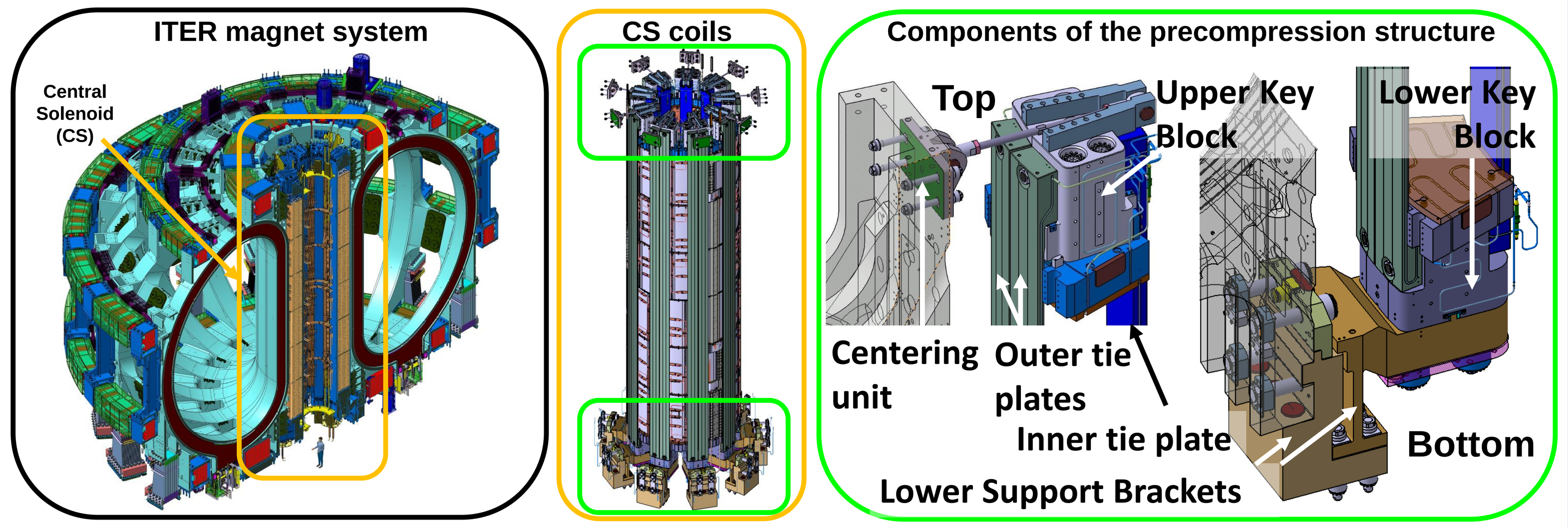
Examination and Assessment of Large Forged Structural Components for the Precompression Structure of the ITER Central Solenoid

S. Sgobba[1], I. Aviles Santillana[1], G. Arnau Izquierdo[1], P. Libeyre[2], T. Reagan[3] and D. Hughes[3]

[1]CERN, CH-1211 Genève – Switzerland
[2]ITER Organization, 13067 Saint Paul Lez Durance Cedex – France
[3]US ITER Project, Oak Ridge, TN 37830 - USA

