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# MODELLING OF THE DIPOLE MAGNET COILS FOR THE ALICE DIMUON ARM SPECTROMETER

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**Abstract**

The JINR design of the Dipole Magnet and the description of the proposed manufacturing procedure is presented. The proposed Coil fabrication technique is based on the winding of flat pancakes, which are subsequently bent on cylindrical mandrels. The pancakes stacked and cured with the prepreg insulation. This method was demonstrated on the prototype, which consists of a pancake made with the aluminium conductor of the similar size. The results of measuring of mechanical and electrical characteristics of materials related to the coil composite structure are discussed.

**Key-words:** ALICE experiment, dipole magnet, winding, pancake, aluminium conductor

# 1. Introduction

A general description of a design of the Dipole Magnet (DM) of DiMuon Arm Spectrometer of ALICE experiment at the LHC and a current status of the work is presented in [1] -[3]. The most important part of the DM is the winding. The JINR coil manufacturing concept, which implies winding of the flat rectangle pancake, and shaping it on a cylindrical fixture is presented. Modelling of the technology process stages and studying of the characteristics of the materials used in the winding are described in this work.

# 2. Dipole Magnet coil

The schematic view of the magnet is shown in Fig.1. The DM winding consists of two identical cylindrical saddle shape coils covered by eight clamps, enveloping the coils via rubber gasket and joined one to another by assembly plates. The coils are fixed at bottom and top beams of the iron yoke. The coils are wound from single cut hollow aluminium conductor. Each coil includes 12 shaped pancakes glued together and enveloped by ground wall insulation. The winding is installed in the iron yoke. Circulating de-mineralised water cools the coils. A maximum temperature rise in the cooling water is the 30°C. Conductor material for the coils is the hollow extruded aluminium conductor of AD0 type of 99.5% purity (max. electric resistance at 20°C < $2.95 \times l0^{-8} Ohm \times m$).

A coil insulation system includes turn-to-turn, pancake-to-pancake and ground wall insulation (correspondingly $1^{+0.1}$mm, $1^{+0.1}$mm, $5^{+1}$mm overall thickness after curing). The "B-stage" system - prepreg PST-206 of NPO "Stekloplastic", Russia was chosen as a material for the insulation. The prepreg consists of a glass cloth (E3-100, 0.1 mm thick) and an epoxy compound EDP-1 (mixture of epoxy resins ED-8 and ED-20) as a bonding material. The mass part of a bonding material in the prepreg amounted to 34±3%. The lifetime of PST-206 is about 3 months at temperatures ≤ 25°C and 4 months at temperatures ≤ 8°C. A curing regime of the prepreg stipulates a continuous temperature increase up to 150°C during 100-200 min, the temperature holding for 180 minutes and the specific pressure of 2-3 Bar.

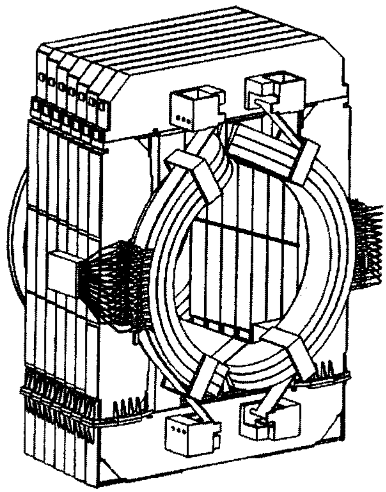

Figure 1: The schematic view of the Dipole Magnet

# 3. Coil manufacturing concept

A coil-manufacturing concept implies winding of a flat rectangle pancake and shaping it on a cylindrical fixture. A machine application of conductor turn insulation, forming trapeze cross-section and cleaning of a conductor surface by metal brushes are carried out during the winding of flat pancakes. After the shaping process the turn-to-turn insulation is pressed and cured by an electrical heating of the conductor. The cured pancake has undergone dimension and electrical tests and has been wrapped by an interlayer prepreg insulation. After that procedure it is placed and adjusted on the surface of the assembly fixture (Fig.2). Then pancake is uniformly clamped to the fixture surface by hold-down tools (pressing beams and pressing jacks). The pressure value is kept for at least one hour for an epoxy resin free relaxation. After that the part of hold-down tools (except pressing jacks on the sides of the pancakes) are removed and a second insulated pancake is placed from above. Both pancakes clamped by pressing beams starting from the top of the fixture. The pressing jacks on the first pancake sides continue to fix pancake sides to the assembly fixture surface. At a last moment pressure jacks on the lower pancake are removed and transferred to an upper section. A spring back shift (this shift is caused by residual stresses in the conductor after bending) of the lower pancake sides is prevented by an adhesiveness of surfaces covered by raw prepreg for several minutes during a replacement process. According to tests, a separation effort for the uncured insulation layer and a metal surface makes $0.3 \div 0.4$ MPa for the compression pressure of 0.2 MPa and for the compression time $\geq 2$ hours. Following this, the procedure sequentially repeats for the following pancakes. The coil is wrapped with ground insulation and pressed after final assembly of all pancakes. The final operation is the prepreg insulation curing.

