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WELDING AND QUALITY CONTROL FOR THE CONSOLIDATION OF THE LHC SUPERCONDUCTING MAGNETS AND CIRCUITS

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Abstract

The first LHC long shutdown (LS1) was driven by the need to consolidate the 13 kA splices between the main superconducting magnets to safely attain the center of mass design energy of 14 TeV. Access to the splices implies the orbital cutting of welded stainless sleeves. After consolidation, the sleeves are re-welded using a TIG orbital welding process.

The welding process has been modified from the original "as-new" installation in order to better adapt to the "as repaired" situation. The intervention has been thoroughly prepared through qualification of the process, organisation of welding teams, their training and their follow-up.

For the quality control of the single weld, the joint geometry implies that non-destructive techniques find limited application. Quality control is based on the qualification of the welding process, equipment and operators; the recording of production parameters using new, modern instrumentation; regular process audits and production samples; visual inspection through an official notified body, using novel recording orbital videoscopes.

The paper also describes welding and quality control of special intervention cases, with issues of difficult access requiring innovative ad-hoc solutions.

This work concerns approximately 10 000 welded joints, 40 engineers and technicians over a period of 18 months. The experience and learning are applicable to similar large, complex projects.

INTRODUCTION

Throughout the LS1, the consolidation of the 13 kA interconnections (IC) consists of opening the cryogenics lines, the so-called M sleeves (M1 and M2 for the main quadrupole bus-bars and M3 for the dipole bus-bars), by orbital cutting in order to access the bus-bars and install the consolidation system, which comprises shunts, electrical insulation and mechanical restraints. Once the features are installed, the previously cut sleeves have to be re-welded [1].

ICs in the continuous cryostat have been designed to have a flange/sleeve edge weld configuration presenting the following advantages (see Fig. 1):

- Option to disconnect / reconnect several times;
- Eliminating the need for protective shielding gas during welding, given the very large volumes;
- Exclusive use of orbital welding machines;
- Edges serve as filler metal as the weld is performed without any addition.

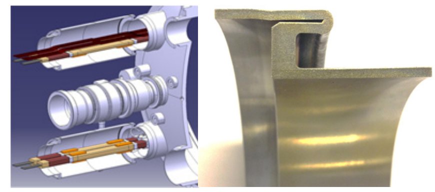

Figure 1: M lines and the flange/sleeve configuration.

These welds are performed with a very limited radial clearance of 45 mm. The choice of Tungsten Inert Gas (TIG) welding and automatic orbital machines associated with the specific geometry of the weld allows all the requirements to be met reliably.

PREPARATORY PHASE

"A project begins before it begins"

The LS1 preparation started just after the decision to resume the LHC operation at 3.5 TeV in 2009, benefiting from the experience acquired with the IC of the LHC installation.

The availability of adequate human resources is crucial for success: major efforts were made to deploy CERN internal resources towards LS1, to initiate collaborations with international institutes and establish industrial service contracts. A considerable, detailed preparation effort took place in the two years prior to the LS1 start: teams building, development of procedures, and Engineering Change Request (ECR). Following three reviews by an international committee, design, detailed procedures and quality assurance were finalised and approved by end 2012. Detailed schedules were defined and approved [2].

ORGANISATIONAL ISSUES

Although the delicate operations on the splices are at the heart of the Superconducting Magnets And Circuits Consolidation (SMACC) project. Most of the resources are used to provide access to the splices and to re-weld after the consolidation interventions [3].

To keep the ambitious consolidation schedule and on the basis of past experience the work process was designed to produce an average rate of ~53 IC re-welding activities per week (twice the rate achieved during the initial assembly of the LHC), and the team was sized for a capacity of about 70 IC activities per week. Work was carried out over 2 overlapping shifts per day, but not for the same activity, typically one shift for production and one for its related quality control. In order to ensure adequate supervision, it was necessary to limit the

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geographic dispersion of activities: each activity was progressing from one sector to the adjacent one, with the overall chain extending over three adjacent sectors. The re-welding task was carried out by a mixed team of experienced CERN welders (staff and industrial support) and collaborators from the National Center for Physics/ Pakistan Atomic Energy Commission (NCP / PAEC).