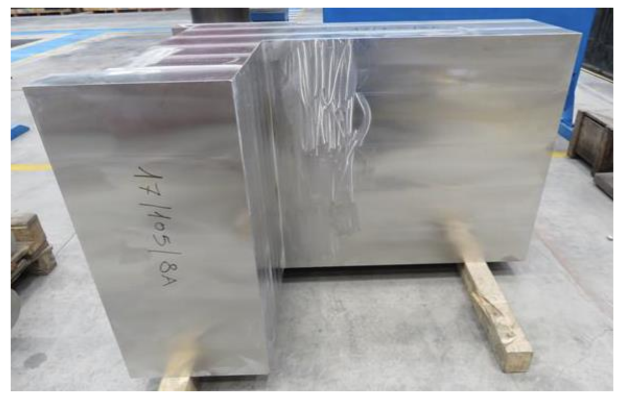
Abstract: Large structural forgings of complex shape are required for several components of the precompression structure of the ITER Central Solenoid (CS), consisting of a stack of six electrically independent modules and featuring a total height of 18 m and a diameter of over 4 m. The precompression structure allows the vertical tensile loads to be reacted and adequate preload to be maintained, in order to insure the contact between the modules during plasma operation. Several components of the precompression structure such as tie plates, lower and upper key blocks, lower and upper components are machined from open die forgings of an unprecedented combination of complex shape and large size. The selected material is FXM-19, a high strength nitrogen bearing austenitic stainless steel. A specific manufacturing schedule including redundant multidirectional forging is applied in order to achieve the required properties and microstructure of the final parts. The paper summarises the lessons learned from the series production of the components. The achievement of a fine and homogeneous microstructure, which is of paramount importance for final inspectability of the parts and to obtain the mechanical properties, is particularly challenging taking into account their large size. It requires a perfect mastering of the whole manufacturing process, from the steelmaking route, based in some cases on sequential remelting of electrodes from different master heats to create large Electroslag Remelted (ESR) ingots, to the sequence of the thermomechanical steps, from the initial upsetting of the ingots to the final solution annealing of the as-forged parts. Non-Destructive Examinations are based on stringent acceptance criteria. A fine microstructure is indispensable to allow full volumetric inspection with sufficient lateral resolution. Indeed, inspectability of the full thickness of the parts by Ultrasonic Testing, compatible with the criteria imposed by the technical specification and the structural requirements of the single components, is only possible in absence of unrecrystallised areas or excessive grain growth.

INTRODUCTION



⇑ The ITER Central Solenoid consists of six stacked electrically independent modules. A field up to 13 T will be reached in its centre. A pre-compression structure is used to provide a sufficient preload and maintain together the modules during all stages of plasma operation. The CS pre-compression system is segmented into nine independent subsets. Each subset includes structural components manufactured from large stainless steel open die forged blocks, namely Upper (UKB) and Lower Keyblocks (LKB), three different types of tie plates (outer right, outer left hand and inner, respectively) of over 15 m length, a Load Distribution Plate (LDP), as well as lower components such as lower support Flex Brackets (FB) and TF Brackets.

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



Other products such as lower support brackets, UKB and LDP are issued from forgings where the applied reductions are more isotropic (example of a FB, courtesy of Company A) ⇒

MATERIAL

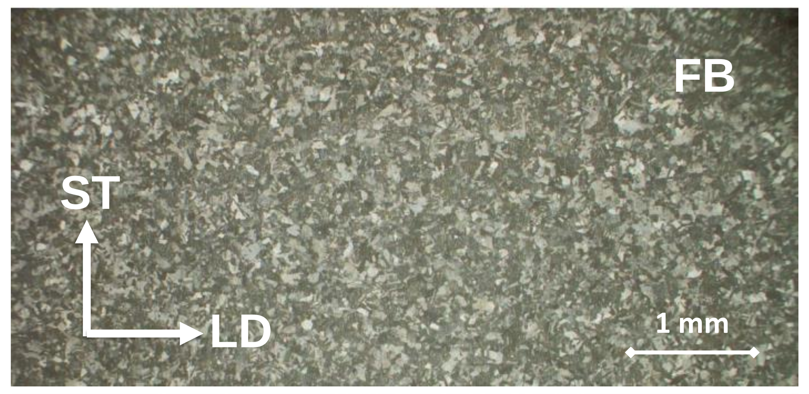
- The large structural forgings are in FXM-19, a high strength nitrogen bearing austenitic stainless steel particularly suited for application at temperatures as low as 4.5 K.
- The material is submitted to a stringent specification in terms of fineness of the grain, inclusion cleanliness, relative magnetic permeability μ_r at Room Temperature (RT) not to exceed 1.03 and ferrite content (maximum 1 %).
- Steelmaking includes mandatory Electroslag Remelting (ESR). ESR follows primary melting in an Electric Arc Furnace (EAF), refining in a Ladle Furnace (LF), Vacuum Oxygen De-carburization (VOD) and Vacuum Degassing (VD).

