel surface. Each module is composed of a First Wall (FW) and a Shield Block (SB). Figure 1 illustrates the poloidal segmentation; rows 1–6 correspond to the inboard wall, rows 7–10 to the top wall, and rows 11–18 to the outboard wall. The segmentation ensures full toroidal coverage and allows for maintenance accessibility. This arrangement provides structural integrity, neutronic shielding, and thermal protection under fusion operating conditions [2].

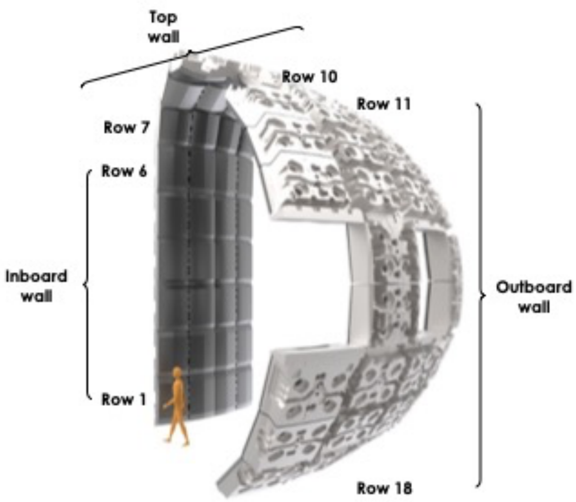


Fig. 1 *Schematic of the ITER Blanket Module segmentation*

SS316L(N)-IG (ITER Grade) was selected as the structural material for the BSB due to its balanced combination of corrosion and irradiation resistance, and mechanical strength as well. It is essentially a low-carbon 316L stainless steel with tightly specified alloying ranges and nitrogen control [3, 4]. Its closest industrial analogue is X2CrNiMo17-12-2 steel, defined in RCC-MR 2007 [5]. Developing a validated materials database is essential for ITER designers, since predictive assessment of BSB performance requires reproducible and traceable input properties. Figure 2 shows representative geometries of the inboard modules (rows 01–06), top modules (rows 07–10), and outboard modules (rows 11–18). Each module is designed to attach to the vacuum vessel and incorporates complex internal cooling channels, structural reinforcements, and neutron shielding features. The differences in geometry reflect variable interfaces and spatial positions within the ITER tokamak.

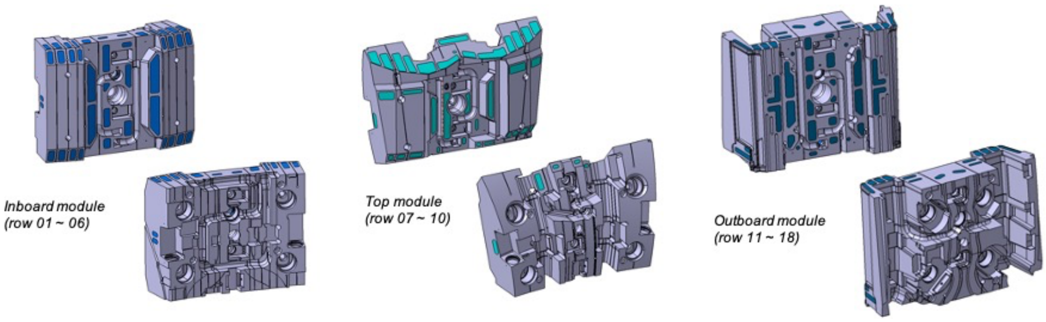


Fig. 2 Typical configurations of the ITER Blanket Shield Blocks (inboard, top and outboard modules)

2. MATERIAL FABRICATION

2.1. Requirements

The ITER-grade specification defines narrow tolerances for alloying elements and impurity limits compared with conventional 316L stainless steels as shown in Table 1. Ladle (cast) and product analyses must be confirmed compliance with these ranges. Carbon is restricted to ≤0.030 wt.% to suppress sensitization, while nitrogen (0.060–0.080 wt.%) is intentionally controlled to enhance strength and irradiation stability. Chromium (17.00–18.00 wt.%), nickel (12.00–12.50 wt.%), and molybdenum (2.30–2.70 wt.%) provide corrosion resistance and mechanical integrity. Minor elements such as Cu, Ti, Nb, Ta, and Co are also tightly limited to ensure uniform performance and to regulate radiation protection under fusion operating conditions.