The execution of the 1695 interconnections work took exactly one year (see Fig. 2). From May to December 2013, the welding rate was not defined by the welding capacity but by the release rate of IC to be welded. Then, up to May 2014, the production rate routinely reached 60 ICs per week.

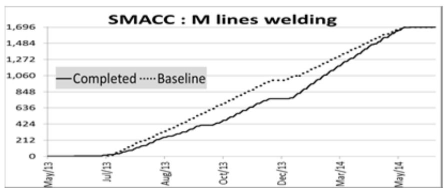

Figure 2: M welding production rates.

QA STRATEGY

The geometry of these welds implies that non-destructive testing methods find only limited application. Consequently rigorous Quality Assurance (QA) is applied to this activity. The QA strategy is based on five pillars:

1) Prior qualification of the processes and personnel including skilled welders/ welding operators;
2) Qualification of orbital welding equipment;
3) Strict application of qualified procedures and full traceability;
4) Process and welders/ welding operators audits;
5) Non-destructive testing (NDT).

Qualification of Processes

The "as repaired" situation means re-welding on partially consumed parts (sleeves and flanges) with degraded geometry. New orbital welding programs were developed based on stepping technology. In step mode, the electrode travel is stopped or slowed during the high current pulse to allow optimal penetration and the travel is at a normal speed during the low current pulse. The effect is similar to a series of overlapping spot welds or manual welds.

All welding procedures qualifications were carried out in accordance with the requirements of EN ISO 15613 and EN ISO 15614-1 and issued by a national accreditation body.

Qualification of Personnel

The human factor plays a key role in welding production. The welding team is based on welders and International Welding Technicians. All welding team members working for LS1 were trained on representative mock-ups then subsequently qualified by appropriate tests by an independent accreditation body. The welder qualifications are according to EN 287-1 and operator qualifications according to EN 1418. Moreover, all welders attended a visual inspection training according to ASNT L II (The American Society for Non-destructive Testing) given by a notified body.

Qualification of Equipment

All welding machines power supplies were refurbished and their calibration rechecked regularly every six months. New welding heads were developed and fabricated in collaboration with industry. A dedicated maintenance team was set up, trained and equipped for maintaining equipment in satisfactory operating condition and minimising the down-time and on-site urgent troubleshooting.

Full Traceability

The very tight schedule, the complexity of the consolidation sequences, the strict quality standards applied required the creation of an ad hoc tooling in order to pilot and coordinate the activity on the worksite dispersed along the accelerator.

Traceability of welding and quality data was recorded daily and monitored through efficiency parameters (operator, equipment, procedures critical welding parameters of all joints). Traceability was based on the powerful database application WeldTrack, designed in house. WeldTrack indeed provides valuable analysis possibilities, "real time" status of complete or unfinished work and statistical reports and searchable electronic archive of welding data.

The software tools allowed flexible analysis, quick decision-making based on correct information and time savings due to improved resource management: for example, by identifying the work performed in a certain time-period, the welding anomalies by a specific welder, power source or welding head.

Process Audits

Auditing, which is the control of the process (distinct from inspection of the result), and was performed regularly. The audits were performed by experienced CERN staff in the tunnel at the workplace covering the following areas:

- Procedures and personnel: this allowed faster improvement of quality issues and was highly appreciated by operators as a channel of information and feedback. The audits were applied at the rate of one audit per welder per month.
- Parameters monitoring: since the internal recording sampling rate of the original orbital welding machines was too slow (data was recorded every 10° of rotation), although this was still regularly printed, scanned and traced, a new external monitoring was introduced. It is based on digital high-resolution (up to 50 kHz) data recording offering comparison with reference welding curves and quality marks (see Fig. 3). These audits took place at the rate of one per machine per week;
- Production witness samples (for off-line destructive testing by metallographic observation): the sample

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welds were performed in the tunnel at rate of once per welder per week (during the first four week) and thereafter once per welder per month.