FXM-19 Forgings, chemical composition of the products

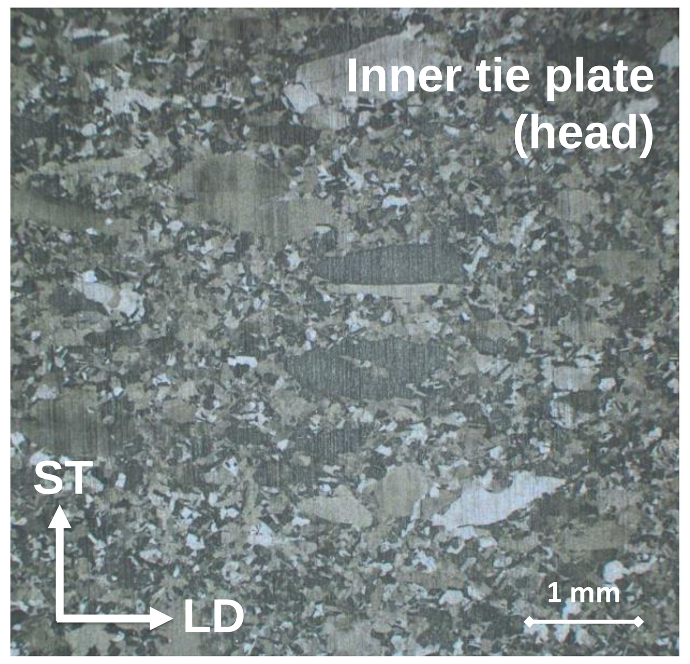
Component, Forging shop	Steelmaking route and Heat Number (HN)	Chemical composition (% by mass)											
		C	Cr	Ni	Mo	Mn	Si	P	S	N	V	Co	Nb+Ta
		Specified composition limits											
		0.03 max	20.5-23.5	11.5-13.5	1.50-3.00	4.0-6.0	0.75 max	0.045 max	0.030 max	0.20-0.35	0.10-0.30	0.10 max	0.10-0.30
FB, Company A	EAF+LF+VOD+VD+ESR, heat 117178	0.030	21.8	12.1	2.14	5.09	0.45	0.021	0.0009	0.30	0.13	0.05	0.152
Outer tie plate, Company B	EAF+LF+VOD+VD+ESR, heat 117103	0.025	20.7	11.9	1.55	4.29	0.45	0.020	0.0010	0.26	0.12	0.03	0.136
Inner tie plate, Company B	EAF+LF+VOD+VD+ESR, heat 118119	0.014	20.9	12.5	1.84	4.73	0.53	0.016	0.0012	0.30	0.14	0.03	0.159
UKB, Company C	EAF+LF+VOD+VD+ESR heat 117076	0.028	20.8	12.7	2.13	5.11	0.45	0.017	0.0010	0.32	0.12	0.04	0.150
LDP, Company C	EAF+LF+VOD+VD+ESR heat 117078	0.026	20.7	12.6	2.12	5.11	0.45	0.017	0.0010	0.33	0.12	0.04	0.149

RESULTS AND DISCUSSION

A. Macro and microstructural examination, inclusion content



⇑ Example of results of macrographic examination of a sample issued from the forging for the FB. Longitudinal Direction (LD) that coincides with the direction of maximum flow, Transverse Direction (TD) and Short Transverse (ST) direction are identified. The macrostructure is homogeneous within the cross sections, due to the lack of segregation and homogeneous grain size.



