Investigation of Materials and Welds for the Precompression Structure of the ITER Central Solenoid

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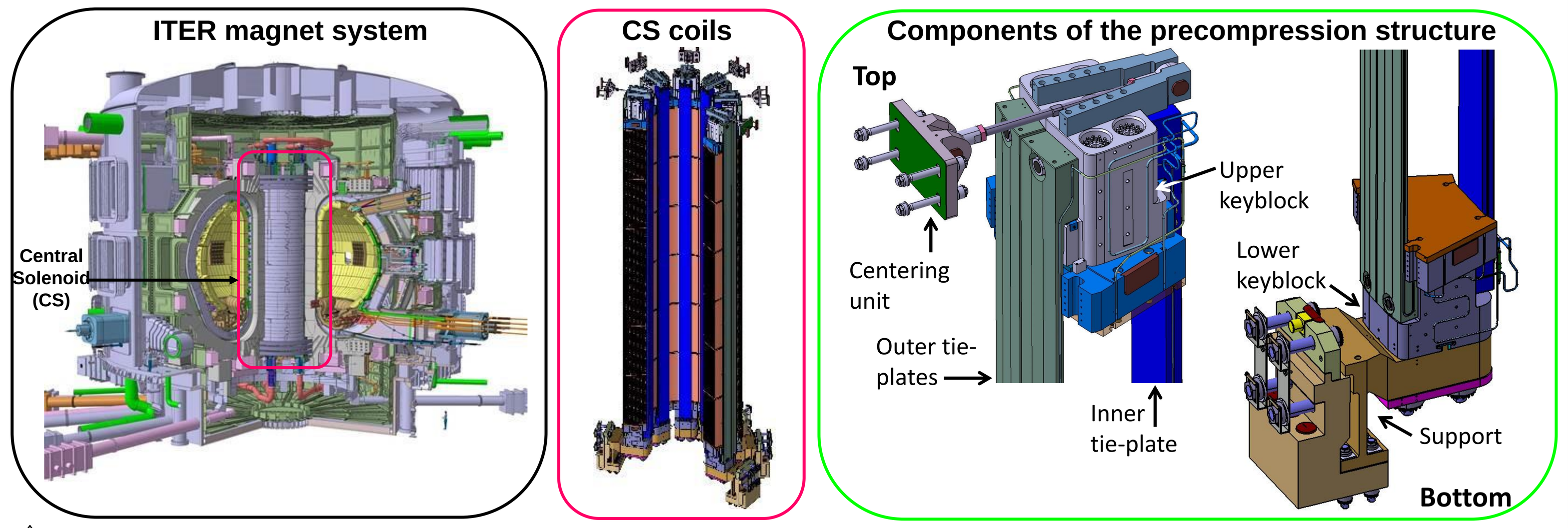
Abstract: The Central Solenoid (CS) is the backbone of the ITER magnet system. It consists of six independent coils held together by a vertical pre-compression structure that must react tensile loads and provide sufficient preload to maintain coil-to-coil contact during all stages of plasma operation. Material selection and specifications applicable to the structural components of the pre-compression structure are particularly demanding. These include large forgings manufactured from a high strength austenitic stainless steel (FXM-19) with a stringent specification in terms of microstructure and maximum allowed magnetic permeability. Stringent requirements are also imposed on all welded joints. In particular, the attachment welds of the cooling pipes to the structure are subject to challenging restrictions in terms of weld imperfections and geometry. They must induce limited distortion of the components and are submitted to inspections carried out in accordance with the most severe acceptance levels of applicable national and international standards. The paper focuses particularly on the quality achieved at the microstructural and macrostructural level. The influence of the microstructure on the final properties and on the inspectability of the material by non-destructive examinations is also discussed.

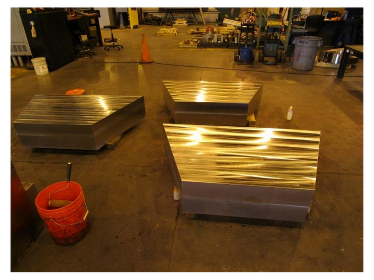
INTRODUCTION



⇑ The ITER magnet system includes a Central Solenoid (CS) that provides the inductive flux to drive the plasma, assists in shaping the plasma and contributes to the control of its vertical stability. It consists of a stack of six independent coils held together by a precompression support structure aimed at maintaining coil-to-coil contact and sufficient pre-load when the solenoid is energized. The CS pre-compression system includes three different types of tie plates (inner, outer right and left hand, respectively), Lower (LKB) and Upper Keyblocks (UKB), Load Distribution Plates (LDP), centering units and tubing that will carry supercritical helium at temperatures as low as 4.5 K.