Table 1 Requirements for the chemical composition range of SS316L(N)-IG

Element		C	Mn	Si	P	S	Cr	Ni	Mo	N	Cu	Ti	Others*
Content wt. %	min.	-	1.60	-	-	-	17.00	12.00	2.30	0.060	-	-	Nb: 0.10
	max.	0.030	2.00	0.50	0.025	0.010	18.00	12.50	2.70	0.080	0.30	0.10	Ta: 0.01 Co: 0.05

* Radiation protection requirements

Mechanical properties are required involving tensile testing at both room temperature (RT) and elevated temperature (250 °C) as shown in Table 2. Tensile strength must fall within 525–700 MPa, with a minimum 0.2% yield strength of 220 MPa and elongation greater than 45% at RT. The minimum tensile strength is set to 415 MPa and yield strength to 135 MPa at 250 °C. These requirements ensure that the material provides sufficient strength, ductility, and structural integrity under both ambient and operating conditions, and every procurement batch must satisfy these criteria through standardized testing.

Table 2 Specified mechanical property requirements for SS316L(N)-IG

Test Temperature °C	Tensile Strength MPa	Yield Strength (0.2%)_min. MPa	Elonggation_min. %
RT	525 ~ 700	220	45
250	min. 415	135	

2.2. Fabrication

Figure 3 shows fabrication process for SS316L(N)-IG. The process was optimized to ensure chemical homogeneity, low impurity levels, and stable microstructure. Primary melting was applied in an Electric Arc Furnace (EAF), followed by Argon Oxygen Decarburization (AOD) for carbon and impurity control. The refined alloy undergoes Electro-Slag Remelting (ESR) to minimize inclusions and achieve uniformity. Large ESR ingots were subsequently shaped through open-die forging and then subjected to solution heat treatment at 1050–1150 °C with water quenching. Final machining (surface finishing), non-destructive examinations (ultrasonic and liquid penetrant testing), metallographic evaluation and mechanical testing were performed to validate quality. This integrated process ensures the quality and reproducibility of SS316L(N)-IG properties required for Blanket Shield Block applications.

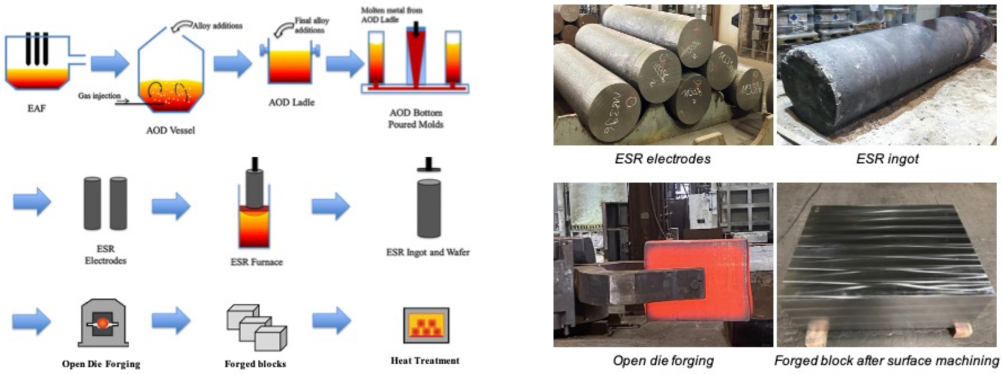


Fig. 3 Fabrication process and photos in each process for SS316L(N)-IG used in ITER Blanket Shield Blocks

3. CHEMICAL AND MECHANICAL PROPERTIES

Chemical and mechanical property evaluations were performed on test coupons according to ITER procurement specifications as shown in Figure 4. Samples were cut at least 20 mm from the nearest skin and 40 mm from other surfaces to avoid surface effects. Tensile specimens were oriented perpendicular to the main forging direction to capture transverse properties. Two tensile tests were conducted per lot at RT and 250 °C. Test coupons were also used to determine ferrite content, magnetic permeability, grain size, and macro-inclusion levels (1 test per lot), as well as product chemical analyses (1 per heat). Non-metallic inclusion examinations were carried out once per forging. This systematic testing protocol ensures representativeness of the bulk material and compliance with ITER requirements.

