Possible Fabrication Techniques and Welding Specifications for the External Cylinder of the CMS Coil

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***Abstract*--The Compact Muon Solenoid (CMS) is one of the experiments, which are being designed in the framework of the Large Hadron Collider (LHC) project at CERN. The design field of the CMS magnet is 4 T, the magnetic length is 12.5 m and the free aperture is 6 m in diameter. This is achieved with a 4 layer and 5 module superconducting Al-stabilized coil energized at a nominal current of 20 kA at 4.5 K. In the CMS coil the structural function is ensured, unlike in other existing Al-stabilized thin solenoids, both by the Al-alloy reinforced conductor and the external cylinder. The calculated stress level in the cylinder at operating conditions is particularly severe. In this paper the different possible fabrication techniques are assessed and compared and a possible welding specification for this component is given.**

I. INTRODUCTION

In the CMS magnet, an "external cylinder" will be used as an outer winding mandrel and a mechanical reinforcement structure. It will also work as a cooling wall and quench back tube during cool-down, energizing and fast discharge of the coil. Each one of the 5 modules of the superconducting coil will be wound inside a module of the external cylinder, having an inner diameter of 6.84 m, a thickness of 50 mm (except for a 100 mm thick flange at each end) and a length of 2.53 m (see Fig. 1). Due to its large dimensions, each module will be possibly fabricated by circularly welding rolled rings or circularly welding rings obtained from longitudinally welded calendered plates.

2D and 3D Finite Element Analysis (FEA) have been performed on the CMS coil and external mandrel [1] by taking into account the loads acting on the cylinders (gravity, forces due to the 4 T magnetic field and forces applied locally by the suspension system). FEA shows that the stresses are maximum when the solenoid is energized, and at 4 K. Three different levels of stress act on regions: 1) of the shoulder, 2) of the weld around the shoulder and 3) on the rest of the module, where weld seams are also located. The calculated stresses in these 3 regions are given in Table I. Using the 2/3 safety factor, the yield strength of the retained Aluminum Alloy (AA) at 4 K shall be at least 235 MPa in the base material, and 195 MPa in the weld seam. These requirements are particularly severe for an AA, especially as the semifinished modules might undergo stress relieving cycles during fabrication and that the whole magnet will undergo curing cycle (possible partial annealing) after winding.

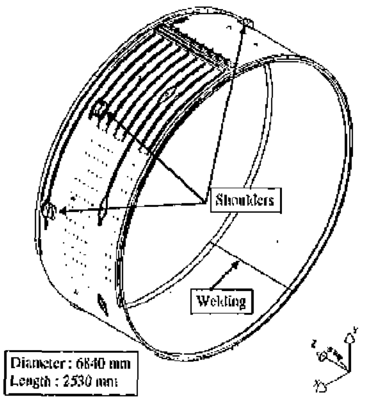

Fig. 1. Module of the external cylinder. Each module is composed of 3 elements: a 50 mm thick shell, two 100 mm thick end flanges, and shoulders where the coil support system is attached through tie rods.

II. PREVIOUS CONSTRUCTIONS VS. CMS

Almost all large, indirectly cooled solenoids constructed to date (e.g. Zeus, Aleph, Delphi, Finuda, BaBar) have consisted of AA cylinders made up by calendered plates [2-6], chamfered and TIG or MIG welded. Intermediate thermal treatment or treatments (up to two) of stress relieving during fabrication were usually applied in order to relax stresses of the cylinder, necessary to fulfill the requirements of geometrical tolerances. Times and temperatures of these treatments were ranging from 8 h at 180 °C to 5 h at 380 °C. Acceptable levels of thickness homogeneity (in some case < ± 1.0 mm) and circularity (e.g. 0.2 mm over 3.0 m diameter) have been obtained.