⇑ Tie plates are manufactured from single forgings involving blanks of more than 15 m length (courtesy of Company A)

⇐ Redundant, multidirectional forging is applied to the other components as well. Shown here is the example of UKB (left) and LDP (right), respectively, pre-machined for 100 % Ultrasonic Testing (UT) performed following ASTM A745/A745M, with acceptance criteria adapted to the functional requirements of the individual components (courtesy of Company B) ⇒



MATERIAL

- The selected material for the tie plates and for the other precompression components also issued from large structural forgings is FXM-19, a high strength N and Mo bearing austenitic stainless steel suitable for cryogenic applications also known through its proprietary designation Nitronic®50. The material is submitted to a stringent specification in terms of fineness of the grain, inclusion cleanliness, relative magnetic permeability μ_r at Room Temperature (RT) not to exceed 1.03 and ferrite content (maximum 1 %).

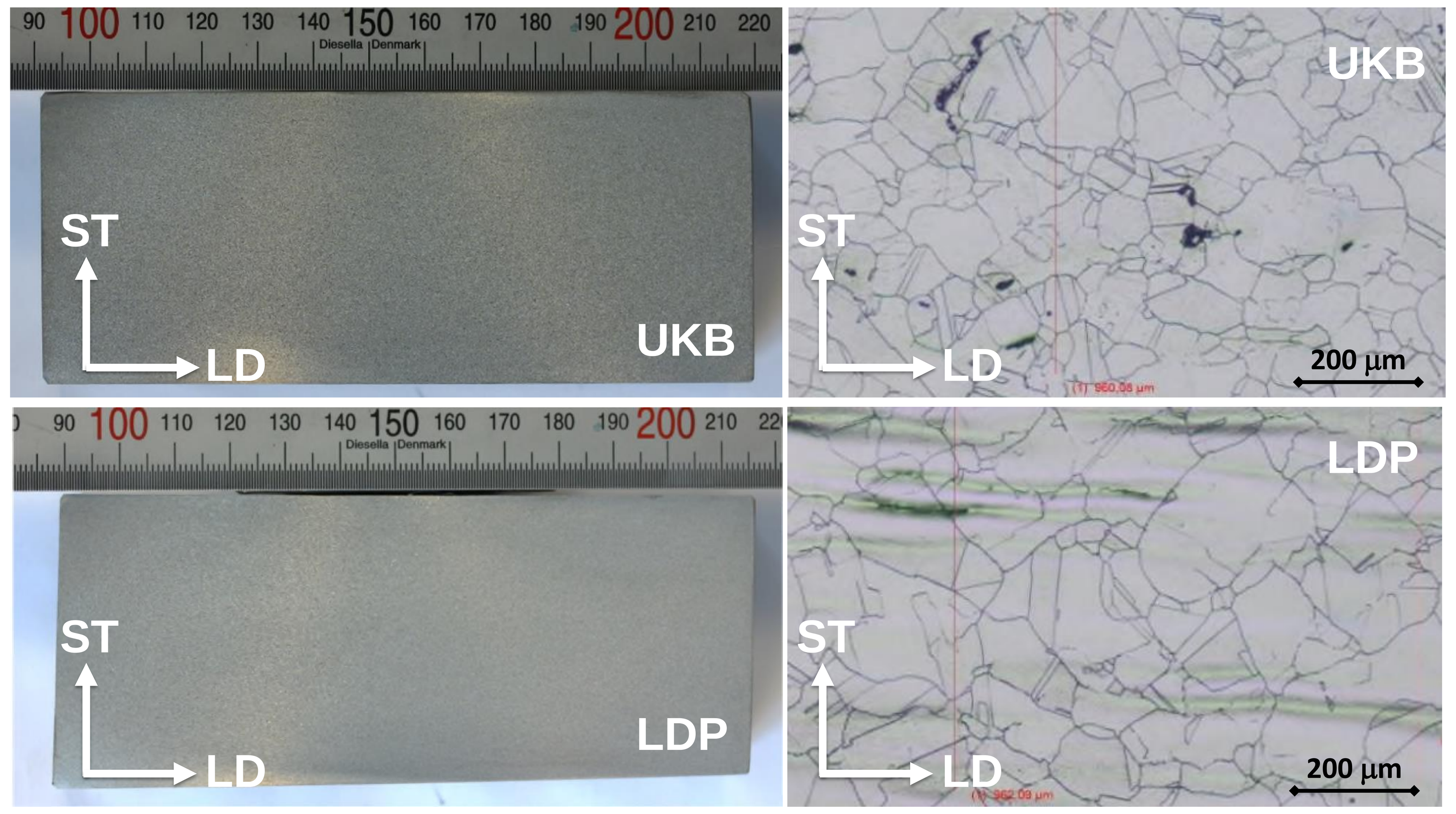
- In order to meet these requirements, an adapted steelmaking and processing route including Electroslag Remelting (ESR) must be followed. The melt chemistry is specially tailored.