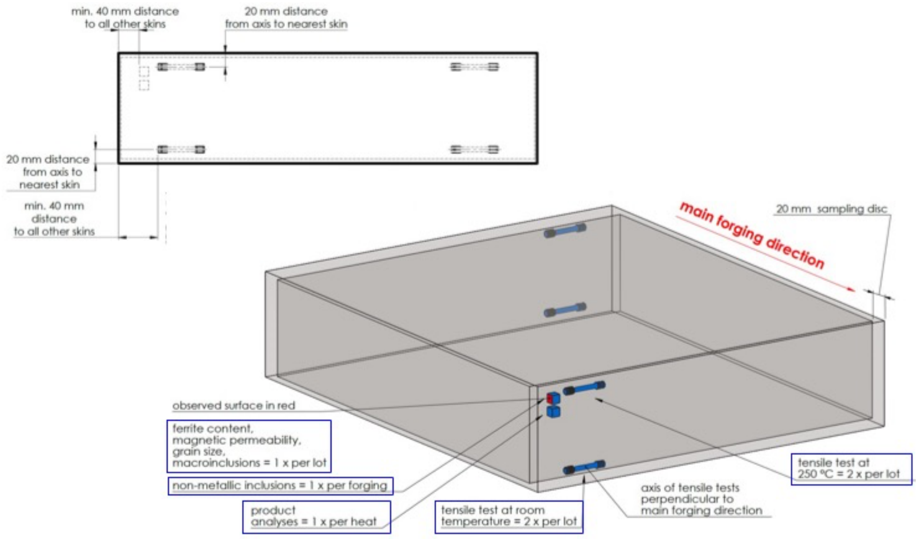


Fig. 4 Location of test coupons extracted from SS316L(N)-IG forged blocks with respect to the main forging direction.

3.1. Chemical composition

Chemical composition of SS316L(N)-IG (Heat No. 725051 as an example) both ladle and product analyses were confirmed that it is fully compliance with the ITER procurement specification as shows in the Table 3. The measured carbon content (0.021–0.023 wt.%) is well below the 0.030 wt.% maximum, ensuring resistance to sensitization. Chromium (17.69–17.76 wt.%), nickel (12.13–12.38 wt.%), and molybdenum (2.46–2.47 wt.%) were measured within the narrow-specified ranges, providing corrosion resistance and mechanical strength. Nitrogen content (0.065–0.066 wt.%) satisfied the controlled 0.060–0.080 wt.% range, contributing to enhanced stability under irradiation. Trace elements such as Cu, Ti, Nb, Ta, and Co remained within strict limits, confirming the uniformity and quality control of SS316L(N)-IG mass production for ITER Blanket Shield Blocks.

Table 3 Example of chemical composition for SS316L(N)-IG (Heat No. 725051)

Element		C	Mn	Si	P	S	Cr	Ni	Mo	N	Cu	Ti	Others
Content wt. % (Heat 725051)	ladle	0.021	1.79	0.38	0.017	0.0005	17.76	12.38	2.47	0.066	0.105	0.002	Nb: 0.004 Ta: 0.005 Co: 0.036
	product	0.023	1.70	0.35	0.015	<0.001	17.69	12.13	2.46	0.065	0.09	<0.01	Nb: 0.02 Ta: 0.002 Co: 0.04

3.2. Microstructural characterization

Ferrite content was evaluated from equivalent contents $Ni_eq = Ni + 21C + 11.5N + 0.5Mn$ and $Cr_eq = Cr + 2Mo + 3Si$. For a representative heat (No. 725051), ladle and product analyses give $Ni_eq \approx 14.21–14.48$ and $Cr_eq \approx 23.66–23.84$, placing the composition in the fully austenitic field of the diagram and predicting δ-ferrite ≤ 0.5%, in compliance with the ITER procurement requirement for BSB forgings. The controlled nitrogen range (0.060–0.080 wt.%) together with Mo ≥ 2% biases phase stability toward austenite after solution heat treatment, effectively suppressing δ-ferrite formation.