Table II shows some representative parameters of previously constructed solenoid detectors. The cylinder thickness was minimized for these magnets that had to guarantee high transparency to the particles. The AA used for the construction of previous cylinders was EN AW-5083-O (fully annealed), a general purpose readily weldable alloy, largely used in cryogenic installations. In previous

TABLE I
STRESSES ON THE EXTERNAL MANDREL (SOLENOID ENERGIZED).

Shoulder:	157 MPa
Shoulder weld region:	130 MPa
Rest of the module:	120 MPa

The shoulder weld region is a 400 mm square region around the shoulder where welds are located.

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TABLE II
SOME MAGNETS PARAMETERS

	Zeus (*)	Aleph (**)	Delphi (**)	Finuda (**)	BaBar (**)
Central field [T]	1.8	1.5	1.2	1.1	1.5
Radius [m]	0.94	2.5	2.7	1.46	1.49
Current [A]	5000	5000	5000	2900	3500
Cylinder thickness, [mm]	18	45	40	25	35
AA grade and temper	5083-O	5083-O	5083-O	5083-O	5083-O
Type of plate welds	MIG, manual	MIG manual	TIG, manual	TIG, manual	TIG, manual
Stress relief thermal treatment	180 °C, 8 h	260 °C, 1 h	250 °C, 10 h	380 °C, 4.5 h	350 °C, 3 h
Final inner cylinder circularity [mm]	0.26	0.4	1.5	0.2	0.35
Final cylinder thickness uniformity [mm]	< +/- 1	+/-1	< +/- 4	< +/- 2	< +/- 1

(*) Shrink-fitted coil, (**) inner wound coil.

constructions, the fully annealed temper state was compatible with computed stresses, never exceeding 70 MPa. The level of stress foreseen in the CMS cylinder at 4 K imposes an alternative choice of alloy and/or temper state and/or fabrication techniques for the construction of the cylinder, since EN AW-5083-O and its weldments would not satisfy the required tensile properties at 4 K (see §1 and Table III). HT alloys such EN AW-6061 in precipitation hardened state might also be considered, although they are less familiar to constructors in terms of weldability (particularly in case Electron Beam would be the retained welding technique). Finally, EN AW-2219 is scarcely available in Europe, and shows reduced ductility of the joints. The advantage of general purpose EN AW-5083 is its wide availability and relatively low cost (about $42 \cdot 10^3$ kg are needed). From Table III it appears that the thermomechanical state for this alloy, alternative to the O temper, which guarantees sufficient JYS, is the strain hardened and stabilized state H321 (defined according to EN 485). This is true under the condition that possible stress relieving treatments during fabrication are optimized to maintain strain hardening. MIG weldability of EN AW-5083 has been largely proved by previous constructions.

TABLE III
TENSILE PROPERTIES AT 4.2 K OF DIFFERENT AA

AA grade and temper EN AW-	YS /MPa	+filler	JYS /MPa	Joint Efficiency /%	Elongation in 4D
5083 -O	178	**5183**	174	69	27
5083 – H321	279	**5556**	238	83	13
6061 – T6(51)	>360	**4043**	259	63	13.5
2219 – T851	>480	**2319**	277	62	2.5

Properties of both Non-Heat Treatable (NHT) and Heat Treatable (HT) AA, and their arc weldments (base metal Yield Strength: YS, Joint Yield Strength: JYS) from [7], [8]. No post-weld Treatment is applied on HT alloys.

In this paper a MIG Welding Procedure Specification (WPS) performed according to the standard EN 288-4 is assessed in order to confirm the applicability of the MIG welding technique to the cylinder of CMS. Moreover a dedicated campaign of room temperature (RT) and low temperature tensile tests aimed to assess the tensile properties of the weld under the different possible construction and operation scenarios, is presented.

