Design, Construction, and Quality Tests of the Large Al-Alloy Mandrels for the CMS Coil

S. Sgobba, C. D'Urzo, P. Fabbricatore, S. Farinon, A. Gaddi, A. Lauro, B. Levesy, L. Loche, R. Musenich, F. Rondeaux, S. Sequeira Tavares, and N. Valle

***Abstract*—The Compact Muon Solenoid (CMS) is one of the general-purpose detectors to be provided for the LHC project at CERN. The design field of the CMS superconducting magnet is 4 T, the magnetic length is 12.5 m and the free bore is 6 m. Almost all large indirectly cooled solenoids constructed to date (e.g., Zeus, Aleph, Delphi, Finuda, Babar) comprise Al-alloy mandrels fabricated by welding together plates bent to the correct radius. The external cylinder of CMS will consist of five modules having an inner diameter of 6.8 m, a thickness of 50 mm and an individual length of 2.5 m. It will be manufactured by bending and welding thick plates (75 mm) of the strain hardened aluminum alloy EN AW-5083-H321. The required high geometrical tolerances and mechanical strength (a yield strength of 209 MPa at 4.2 K) impose a critical appraisal of the design, the fabrication techniques, the welding procedures and the quality controls. The thick flanges at both ends of each module will be fabricated as seamless rolled rings, circumferentially welded to the body of the modules. The developed procedures and manufacturing methods will be validated by the construction of a prototype mandrel of full diameter and reduced length (670 mm).**

***Index Terms*—Aluminum alloys, cryogenic material properties, ring rolling.**

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 five modules of the superconducting coil will be wound inside a module of the Al-alloy (AA) external cylinder. Each module of the cylinder, having an inner diameter of 6.84 m and a length of 2.53 m is composed of three elements (Fig. 1): a 50 mm thick shell, two 130 mm thick end flanges and radial shoulders where the coil support system is attached through tie-rods. The central module has thicker end flanges (180 mm) that include shoulders for longitudinal tie-rods.

Seamless ring rolling has been retained for the fabrication of the ten end flanges, while the shells will be obtained as a welded construction.

Manuscript received September 24, 2001.

S. Sgobba, A. Gaddi, and S. Sequeira Tavares are with CERN, CH-1211 Geneva, Switzerland (e-mail: Stefano.Sgobba@cern.ch).

C. D'Urzo, L. Loche, and N. Valle are with Ansaldo Superconduttori, I-16152 Genova, Italy.

P. Fabbricatore, S. Farinon, and R. Musenich are with INFN, I-16146 Genova, Italy.

A. Lauro is with the Italian Institute of Welding (IIS), I-16141 Genova, Italy.

B. Levesy and F. Rondeaux are with CEA Saclay (Dapnia), F-91911 Gif-sur-Yvette, France.

Publisher Item Identifier S 1051-8223(02)03578-9.

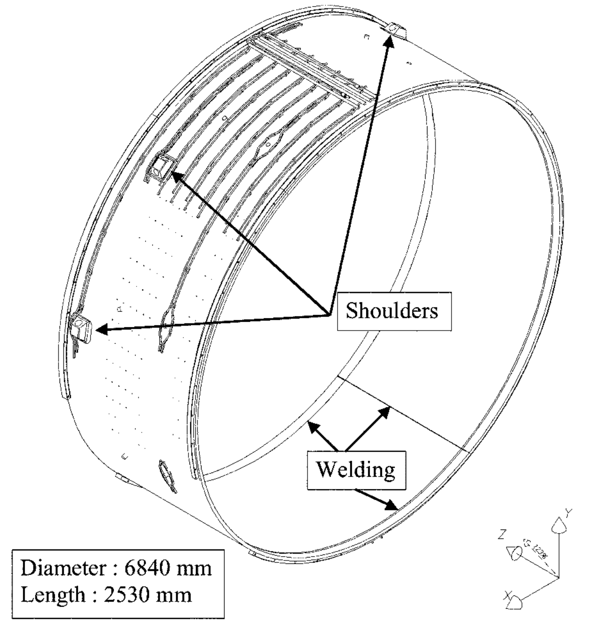

Fig. 1. Module of the external cylinder. Each module is composed of three elements: a shell, two end flanges, and shoulders for the tie-rods.