FXM-19 Forgings, chemical composition of the products

Component	Steelmaker and heat number	Chemical composition (% by mass)											
		C	Cr	Ni	Mo	Mn	Si	P	S	N	V	Co	Nb+Ta
		Specified composition limits											
		0.03 max	*20.5-23.5*	*11.5-13.5*	*1.50-3.00*	*4.0-6.0*	*0.75 max*	*0.045 max*	*0.030 max*	*0.20-0.35*	*0.10-0.30*	*0.10 max*	*0.10-0.30*
Tie plate, Company A	Kind & Co. /DE, ESR heat 713148	0.020	20.6	11.9	2.07	4.6	0.45	0.032	0.0010	0.22	0.14	0.05	0.160
UKB, Company B	Breitenfeld /AT, ESR heat 116020	0.025	21.3	11.9	2.12	4.1	0.43	0.025	0.0001	0.28	0.14	0.06	0.132
LDP, Company B	Breitenfeld /AT, ESR heat 116017	0.028	20.9	11.7	2.14	4.1	0.43	0.017	0.0001	0.27	0.14	0.05	0.122

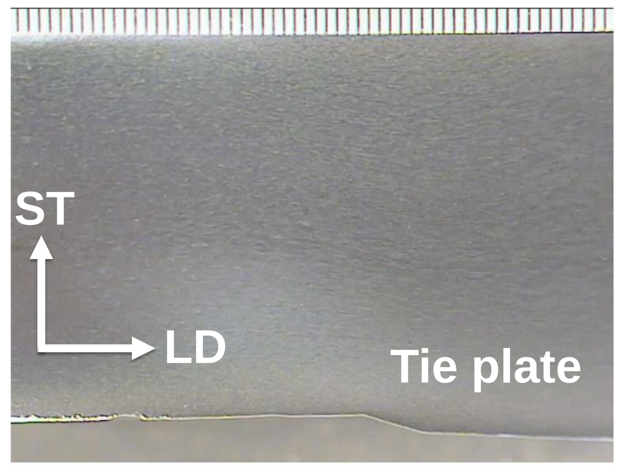
RESULTS AND DISCUSSION

A. Results of metallographic examinations



⇑ Macrographic examination results of forged blocks. Example of samples issued from the UKB and the LDP, respectively. Short Transverse (ST) and Longitudinal Direction (LD) with respect to the original forgings are identified. For all examined samples no segregation is observed and the microstructure is homogeneous.

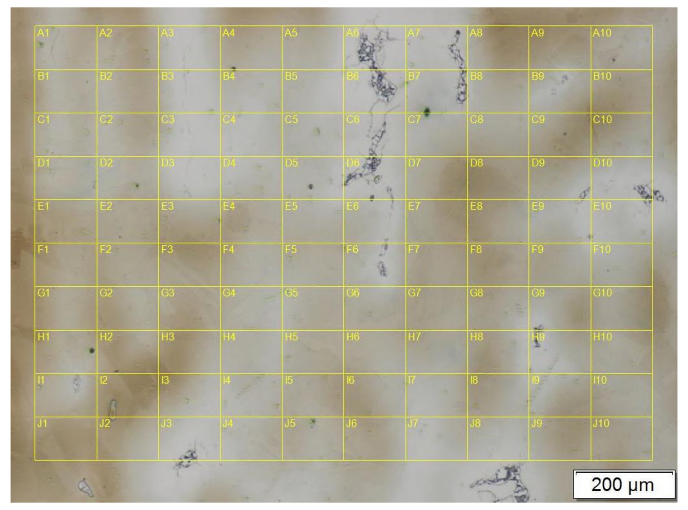
⇑ Micrographic examination, oxalic acid etching. Ferrite stringers are visible in the LDP sample, aligned along LD. For the UKB and LDP, the grain size number is 5±1 (specified 2 or finer), for the tie plates 6.5±0.5 (specified 3 or finer). Dispersion is also within specification allowance (±1).