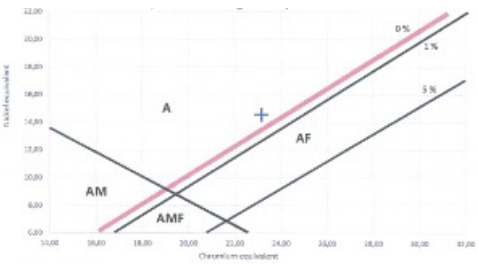


Fig. 5 Ferrite content assessment using the Schaeffler diagram (RMC 1341.2), modified by Pryce and Andrews

Optical micrographs show an equiaxed austenitic structure; the circled area illustrates the intercept/planimetric counting method used to assign the grain size number. The results satisfy the specification of grain size number grater than 3 after solution heat treatment at 1050–1150 °C followed by water quenching. The Electron Backscatter Diffraction (EBSD) inverse pole figure map corroborates a recrystallized, uniformly oriented microstructure with annealing twins, consistent with stable mechanical properties across melts and forgings.

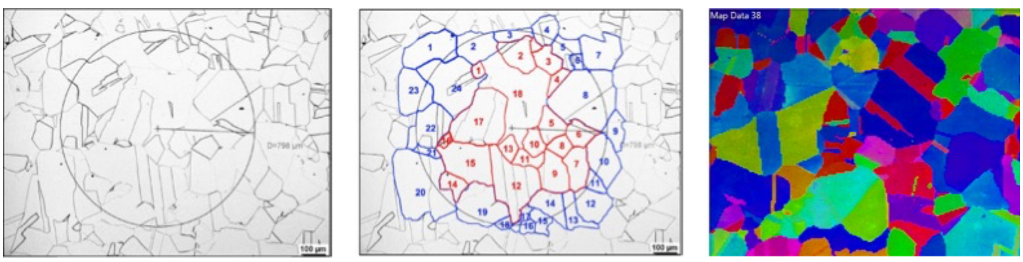


Fig. 6 Grain size determination according to EN ISO 643

3.3. Mechanical properties

Mechanical properties were evaluated at both RT and 250 °C. The tensile curves exhibit typical stainless steel behaviour under both test conditions, demonstrating reproducibility across multiple forgings as shown in Figure 7. The material shows an average tensile strength of ~538 MPa, a yield strength of ~258 MPa, and elongation exceeding 57%, indicating high ductility and toughness at RT. Tensile strength decreases slightly to ~424 MPa with yield strength ~167 MPa, while elongation remains above 50%, confirming the retention of adequate ductility at elevated temperature. These results validate that the SS316L(N)-IG satisfies specification requirements, and the consistent S–S response confirms excellent batch-to-batch uniformity essential for ITER Blanket Shield Block applications.