The CMS coil will be indirectly cooled with saturated liquid He at 4.5 K, through cooling tubes circumferentially welded to the outer part of the cylinder. Therefore the working temperature will be 4.5 K and the relevant material properties of the cylinder have to be verified at the liquid He temperature (4.2 K).

Tight tolerances on thickness (less than ± 1.0 mm) and circularity (± 1.0 mm over 6.84 m diameter) are imposed.

The high forces acting on the CMS cylinder will result into calculated stresses up to 209 MPa. Therefore, stress relieving treatments as applied to AA and their welds during the construction of cylinders of former solenoids (e.g., Delphi, Finuda, Babar) are not compatible with the tensile strength required for the CMS magnet, since they would result in an unacceptable loss of tensile properties [1]. Moreover, a stress relieving treatment applied to a cylinder of such dimensions would imply heavy handling and transportation issues at one of the rare sites where very large furnaces for heat treatment of AA are available.

The highest stresses are located around the shoulders of the central module. Since these shoulders are included in the seamless flanges, the peak stresses will act on base material and not on welds.

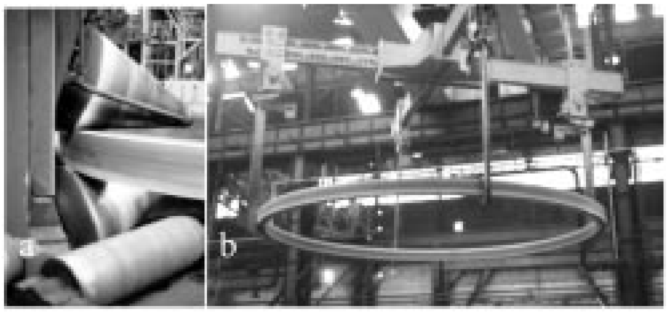

Fig. 2. A 6.8 m diameter ring during two phases of fabrication: (a) seamless ring rolling and (b) transfer of the rolled ring to the quench bath.

Fig. 3. A pre-machined ring during insertion in the shipment box (courtesy of Dembiermont).

II. Materials Selected and Fabrication Techniques

An extensive and comparative characterization of the low temperature properties of different AA and their welds resulted in the selection of the general-purpose alloy EN AW-5083-H321 as the base metal for the welded fabrication of the shell [1]. The strain-hardened and stabilized temper H321 guarantees a safe Yield Strength ($R_{p0.2}$) of 254 MPa measured on plates at 4.2 K. The MIG weldability of the alloy has been proved and specified [2]. Moreover, the $R_{p0.2}$ of the joint at 4.2 K, produced with an EN AW-5556 filler, has been measured between 203 MPa and 233 MPa which is satisfactory for the application [1].

Plates 75 mm thick (to be further reduced in thickness by machining after welding) in EN AW-5083-H321, as required for the shell, are industrially available and certified according to ASTM B209M. This standard covers, for plates in H321 temper, a thickness up to 80 mm and guarantees a minimum Room Temperature (RT) $R_{p0.2}$ of 200 MPa (measured: 199 MPa). Since the strength decreases with increasing thickness, the properties associated to this temper would no longer be certified, and possibly might not be adequate for the flanges or the shoulders thicker than 80 mm. As an alternative to a welded construction, the ten end flanges are obtained from seamless rings. The shoulders that have not been integrated into the thickness of the flanges (see Section I) will be machined from forged blocks of the same alloy with minimum specified and guaranteed strength.

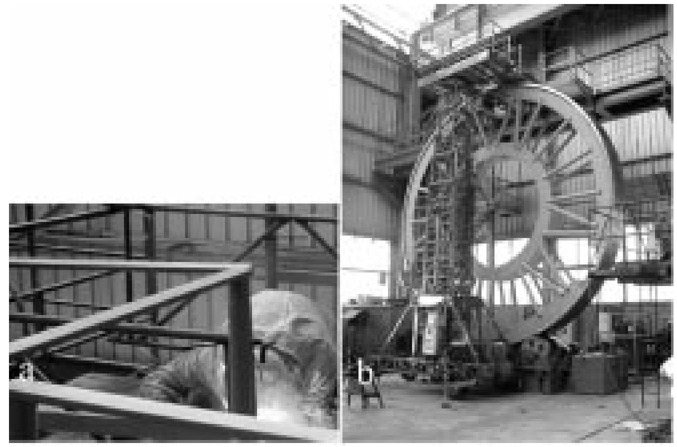

Fig. 4. The shell of the prototype mandrel during (a) welding, (b) on the roll-type positioner.