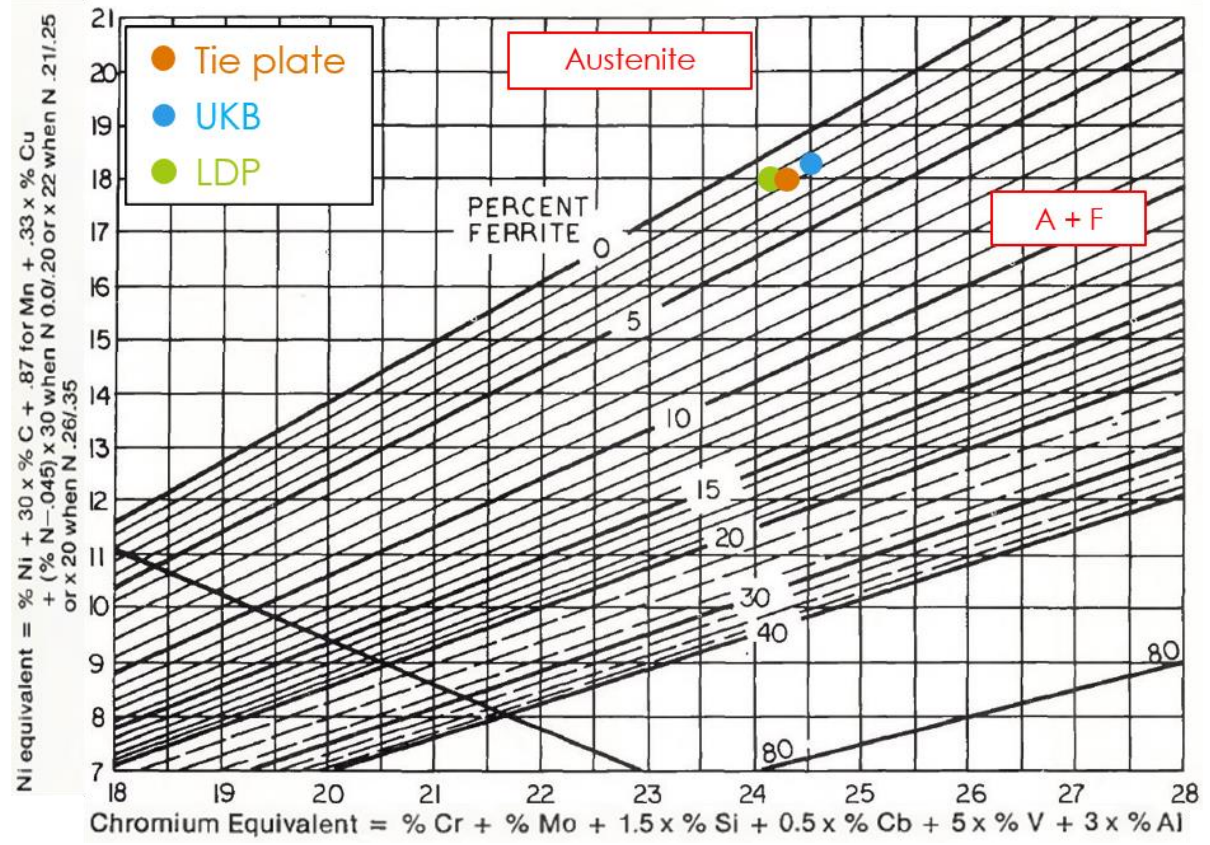
The UKB and LDP forgings show isotropic microstructure, while ⇐ the tie plate features a longitudinally oriented structure with fine longitudinal bands, due to the major reduction occurring during forging in the LD.

The following severity levels are permitted for inclusions by specification: type A and C less or equal to 0.5; type B & D less or equal to 1.0. The UKB sample that was examined fulfils the requirements, as well as the LDP sample apart from two C fields of thin type of severity 1, over 350 fields counted. The inclusion content of the tie plate also fulfils the specification requirements.

B. δ-ferrite and magnetic permeability, predictions of Espy constitution diagram



⇑ Identification of δ-ferrite through Lichtenegger and Bloech colour etchant: the austenite is coloured blue to brown while the δ-ferrite remains white (example for the UKB). The grid for the assessment is chosen based on Table 2 of ASTM E562. δ-ferrite is present only in traces in the UKB (0.70 %) and LDP (0.45 %) forgings, respectively, within requirements of the technical specification (maximum allowed 1.0 %). No δ-ferrite was identified in the tie plate sample.
Consistently, the measurements of μ_r resulted in values well below the limit of 1.03 allowed by the technical specification. For the UKB, the maximum value obtained for μ_r was 1.013 and for the LDP 1.019. For the tie plate featuring no δ-ferrite values between 1.003 and 1.005 were measured, which is the expected range of permeability for a fully austenitic microstructure.