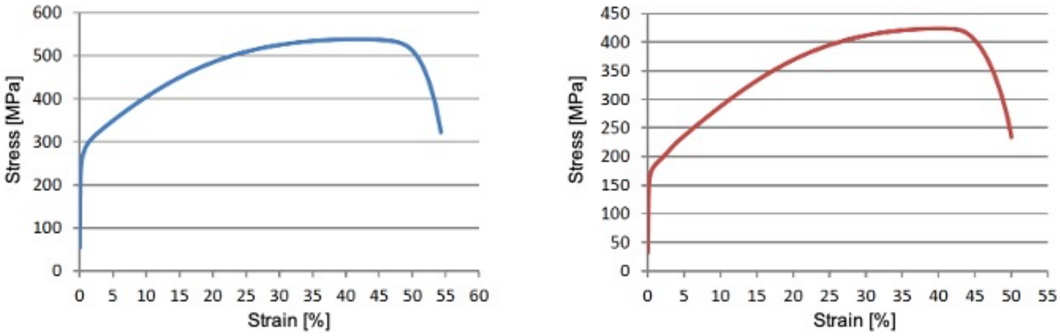


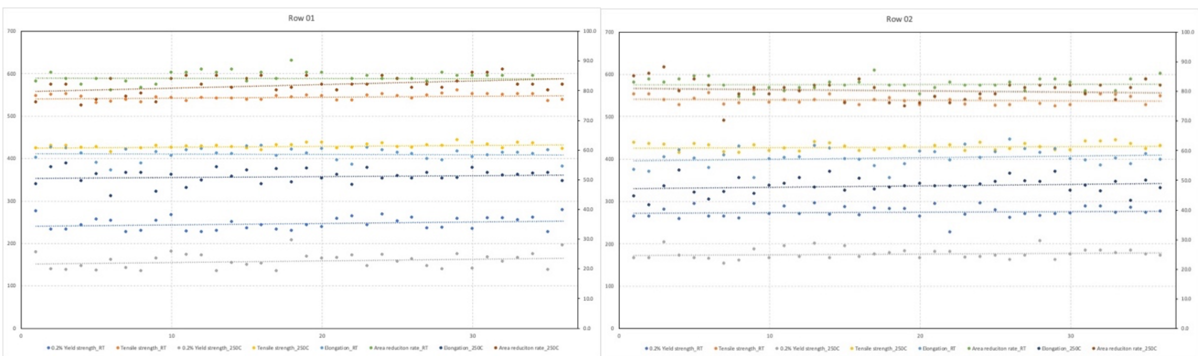
Fig. 7 Typical stress-strain (S-S) curves of SS316L(N)-IG forged block at rooom temperature (left) and 250 °C (right)

4. MATERIALS DATABASE

A total of 220 forged blocks and more than 440 tensile specimens were characterized. Figure 8 compiles results from 440 forged blocks across different poloidal rows of the blanket location, presenting values of 0.2% yield strength, tensile strength, elongation, and area reduction at both RT and 250 °C. Data demonstrates narrow scatter around the average trend lines, confirming that the production process achieved excellent batch-to-batch reproducibility. The scatter bands of yield and tensile strengths, as well as ductility parameters, remain within ±5% of the average trend line across all SB poloidal rows. This demonstrates that the forging and heat treatment processes are highly reproducible and independent of block location in the tokamak assembly.

Each SB as a final product retains full traceability to its manufacturing history and associated property data through material tracing sheets and manufacturing/inspection reports. This traceability ensures that physical and mechanical properties are systematically linked to procurement records, forging batches, and heat analyses. Such documentation guarantees the reliability of SS316L(N)-IG mass production for ITER application and provides a robust reference for engineers in both design verification and operational safety assessments.

Batch-to-batch variation is well controlled, supported by stable chemical composition and microstructure. The tight specification of alloying elements, controlled nitrogen range, and optimized forging route contribute to the suppression of δ-ferrite and to uniform grain size distribution. As a result, the mechanical properties are stabilized, ensuring confidence in the reliability of mass production.