For these thick components, the choice of an alternative high-strength heat-treatable alloy, such as EN AW-6082-T651, has been discarded due to the measured strength losses in its weld heat affected zones. This softening, typical for the AlSiMg family of alloys, is known and well interpreted [3]–[6].

III. Seamless Ring Rolling for the End Flanges

Ring rolling [Fig. 2(a)] is a metalforming process allowing seamless annular components to be obtained starting from a pierced, pre-formed and pre-heated blank.

The firm Dembiermont in Hautmont (F) is capable of producing seamless rings up to 8 m diameter and 40 t weight. The use of a computer controlled, multiple mandrel, radial-axial ring mill of German fabrication (the largest in Europe) allows rings of high planarity and circularity tolerances to be obtained [Fig. 2(b)]. A relationship between radial and axial cross-sectional reduction is selected, controlling the diameter growth rate during the rolling. Rolling is followed by a final cold expansion (performed in an expander capable of treating rings up to 8 m), aimed to calibrate the ring and, in our case, to confer the adequate mechanical properties to the ring by cold stretching. The rings are subsequently pre-machined (including the welding chamfers) by Dembiermont on a vertical lathe.

For the transportation, each ring is sealed in an envelope containing silica gel. During the shipment, two rings are housed in a wooden box, reinforced by a steel basement and equipped with fastening belts (Fig. 3). A wooden wall separates the two rings in the box. A road transportation is foreseen between Hautmont and Dunkerque (F), a sea journey between Dunkerque and Genoa (I) and a final road transportation between the harbor of Genoa and the workshop of the firm Seigen (I), where the assembly of the rings to the welded shells will be performed.

IV. Fabrication of the Shells and Circumferential Welding to the End Flanges

Each shell is fabricated starting from plates, by forming three 120° arcs to the right diameter and then welding them together. The formed arc is fixed in a positioner where the longitudinal chamfers are machined. The inner diameter of each arc and the geometry of the grooves (symmetric double-J-grooves, see Section V-B) are checked by a suitable template.

The shell is assembled by longitudinal welding. First, the correct facing of the roots of the grooves is verified, then tack-welding is performed according to an approved Welding Procedure Specification (WPS). Stiffeners are inserted into the shell wall to reinforce it and to help to maintain roundness. This stiffened assembly is transferred to a horizontal roll-type positioner (Fig. 4) where the longitudinal welds are performed by an automatic MIG technique, according to an approved WPS (see Section V-B). The three longitudinal welds are performed one after the other. For each weld, after making the first passes on one side, the shell is rotated on the roll-type positioner as many times as required by the alternance of the passes. In this way, each side receives passes in the flat position.

The welded shell is moved on the bed of a vertical lathe by a lifting balance. Up to 4 mm of material are removed from the outer surface by rough turning. The out-of-roundness of the shell is first checked at this stage. Two symmetric double-J-grooves (the second after tilting the shell by 180°) are machined at the ends of the shell on the same vertical lathe. After beveling the shell edges, the stiffener is removed and the inner surface of the shell is turned, removing up to 6 mm of material.

After re-inserting the stiffener, the shell is moved on a surface plate by the lifting balance in order to weld the two seamless end flanges. By keeping the shell in the vertical position, the first ring is tack-welded to the shell after fixing a stiffening plate onto the ring. After tilting this assembly by 180°, the second ring is tack-welded onto the shell following the same procedure. The assembly is moved on the roll-type positioner in order to perform the two automatic MIG welds between the rings and the shell. In this way, the circumferential welding is also performed in flat position with a stationary torch while rotating the assembly.