III. MATERIAL AND EXPERIMENTAL METHODS

To qualify the assessed MIG WPS, a campaign has been performed on plates of EN AW-5083-H321 of representative thickness (65 mm), 1 m length and 1 m width coming from Pechiney Rhenalu (Al-0.1Si-0.21Fe-0.06Cu-0.81Mn-4.78Mg-0.09Cr-0.12Zn-0.02Ti %). The plates are cut at the half width and X-chamfered. The diameter at the center of the chamfer is 16 mm and the opening angle is 20°. Just before welding, the chamfer is alcohol cleaned and scrapped. The plates are pre-heated at 100°C and maintained at the temperature during all the welding operations. The plates are welded in horizontal position using as filler metal a wire of 1.6 mm diameter of EN AW-5556 [7] supplied by FP SOUDAGE with the trade name of AG5MC (heat 6251064L: 0.07Si-0.12Fe-0.63Mn-4.98Mg-0.08Cr-0.01Zn-0.08Ti %) The power source is a FRONIUS TPS 450. The applied technique is spray transfer, with a DC current in the range 244 and 260 A and voltage in the range 30 and 32.5 V depending on the run. The shielding gas is 30 % Ar – 70 % He. The welding speed ranges between 40 and 48 cm/min and the filler wire speed is between 8.4 and 9 m/min. The leading angle of the welding gun is 10° and the working angle is between 10° and 15°. A ceramic backing bar pipe (Ø 15 mm) is used to depose the run 1. Third and fifth runs are gauged to open the chamfer before depositing the following runs.

According to the EN 288-4 standard, the welded plates are submitted to visual examination (following EN 970 standard), to radiographic examination (following EN 1435) or ultrasonic examination (following EN 1714) and to macro/micro-examination (following EN 1321).

The radiographic examination is performed using a MG104L apparatus with voltage of 96 kV and current of 15 mA. The direct contact ultrasonic inspection is performed using a Krautkramer USIP11 apparatus and inclined captor Krautkramer WSY45° with a frequency of 4 MHz and water coupling.

The metallographic investigation is performed on cross sections of polished specimens cut across the weldment. The specimens are observed using a LEITZ DMR microscope.

RT tensile tests required for the WPS approval are performed at CERN according to EN 10002-1 standard on specimens machined according to EN 895 standard, using a universal electromechanical testing machine, UTS Testsysteme (load cell 200 kN). Elongation is measured on a gauge length of 90 mm, using an optical extensometer

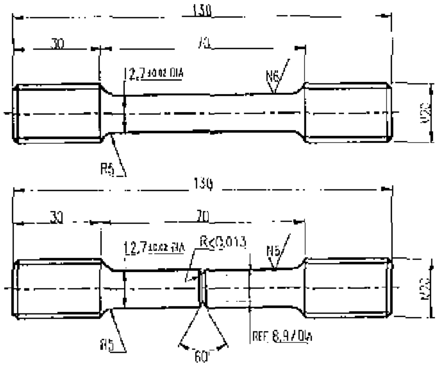

Fig. 2. Unnotched and notched specimens for dedicated tensile test.

UTS 411.01 0.3 µm, accuracy grade 1, according to EN 10002). In the elastic range the stressing rate is 10 N·mm^{-2}·s^{-1} and in the plastic range the straining rate is 1.85·10^{-3} s^{-1}. Bending tests are performed according to the EN 910 standard using the previous tensile machine.

Supplementary tensile tests at RT and low temperature both on as welded specimens and stress relieved welded specimens according to thermal cycles "Aleph"-like (1 h at 260 °C) and "Finuda"-like (4.5 h at 380 °C) are performed following EN 10002-1 both on notched and unnotched cylindrical specimens (see Fig. 2) machined according to the ASTM E 602-91 standard. The ratio of the sharp-notch strength (NTS) to the 0.2 % offset tensile yield strength of unnotched specimens is a significant comparative index of plane-strain fracture toughness [9]. CEA-Saclay performed the tensile tests in liquid helium (4.2 K) with an electromechanical tensile machine (load cell is 150 kN). The specimens are held with tapered grips at both ends. For all tests, the crosshead displacement has a speed of 0.25 mm/min. The specimen elongation is measured with a standard extensometer over a gage length of 37.5 mm. CERN performed the tensile tests at 77 K and RT using the already cited equipment. At room temperature, elongation is measured on a gauge length of 50 mm. The testing at 77 K is performed inside a liquid nitrogen cryostat and elongation is measured from the compensated movement of the stroke of the machine, on a gauge length of 60 mm. In the elastic range the stressing rate is 7.8 Nmm^{-2}·s^{-1} and in the plastic range the straining rate is 8.3·10^{-4} s^{-1}, both at room temperature and at 77 K.