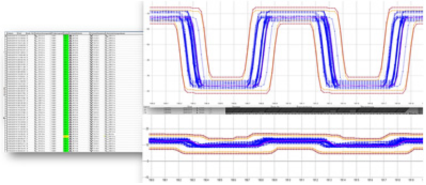

Figure 3: welding data (current and arc voltage).

NDT: Visual Testing

The particular "edge" weld joint geometry implies that X-Ray or ultra-sonic testing is ineffective as a QC technique for TIG welds. An external notified body was mandated to perform and certify 100 % visual inspection of welds according to ISO 5817 Level B (Quality level B corresponds to the highest requirement on the finished weld). Custom made orbital videoscopes were used to inspect each weld (see Fig. 4). All weld inspections were recorded, documented and declared defect free.

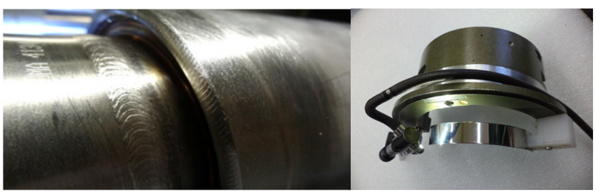

Figure 4: Weld visual aspect and the orbital videoscope.

Leak Tightness

At the level of an extended chain of welds– from one vacuum sub-sector (~ 16 ICs, i.e. 96 welds) to a complete 2.7 km arc sector (~ 212 ICs) – quality control is based on vacuum leak tests that progressively validate the work performed. All welds were leak tested: 10'170 welds, equivalent to about 3'300 m of on-site welded seam.

The leak tightness specification was 1.10^{-9} mbar l sec^{-1}. The root cause of the 17 detected leaks (failure rate of ~ 1.7 ‰) was carefully studied, highlighting two failure mechanisms. The first one (typically 10^{-3} mbar l sec^{-1}, failure rate of 0.6 ‰) is due to liquid metal embrittlement (LME) where polluting metals (Cu, Ag and Sn) were present close to the Heat Affected Zone (HAZ) during welding [4].

Figure 5: Left, LME in the HAZ. Right, shows a macro-inclusion in the bulk material of the flange.

The second one (typically 10^{-7} mbar l sec^{-1} representing a failure rate of ~ 1.1 ‰), originates from the presence of a macro-inclusion in the flanges bulk material. This kind of imperfections can be encountered when dealing with material not produced using ElectroSlag Remelting or equivalent process (see Fig. 5). In comparison the failure rate during LHC installation was 3 ‰.

CONSOLIDATION OF THE DFBA SPLICES

The main dipole and quadrupole circuits are powered through current leads located in 16 electrical and cryogenic feedboxes (DFBA) [5,6]. Inside the DFBAs, there are two additional splices for each busbar: one between the different parts of the DFBA and one between the busbars and the current leads for a total of 135 splices. As these splices are located inside of fully welded liquid helium cooled circuits, their consolidation requires cutting and re-welding nearly 100 sleeves (i.e. 200 welds). In addition to these sleeves a significant number of non-conformities were found that required a large number of particularly complex mechanical cutting/welding operations, requiring innovative ad-hoc solutions, often in extremely difficult conditions with limited accessibility and space. The required cut quality is always very high, since it determines the quality of the subsequent re-welding. For such cases, a technical solution was found, a prototype built and successfully applied.

CONCLUSION

A thorough preparatory phase was essential to enable full achievement of the LS1 goal and implement all the necessary improvements towards optimal reliability.

The added complexity of the repair campaign was successfully met, in particular by introducing new concepts such as: highly qualified welders instead of operators, dedicated training of welders in visual testing as first QC, specific stepping welding program, high-resolution welding parameters recording, orbital videoscopy for NDT and the enhanced traceability via a powerful database application.

The fulfilled, at large scale, stringent quality standards provide a valuable experience for welding activities applicable to future similar projects.

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