This welded module is transferred to the surface plate. At first the stiffeners are provisionally removed and a dimensional check is carried out on the upstanding module; then they are inserted again before re-lifting the module on the bed of the vertical lathe, where the upper flange is rough-turned and the outer surface of the shell is finish-turned to the design diameter. After a final 180° tilting and removing the internal stiffening equipment, the opposite flange is rough-turned and the inner surface of the module is finish turned, keeping an overthickness of 6 mm. A final check of the out-of-roundness of the module is performed.

V. Quality Controls Foreseen and First Experimental Results

A. Seamless Rings

The fabrication of the seamless rings follows an agreed Quality Control Plan. Their delivery is accompanied by the emission of a certificate of type 3.1.B according to the European standard EN 10088. This contains the results of the chemical analysis of the heat, the visual and dimensional inspection, the Ultrasonic Testing (UT) performed according to ASTM B594, the tensile and hardness tests and the exfoliation corrosion test performed following ASTM G66-86.

TABLE I
Tensile Properties of a Real Scale Ring
Measured (specified) tensile properties at RT and 4.2 K of a full scale ring produced by Dembiermont in the three main directions (the longitudinal or rolling direction is the one of maximum flow). Average values over three measurements. Symbols according to EN 10002–1.

Direction	$R_{p0.2}$ /MPa, measured (specified)	R_m /MPa measured (specified)	A /%, measured (specified)	T /K
Longitudinal	253 (200)	334 (285)	18.6 (9)	293
Axial	215 (180)	320 (275)	15.4 (8)	293
Radial	204 (170)	315 (270)	16.9 (7)	293
Longitudinal	308 (-)	554 (-)	32.0 (-)	4.2
Axial	271 (-)	436 (-)	9.4 (-)	4.2
Radial	289 (-)	420 (-)	7.4 (-)	4.2

UT was performed by a contact method according to the standard practice for inspection of AA wrought products for aerospace applications. A 100% control was performed in two directions (axial and radial). Class B of ASTM B594 was selected as the discontinuity class limit. No relevant single discontinuities over the specified limits or multiple discontinuities were detected.

The tensile properties achieved at RT correspond to a H116 temper with the minimum specified mechanical properties reported in Table I. The applied expansion of approximately 5.5% was sufficient to fulfill the specified strength while keeping the required ductility. Table I also reports the measured tensile properties of the rings at both RT and 4.2 K (not specified). The latter are evaluated on specimens of 6 mm^2 square section with a calibrated length of 25 mm, in a special apparatus for tensile testing at 4.2 K developed at CERN [7]. The improved isotropy of the tensile properties and the high ductility in the three directions are advantages of ring rolling compared to rolling of plates. High values of strain at failure (A) are measured down to 4.2 K. Hardness values of approximately 100 HBS were measured on the rings.

Tests performed on each ring show that in H116 temper, the products display no sign of exfoliation corrosion.

B. Welded Construction

To assess the WPS for the circumferential and longitudinal welds, according to the standard EN 288-4, several welded samples have been produced under the supervision of the Italian Institute of Welding. The base materials consist of EN AW-5083-H321 plates. The MIG welding qualification samples are 1000 mm × 400 mm × 65 mm (length × width × thickness). The plates are chamfered with a symmetric double-J-groove. The root radius is 10 mm and the included semi-angle is equal to 20°. Before welding, the plate edges are pre-heated at 100 °C and maintained at this temperature during all the welding operations. The samples are welded in flat position, using an EN AW-5183 filler wire supplied by ESAB, with a diameter of 1.6 mm. The power source is a FRONIUS TPS 4000. A spray-arc transfer mode is retained: a DC current ranging between 270 and 300 A is associated to an arc-voltage ranging between 27 and 30 V, depending on the pass. The shielding gas is 30% Ar and 70% He. The welding speed is between 90 and 100 cm/min and the wire feed speed between 9.6 and 9.8 m/min. The working angle is in the range 0° to 20°. The passes are properly alternated in order to minimize the angular distortion of the welds. Dye penetrant examination has been applied on the root side (after back gouging) before the sealing pass. An acetone cleaning follows the dye penetrant testing.

According to EN 288-4, the welded samples have been submitted to visual (according to EN 970), X-rays (according to EN 1435) and macro/micro examination (according to EN 1321). As well, UT has been performed on the welds in order to reveal possible defects not detected by X-rays (such as lack of fusion). All the requirements specified in the EN 288-4 to qualify the MIG welding procedures adopted for the construction of the shells are fulfilled.