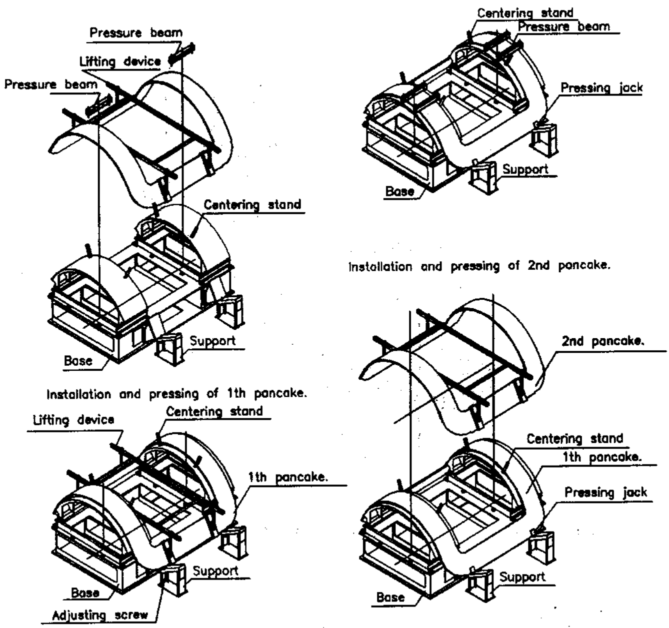


Figure 2: Procedure of the coil assembling

# 4. Tests

Extensive testing of the mechanical and electric characteristics of the conductor and insulation material has been carried out. One of the critical problems of the coil production is a removal of a residual stress in the aluminium conductor after shaping of a pancake. It was supposed that a heating of the conductor would do it during the prepreg insulation polymerisation process. Some experiments on the analysis of the relaxation process for an aluminium material of the conductor of the AD0 type have been made at temperatures of 150°C. Main decrease of the stress takes place during first two hours at the temperature relaxation process. Stress reduction of 42.5% has been achieved at 150°C after two hours of the heating. The yield stress and ultimate strength of the aluminium at 150°C have been reduced respectively from 63 MPa down to 58 MPa and from 110 MPa down to 87 MPa.

Four combined samples, which modelled turn-to-turn and pancake-to-pancake insulation, have been prepared to study the mechanical characteristics of a composite material of the coil (Fig.3). These samples were used for disruption and shear tests of the glued connection between conductor and insulation and for thermo cycling test.

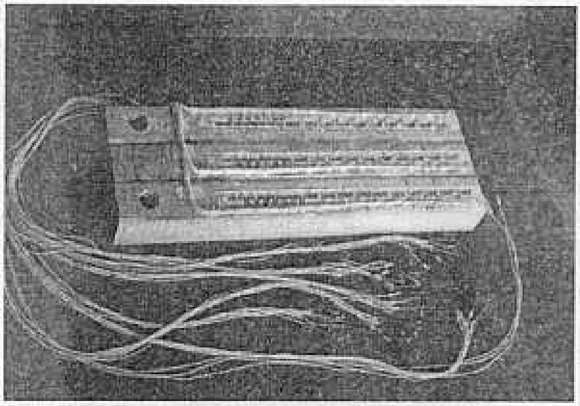

Figure 3: Three bars sample prepared for strain measurements

After testing of samples and prototypes it has been found that the insulation works for the strain together with conductor metal only within elasticity limit of the conductor. After the tensile strength test there was no residual elongation of the insulation material. The value of the insulation shear modulus is about (G$\approx 2 \div 3$ GPa). Face stresses (end effect) subside at a distance of about $180 \div 200$ mm from an edge of the prototype. So it was confirmed that the length of the three bar prototype (l$\approx$ 1200 mm) ,which was used for thermo cycling tests was correctly chosen. Destructive stresses (lower limits) in a disruption test in terms of a short-time reliability taking into account the variation for a quality adhesion are $\sigma_{ds} = 10$ MPa and $\tau = 21$ MPa correspondingly. Destructive stresses with an account of a fatigue at cycle work of a material make $\sigma_{dscyc} = 4.5$ MPa and $\tau_{cyc} = 9.5$ MPa.

The aim of thermo cycle tests was the check of the insulation mechanical strength under temperature loads. According to calculations the maximum shear stress in the three bar prototype which was used for the thermo cycle test is and the maximum shear stress in the winding is $\tau \approx 16$ MPa and the maximum shear atres in the winding is $\tau_{max} \approx 7.8$ MPa. According to the scale model-prototype relationship the full number of the DM operation cycles corresponds to 100 of prototype cycles. During the tests the indications of the displacement sensor, which control mutual displacements of the glued bars end parts, corresponded to the calculated value. Displacement value during tests did not increase. During prototype inspection after tests no damage to insulation has been found. Additionally after the tests four samples with the length of l = 48÷55 mm have been cut from one of the sample faces for insulation disruption tests. Only for the side sample the value $\sigma_{ds}$ = 11.8 MPa has been 12% less than for all other samples. Last tests showed that there was no sufficient decrease of the glue connection strength after the thermocycle tests.