⇑ Ferrite prediction based on Espy diagram. Ferrite is designated as F in the diagram while A is for austenite. The prediction, requested by the technical specification for informational purposes, estimates between 1 % and 2 % δ-ferrite for the different products, respectively. As expected for wrought products, such estimated value based on heat analysis is higher than the real content of δ-ferrite in the forged components.

C. Tensile properties

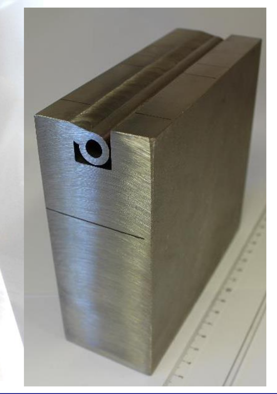
RT tensile properties of tie plates were cross-checked, as tensile strength of the latter is particularly critical since precompression is limited by the allowable stresses acting at RT in the tie-plates. The same minimum specification requirements apply for tensile properties in LD and TD. Tensile properties were tested on both the transverse directions, since only the maximum flow direction was identified in the received sample. Results show that properties are fulfilled for LD, which is the most relevant direction for the application. A slightly lower yield strength than specified is measured for one of the two transverse directions. Yield strength at the lower bound with respect to minimum requirements can be directly correlated to the lower C content specified for this grade (C ≤ 0.030 %, actual content 0.020 %), compared to standard FXM-19, where C is allowed up to 0.06 %. In future melts for the series production the lower C content will be compensated by steelmakers by adjusting N content towards the upper bound allowed by the technical specification.

RT tensile properties of the tie plate

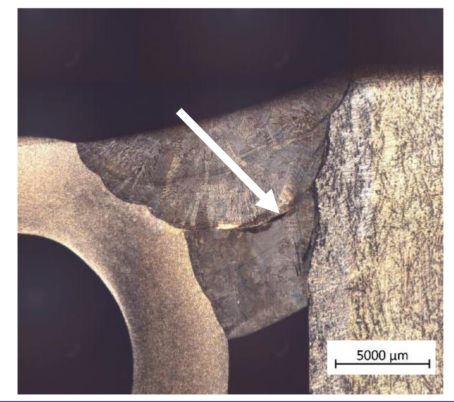
Direction	Yield strength /MPa	Tensile strength /MPa	Elongation /%
LD	384 ± 18	716 ± 1	55 ± 2
TD 1	**371 ± 1**	711 ± 4	59 ± 0
TD 2	381 ± 2	709 ± 2	55 ± 2
Minimum specified	380	690	n.a.

D. Assessment of attachment welds

⇐ Example of tie plate pipe attachment weld (courtesy of Company C). Manual TIG, filler ER316LMn, pipe 316L. The aim of the assessment is to verify the quality level achieved in terms of weld imperfections, with respect to the most stringent requirements of ISO 5817 (level B). Weld imperfections such as lack of interrun and sidewall fusion are unacceptable if judged according to the above standard. However the overall weld geometry is fully compliant: the relative position of the tube is respected for the weld at all cross sections analysed and the throat thickness of the weld is well above the minimum required 4 mm. The dimensions of the weld are reproducible and guarantee the thermal exchange.



⇐ Left: weld sample (pipe attachment weld) showing the cross-cuts performed to obtain two specimens for metallurgical and geometrical examinations. Right: macrograph of the weld. A lack of interrun fusion is observed (indicated by the arrow) ⇒



CONCLUSION

To the extent of the examination performed, this campaign confirms that an outstanding quality has been achieved at the micro and macrostructural level for the different inspected products. The fine grain structure provided by the use of ESR ingots and the redundant, multidirectional forging operations allowed non-destructive examinations, in particular UT, to be carried out on final products in favourable conditions of transparency and lateral resolution. Improvements on specific points have already been implemented for series production, namely targeting an increased N content in order to guarantee tensile properties comfortably above minimum specified requirements to compensate for the lower C content specified for the steel grade. Attachment welds are already qualified for several components; further improvements will be implemented to avoid weld imperfections and reduce weld distortion.

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