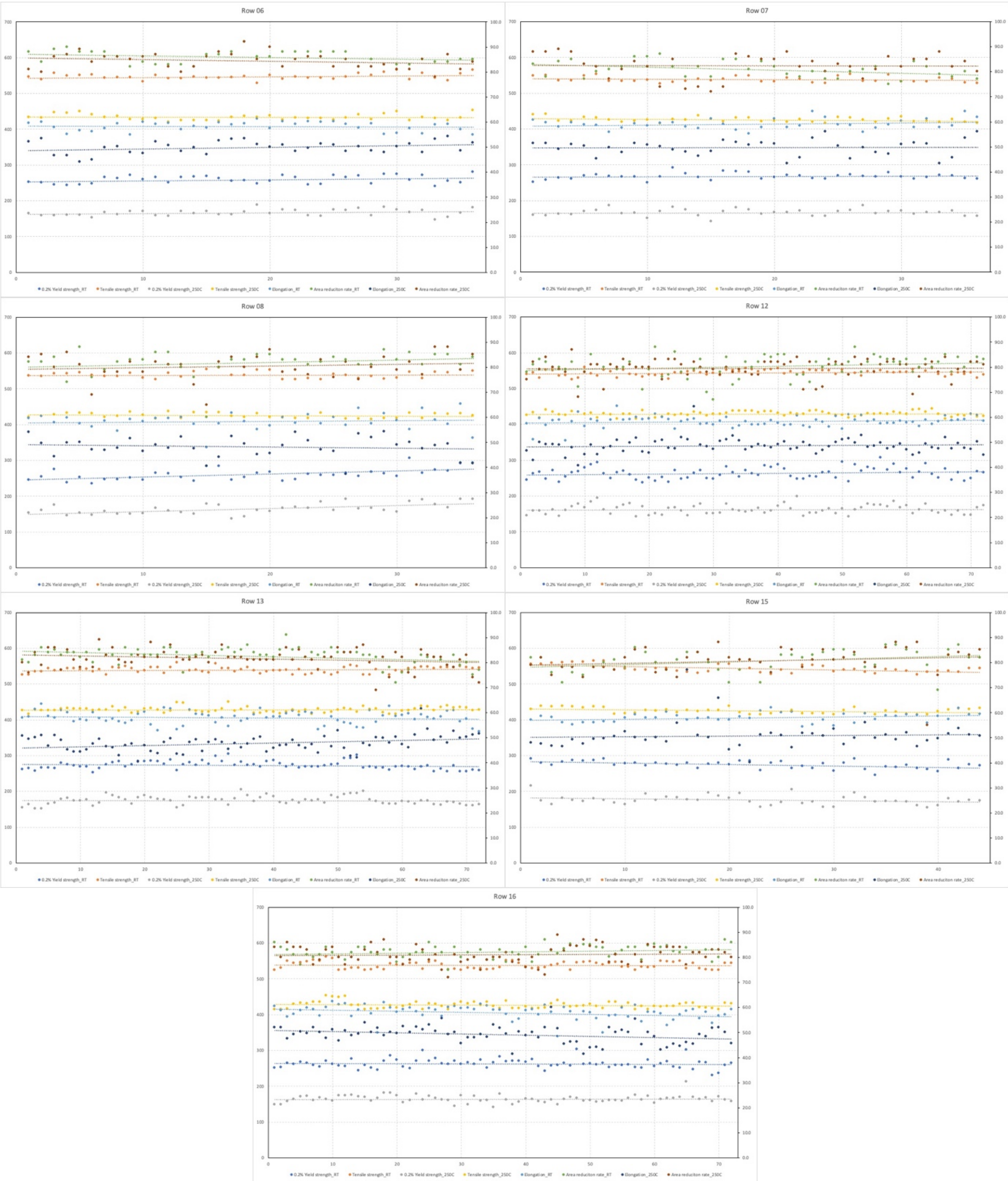


Fig. 8 Mechanical property database of SS316L(N)-IG for ITER Blanket Shield Blocks, shown by poloidal row distributions

The database was established from tensile tests performed on 440 specimens extracted from 220 ESR-forged blocks, evaluated at both RT and 250 °C. Figure 9 reveals that mechanical properties of all forged blocks satisfy the requirements defined in the ITER Technical Specification [3]. Tensile strength, 0.2% yield strength, elongation, and area reduction values consistently exceeded the specified minimum criteria, both temperatures. This confirms the adequacy of SS316L(N)-IG as the structural material for Blanket Shield Blocks. Therefore, it can be concluded that the property database not only confirms the compliance of all manufactured blocks with ITER specifications, but also provides strong evidence of process stability and traceability. The results can serve as a validated dataset for design, qualification, and predictive modelling in ITER and future fusion reactors such as DEMO.