IV. RESULTS

The radiographic investigation, ultrasonic examination and macro/micro-examination reveal the presence in the welding of porosity (defect 201 following EN 30042) and undercut (defect 5011 following EN 30042). These defects are minor and inside the tolerances of the B quality level (stringent) according to the relevant standard.

The results of tensile and bending tests required by the EN 288-4 standard fulfil the requirements. The WPS is therefore approved by the welding procedure test results according to EN 288-4.

TABLE IV
TENSILE PROPERTIES

		RT		77 K		4.2 K	
		BASE	WELD	BASE	WELD	BASE	WELD
TENSILE STRENGTH	MIN	332.8	291	450.3	430.6	530.3	415.2
	MAX	334.3	318	451.2	446.6	532.9	522.7
YIELD STRENGTH	MIN	196.6	.151.5	229	164.3	254.2	208.7
	MAX	199.1	180	230	207.8	255.3	233.6
ELONG. [%]	MIN	19.6	14.2	23.5	30.7	17.9	6.7
	MAX	20.6	18.4	23.8	18.3	18.8	18.7
NTS/YS	MIN.	1.87	1.9	1.86	2	1.7	1.9
	MAX	1.9	2.1	1.87	2.3	1.7	1.9

Properties of the base material and across the welding at different temperatures. Results include tensile strength, yield strength, elongation and notch tensile strength on unnotched yield strength (YS).

The tensile properties of the weld and base material at different temperatures are presented in Table IV. The range of minimum and maximum values of JYS and Joint Tensile Strength are obtained testing cylindrical specimens covering the whole thickness of the joint. For the base materials the specimens are cut at the axe of the plate thickness. The elongation at breakdown is measured on the broken specimens. The NTS and NTS/YS are obtained testing notched specimens.

The effect of the "Finuda" and "Aleph" like stress relieving treatments (partial annealing) on the tensile properties of the base material and weldment are shown in Fig. 3 (RT) and 4 (4.2 K); O state (full annealing) properties (as from literature) are reported for comparison.

Elongation at 4.2 K is always higher than 5.6 % for specimens treated with "Finuda"-like cycle and higher than 5 % for specimens treated with "Aleph"-like cycle.

The NTS/YS is higher than 1.7 for all the tested specimens. This value corresponds to high plane-strain fracture toughness (see ASTM E 602-91).

V. DISCUSSION

All the requirements stated in the EN 288-4 to qualify and approve a MIG welding procedure adapted to the construction of the CMS mandrel are fulfilled. Moreover, the proper selection of the alloy and its temper, EN AW-5083-H321, and of the filler, EN AW-5556, is confirmed by the results of supplementary dedicated tensile tests. Tensile tests at RT and 77 K show that a proper welding procedure results in values of the tensile properties in agreement with literature values [7], [8]; these values are relatively homogeneous within the weld thickness and safe for the application. At 4.2 K the yield strength of the weld fulfills the requirements of the design (min. value 208.7 > 195 MPa); the yield strength of the base material also fulfills the requirements (average 255 > 235 MPa). In case stress relieving could not be avoided during the construction, the results of supplementary tests on thermally treated specimens clearly show that only a thermal treatment comparable or less severe than the "Aleph"-like one (260 °C at 1 h), results in an