⇑ Tie plates are machined from oblong shapes of 15 meters of length with thicker heads, and feature a pronounced longitudinal axis. As the forging reduction in this case mainly occurs in LD, micro-optical observations of tie plate forgings show a more oriented microstructure with grains elongated along the maximum flow. In the thicker heads of the Inner tie plate investigated, individual coarse grain fields are locally identified up to ASTM grain size 0.5 with individual grains of over 1 mm intercept, while in all other locations an average grain size of 5 with scatter between 4 and 6 is measured.

INNER TIE PLATE, INCLUSION RATING ACCORDING TO ASTM E45 METHOD D

Severity Level Number		Type A	Type B	Type C	Type D
0.5	Thin	0	26	1	150
	Heavy	0	0	0	1
1	Thin	0	1	0	137
	Heavy	0	0	0	0
1.5	Thin	0	0	0	4
	Heavy	0	0	0	0

⇐ 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. All products are within specified limits, with exception of the Inner tie plates due to four fields (over 320 counted) of D inclusions reaching a severity level of 1.5. However, taking into account that the non-conformity concerns less than 2% of the fields, moreover of type D (globular inclusions not acting as stress concentrators), this deviation can be considered as minor and not affecting the overall performance of the part.

B. UT inspectability

⇐ Lower support brackets ready for UT inspection following rough machining. Reference blocks with machined artificial defects are available (identified by an arrow) for an inspection according to ASTM A745 using the reference block technique (courtesy of Company A). For all products the fine structure allowed the full or half thickness of the different forgings to be inspected at testing frequency between 1 MHz and 2.25 MHz (an inspection of half thickness from both sides is applied to the thickest parts in specific testing directions).