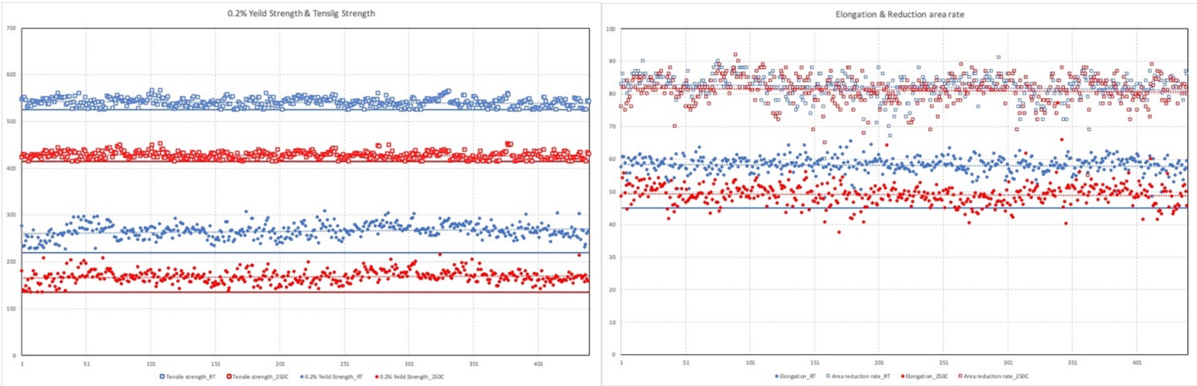


Fig. 9 Comprehensive evaluation of mechanical properties of SS316L(N)-IG compared with ITER requirements

Figure 10 (left) shows the poloidal row-by-row averages of tensile strength and 0.2% yield strength for SS316L(N)-IG, measured at both RT and 250 °C. Error bars represent standard deviation, and the narrow scatter indicates highly stable and reproducible material properties across all fabrication batch. No systematic deviation is observed between rows, confirming uniformity of the forging and heat treatment process throughout the production of 220 forged blocks.
Figure 10 (right) incorporates the experimentally determined yield strength values of SS316L(N)-IG into the ITER Material Properties Handbook database [6]. The average yield strength values obtained from 440 specimens represented as red dot align well with the handbook data and exceed the minimum design curves provided by RCC-MR references. The superposition of experimental points with handbook values demonstrates not only compliance with ITER specifications but also reinforces the robustness of the newly established materials database.
Overall, these results verify that the SS316L(N)-IG materials used for the Blanket Shield Blocks exhibit stable and conservative strength margins, ensuring reliable performance under ITER operating conditions and supporting extrapolation to future fusion devices.

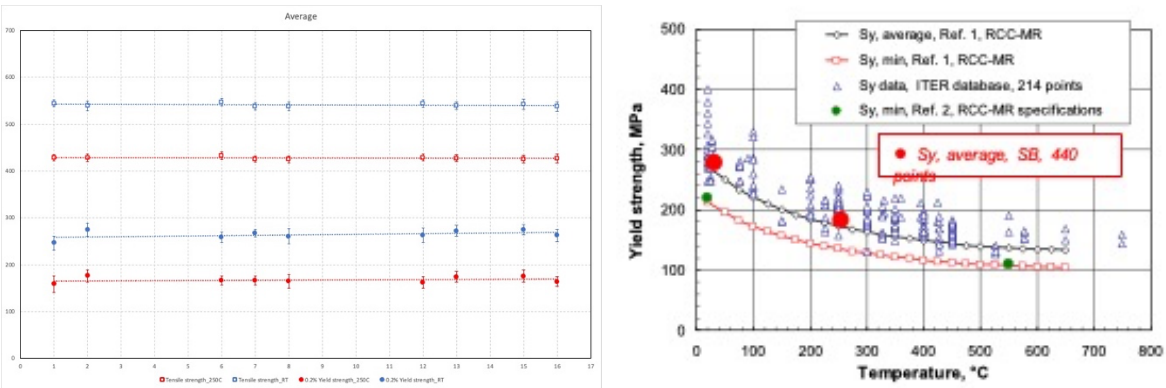


Fig. 10 Comparison of mechanical property averages (left) with ITER database values (right).