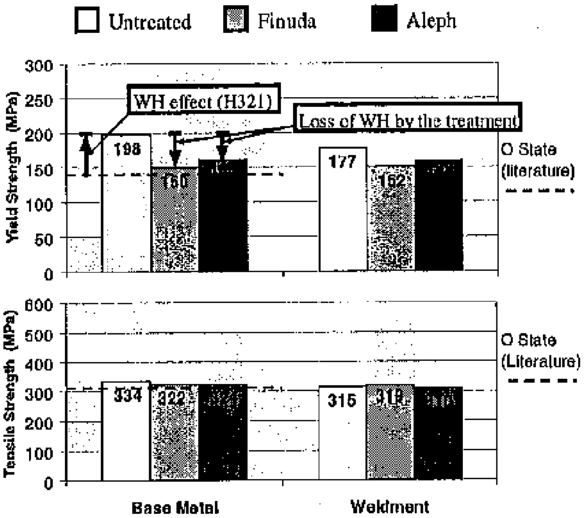

Fig. 3. Effect of stress relieving treatments on average values of yield and tensile strength at RT. The amount of Work Hardening (WH) associated to the H321 state is shown and compared to the loss due to the treatments.

annealing compatible with the alloy and temper selected for the application. Nevertheless, if such a partial annealing is applied, a reduction of the design safety factor cannot be avoided to fulfill the design requirements.

A fabrication path that would possibly avoid applying stress relieving might be rolling of seamless rings, circularly welded by an EB technique. The feasibility of such a production method has been promisingly explored both in terms of ring rolling and EB welding. In particular, plates of EN AW-5083-H321 65 mm thick have been successfully welded at CERN. This fabrication method might also allow the alternative choice of precipitation hardenable alloys of the 6xxx series (although EB weldability might be critical). EN AW-6082-T6 has already been the object of a preliminary campaign of EB welding at CERN, performed on plates 50 mm thick and 1 m long.

VI. CONCLUSIONS

The size of the external cylinder of CMS and the level of stress which will be attained in some of its parts at 4 K, higher than in any previous magnet construction, have imposed a critical discussion of design, alloy, temper selection and applicable fabrication techniques. In particular, a strain hardened alloy (EN AW-5083-H321) has been selected, compared to previous constructions, where a simple solution annealed or "as fabricated" EN AW-5083 could fulfill the design requirements.

A MIG welding procedure adapted to the construction of the CMS cylinder has been defined and qualified resulting in weldments that, as well as the base metal, fulfill the design requirements.

Particular attention shall be paid to possible stress relieving treatments during fabrication, that shall be optimized in order to avoid unacceptable loss of tensile properties. Upper limits to the severity of stress relieving treatments for this application could be defined.

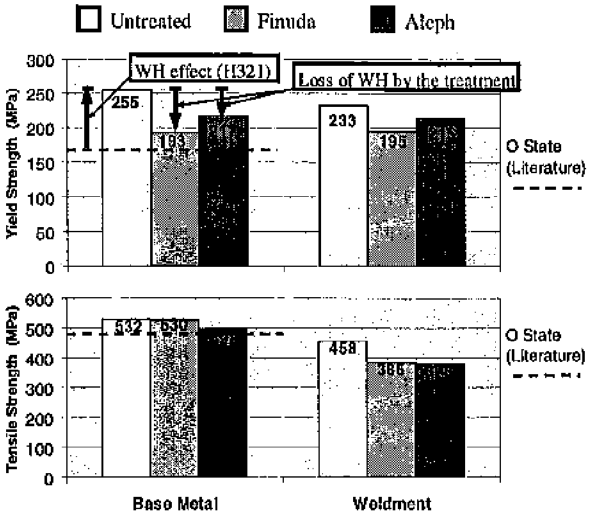

Fig. 4. Effect of stress relieving treatments on average values of yield and tensile strength at 4.2K. The amount of WH associated to the H321 state is shown and compared to the loss due to the treatments.

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