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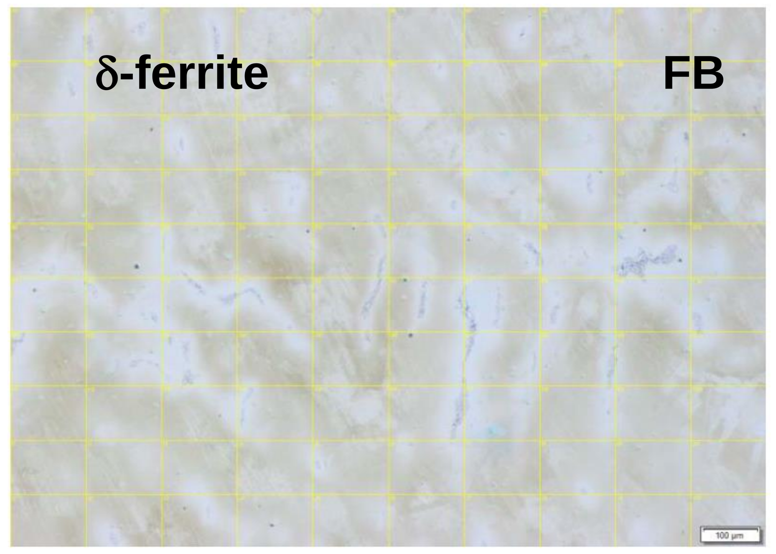
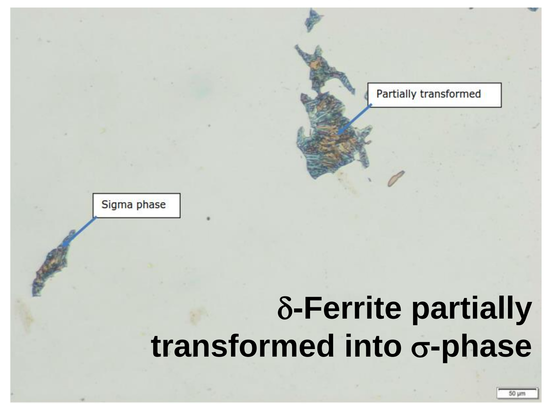
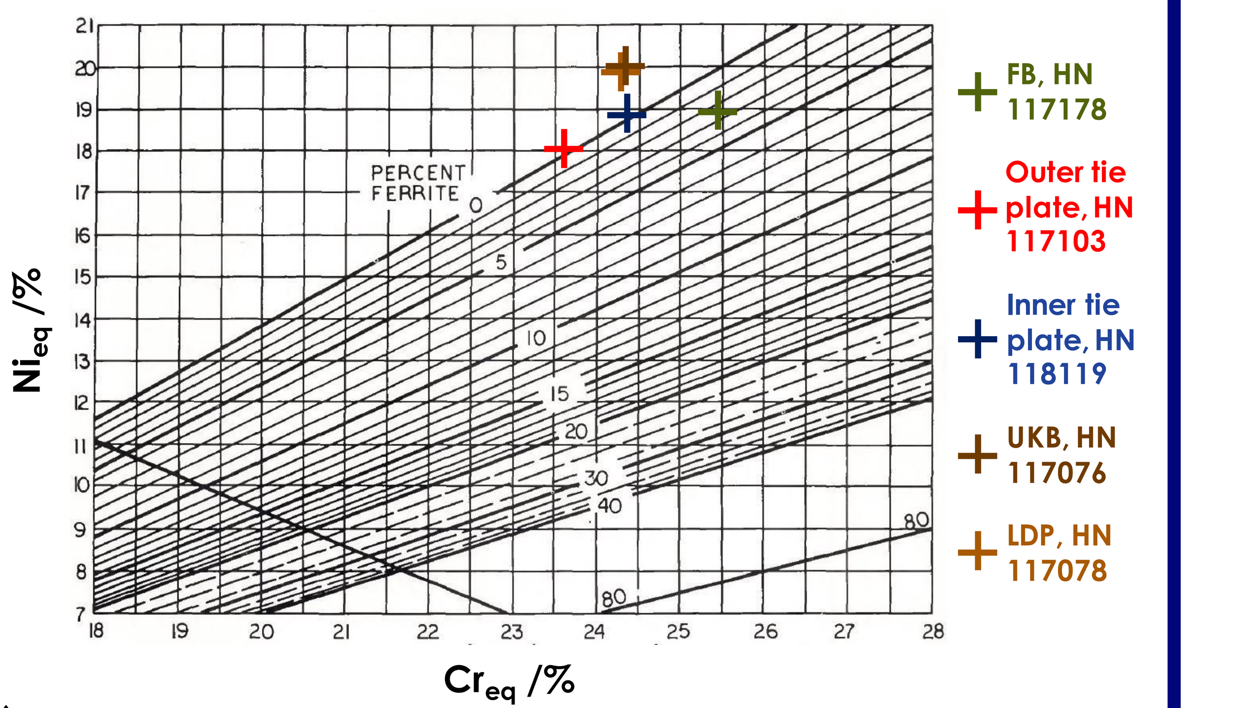
C. Ferrite and σ-phase content, magnetic permeability



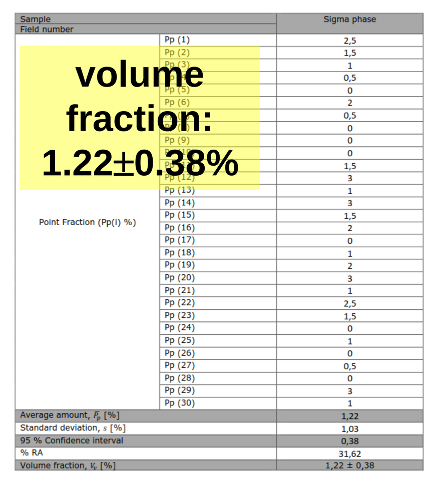
⇑ Intermediate phases such as ferrite and σ-phase have also been directly assessed based on microscopical observations following ASTM E562. This results in a negligible ferrite volume fraction of 0.03% and 0.05% for the UKB and LDP, respectively, and of 0.03 % and 0.15% for the Outer and Inner tie plates, respectively. On the other hand the FB features a higher value of 0.72%, consistently with the prediction of the Espy diagram that positions it in a more ferritic range. These values are well within requirements of the technical specification (maximum allowed 1.0%). Consistently, μ_r shows values within the expected range for a substantially austenitic microstructure. For the UKB and LDP the average value of μ_r was 1.0015 and 1.0023, respectively; for the Outer and Inner tie plates 1.0006 and 1.0018, respectively; for the FB a slightly higher value of 1.0036 was measured. All these values are significantly below the limit of 1.03 allowed by the technical specification.