The plates used for the construction of the shells have an initial thickness of 75 mm, allowing for machining an extra thickness of 25 mm after welding (10 mm from the outside, 15 mm from the inside). During the construction of the modules, possible welding deformations are monitored by intermediate dimensional checks. After the welding, 100% visual, X-rays and UT examinations are performed on the welds of each module. For each longitudinal weld of the shells, run-off and run-on plates of a length of 400 mm are also foreseen for further destructive tests.

VI. Discussion

The solution retained for the fabrication of the modules of the external cylinder of CMS foreseeing seamless rings for the thicker end flanges (where the maximum strength of 209 MPa at 4.2 K is required) and a welded construction for the thinner shells is optimized in several respects:

1) The integration of the shoulders of the central module into the thick seamless flanges confers an increased safety to the construction, since values of $R_{p0.2}$ above 300 MPa at 4.2 K are measured on the rings (for the longitudinal direction).
2) Seamless rings show improved isotropy of properties in the three principal directions (longitudinal, axial and radial) with a minimum $R_{p0.2}$ measured at 4.2 K in the axial direction over 270 MPa. Moreover, the ductility in the longitudinal direction increases with decreasing T (A increases from 18.6% at RT to 32.0% at 4.2 K), while in both transverse directions (axial and radial) a strain at breakdown over 7% is maintained at 4.2 K. Ductility is an important parameter for a structural component working at cryogenic temperature.
3) A construction foreseeing seamless flanges and welded shells is better aimed to avoid stress relieving compared to a full welded construction, since the seamless rings represent a dimensional reference for each module.

The MIG welding procedure adapted to the construction of the shells and qualified at CERN has been optimized resulting in welds fulfilling the requirements of EN 288-4.

The welding procedure itself is aimed to avoid a final stress relieving through a proper succession of alternating runs, accompanied by systematic dimensional checks after each run and a final nonsymmetric machining of the over-thickness. The comfortable over-thickness (over 25 mm on the shell plates) will help to obtain the final dimensional tolerances by machining alone.

VII. Conclusions

The size of the external cylinder of CMS, the mechanical tolerances and the level of stress which will be attained in some of its parts at 4.5 K (higher than in any previous solenoid construction), have imposed a critical discussion of design, choice of alloy (EN AW-5083), temper selection (H321 or H116) and applicable fabrication techniques. In particular, the adoption of seamless rings obtained by ring rolling for the end flanges, and of a welded construction with an optimized procedure for the shells, should eliminate any stress relieving treatment. The developed procedures and manufacturing methods are being validated by the construction of a prototype mandrel of full diameter and reduced length (670 mm).

Acknowledgment

The authors acknowledge the assistance of M. Caccioppoli for the WPS, Y. Forestier, M. Houlmann, and M. Brandt for tensile testing and Dembiermont for providing helpful information on ring rolling.

References

[1] M. Castoldi *et al.*, "Possible fabrication techniques and welding specifications for the external cylinder of the CMS coil," *IEEE Trans. Appl. Superconduct.*, vol. 10, pp. 415–418, Mar. 2000.
[2] CERN WPS no. M1 169 910, 1999.
[3] T. Enjo and T. Kuroda, "Microstructure in weld heat affected zone of Al–Mg–Si alloy," *Trans. JWRI*, vol. 11, pp. 61–66, 1982.
[4] S. Kou, *Welding Metallurgy*. New York: Wiley, 1987, p. 277 ff.
[5] O. R. Myhr and Ø. Grong, "Process modeling applied to 6082-T6 aluminum welds—I. Reaction kinetics," *Acta Metall. Mater.*, vol. 39, pp. 2639–2702, 1991.
[6] ——, "Process modeling applied to 6082-T6 aluminum welds—II. Application of models," *Acta Metall. Mater.*, vol. 39, pp. 2703–2708, 1991.
[7] S. Sgobba, J. P. Bacher, M. Couach, and S. Marque, *Proc. 4th European Conf. Advanced Materials and Processes*, vol. F, Venice-Padua, Italy, 1995, p. 153.