Figure 11 shows that the pie charts present the distribution of tensile strength results for all tested specimens, expressed as the deviation rate from the overall average tensile strength. Each segment represents the fraction of specimens falling within a given deviation range, normalized by the total number of tests.
At RT, more than 75% of the specimens are distributed ±2.0% of the mean tensile strength, with the largest fraction (21.8%) in the ±0.5–1.0% range. Only a very small proportion (<1%) exceeds ±3.0%. And also, a similar distribution is observed; over 70% of the specimens fall within ±2.0% of the mean, with the highest fraction (20.9%) in the ±0.5% range at 250 °C. Furthermore, only a negligible percentage (<2%) shows deviations greater than ±3.0%.
These results demonstrate that the tensile strength of SS316L(N)-IG is extremely consistent across all forgings, with minimal scatter and narrow standard deviation bands. The high percentage of data clustering around the average value confirms the effectiveness of process control during melting, forging, and heat treatment, and validates the database as a reliable foundation for ITER Blanket Shield Block design.

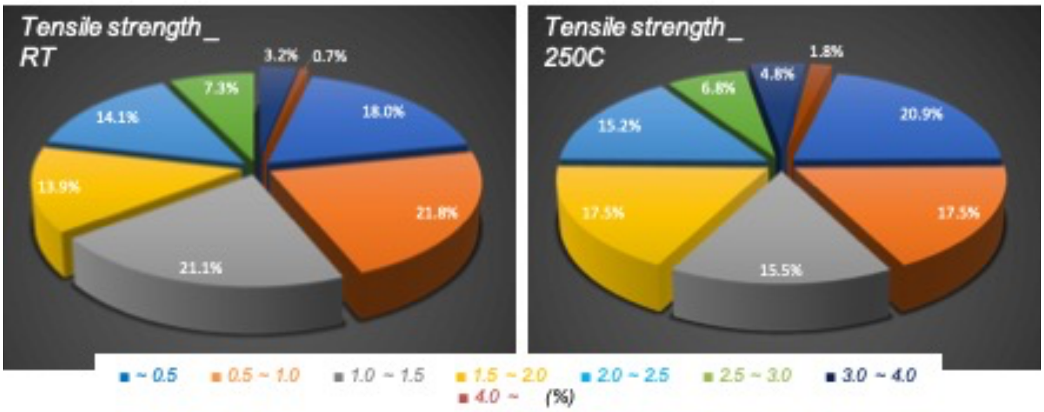


Fig. 11 Statistical distribution of tensile strength deviations from the average at RT and 250 °C.

5. CONCLUSION

A comprehensive materials database for SS316L(N)-IG selected for the Blanket Shield Blocks (BSBs) has been successfully established through the procurement and systematic characterization of 220 ESR-forged blocks and 440 tensile specimens. The results clearly demonstrate that all measured mechanical properties, including tensile strength, 0.2% yield strength, elongation, and area reduction, fully satisfy the requirements defined in the ITER Technical Specification at both room temperature and elevated temperature (250 °C). The scatter of the data is remarkably small, with standard deviations within ±5% of the average trend lines across poloidal rows, confirming the high reproducibility of the forging and heat treatment processes [5, 7]. Furthermore, complete traceability of each block, linking mechanical and physical properties to procurement, manufacturing, and inspection records, provides confidence in large-scale production and validates the long-term reliability of the material. The established database not only confirms the adequacy of SS316L(N)-IG for ITER Blanket Shield Blocks but also provides a critical reference for design verification, predictive modelling, and structural integrity assessments under fusion reactor conditions. Beyond ITER, the outcomes of this work contribute directly to the materials technology required for next-generation fusion systems such as DEMO and compact plasma devices, where reproducibility, radiation resistance, and mechanical reliability are indispensable. This study demonstrates that the stringent procurement specifications and optimized fabrication process of SS316L(N)-IG enable the reliable mass production of fusion-grade structural materials, thereby strengthening the foundation for future fusion energy applications.

ACKNOWLEDGEMENTS

This research was supported by an R&D Program "Manufacturing and Procurement of ITER Blanket Shield Block (2710000407)" through the Korea Institute of Fusion Energy (KFE) funded by government grants from the Republic of Korea. The views and opinions expressed herein do not necessarily reflect those of the ITER Organization and Korea Domestic Agency.

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