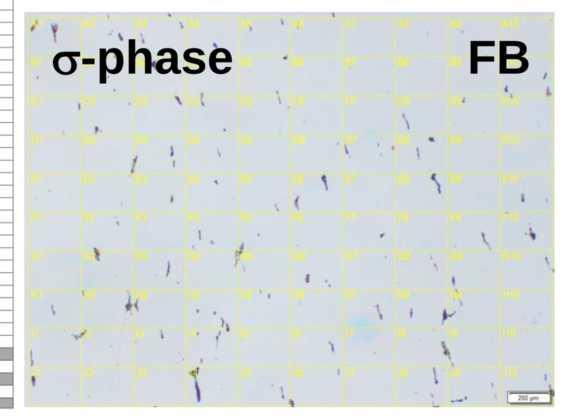


⇑ Position of the different heats of the examined forged parts in the Espy diagram. The composition falls fully in the austenitic region above the 0% ferrite line for all the products with the exception of the FB that falls in the 0% to 5% region. On this basis, ferrite is expected to be absent or present in small traces in all the products. .

Assessment of the quantity of σ–phase in the FB according to ASTM E562. The samples were etched with Murakami etching for 5 min at 70 ºC ⇒



Sample / Field number		Sigma phase
Point Fraction (Pp(i) %)	Pp (1)	2,5
	Pp (2)	1,5
	Pp (3)	1
	Pp (4)	0,5
	Pp (5)	0
	Pp (6)	2
	Pp (7)	0,5
	Pp (8)	0
	Pp (9)	0
	Pp (10)	0
	Pp (11)	1,5
	Pp (12)	3
	Pp (13)	1
	Pp (14)	3
	Pp (15)	1,5
	Pp (16)	2
	Pp (17)	0
	Pp (18)	1
	Pp (19)	2
	Pp (20)	3
	Pp (21)	1
	Pp (22)	2,5
	Pp (23)	1,5
	Pp (24)	0
	Pp (25)	1
	Pp (26)	0
	Pp (27)	0,5
	Pp (28)	0
	Pp (29)	3
	Pp (30)	1
Average amount, $\bar{P}_p$ [%]		1,22
Standard deviation, s [%]		1,03
95 % Confidence interval		0,38
% RA		31,62
Volume fraction, V_v [%]		1,22 ± 0,38



⇐ Distinctive appearance of δ-ferrite and σ-phase following a Murakami etching (#98 as per ASTM E407). The latter colors not only the σ-phase in blue, but also δ-ferrite in yellow/brown. Therefore, taking into account that for austenitic stainless steel, the preferential location of precipitation of σ-phase is the austenite – ferrite interface, it is very common to find the secondary phases mixed together.

LESSONS LEARNED AND CONCLUSIONS

The paper summarises results from a large variety of forged parts issued from the series production of the components of the ITER CS precompression structure, hence fully representative of the parts which will be mounted in the tokamak. In spite of the large variety of shapes, sizes and suppliers, all the forged products covered by the present investigation feature an excellent cleanliness, homogeneity and fineness of microstructure. The achievement of such results was particularly challenging taking into account the large size of the products and required a perfect mastering of the whole manufacturing process, from the steelmaking route to the forging sequence. The application of ESR and open die forging including multiple upsetting allowed to generally reach an isotropic structure with absence of segregation and unrecrystallized areas.

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