# 5. Pancake prototype

During 1999-2000 JINR has produced a full-scale pancake prototype with reduced number of turns and reduced length. The aim of the prototyping work was the development of a simplified model of a coil pancake to prove the design and the manufacturing technology. This winding has been produced with 12 m long bars of high purity aluminium conductor with the cross-section $54.5 \times 54.5\ mm^2$ and the central hole of 23 mm in diameter. The Al bars have been welded together by a butt argon-arc welding in order to obtain a 69 m long single conductor. The welding joints were distributed on the conductor length in such a way that their locations were avoided in bending area during winding procedure. Flat pancake of the prototype consisted of 5 turns. The shape of the pancake was a rectangle with minimal rounded radius 250 mm. The inner/outer dimensions were 5192 mm×1000 mm /5762 mm×1570 mm.

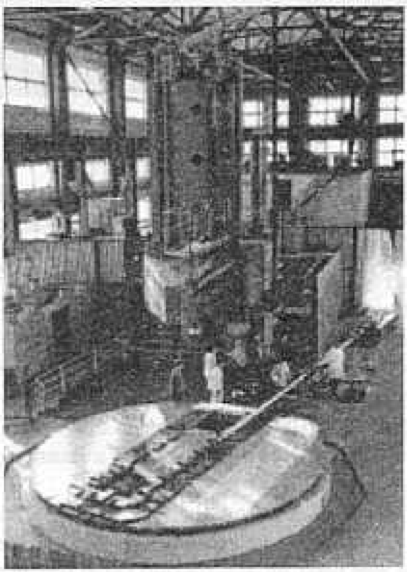

Figure 4: The winding process of the flat pancake

Prototype facilities have been used to wind, to insulate and to shape the saddle type pancake. The conductor was passed through a straightening-tightening device, which provided the tension of the conductor about 15 kN. A prevention of a forming trapeze cross-section of the conductor in places of a bending was done by a preliminary elimination of a material excess.

Dimensions of the reverse trapeze were determined by a calculation and were confirmed by a model experiment. The conductor has been insulated with the prepreg fibreglass tape. Servings of the half-lapped turn-to-turn insulation were applied by means of two automated winding devices. Depending on a prepreg elasticity rate the tension of the tape was 3-5 kg.

The flat pancake was wound on the turntable of the milling machine SKTJ (Fig.4). The wound flat pancake was taken off from the mandrel and covered by two servings of teflon tape and by two servings of glass tape LES 25×0.25.

The shaping device has been used to shape the flat pancake (Fig.5). The bending radius was 2039 mm. The flat pancake straightforward parts were fixed between massive straps and were not submitted to deformation. The first stage of the shaping was undergone under pancake's own weight. Then the crane effort was applied through a system of blocks. Slims tension was controlled by the dynamometer suspended on crane hook. The maximum force during the bending process was 33 kN.

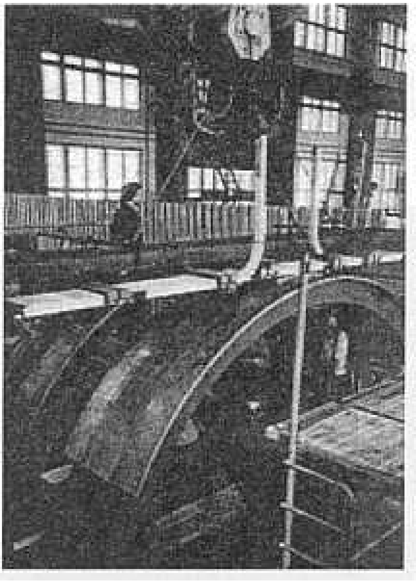

Figure 5: Procedure of the flat pancake shaping

On a bending jig the necessary quantity of clamps was provided to fix and to press the pancake in all directions. The pancake was pressed by means of transverse beams through steel sheets of 5 mm thick and incurved c-form channels. The keeping of the pressure force during the heating process was achieved by means of springs.

The next step after the bending and pressing of the pancake was a polymerisation of the prepreg insulation and simultaneous removal of residual deformations of the conductor material. The heat treatment of the pancake was done after the final correction of the pancake dimensions by means of clamps and jacks. 12 chromel-alumel thermocouples were installed on the jig and on the current leads of the pancake to control the temperature of the pancake. The pancake was thermo insulated by a glass wool material. The heating was realised by means of a direct current, which was passing through the conductor from 2-anchor AC/DC converter NGM-90. Additionally AC flat tape heaters heated the jig. The process control system was built on the base of the PC and ADVANTECH ADAM circuits. A PI-regulator program was used to control the heating process. Heat treatment mode for prototype insulation was the following:

- Temperature rise up to 150°C during 2 hours 45 minutes.
- Temperature stabilisation of 150°C during 2 hours 40 minutes.

The finished pancake (Fig.6) has been subjected to dimensional checks and electrical tests.

The geometry measurements of the conductor and wound pancake showed that the average thickness of the applied insulation on the conductor before the winding of the flat pancake was 1.46 mm (max 1.51 mm, min 1.42 mm). The thickness of the applied insulation (after pressing and before polymerisation) averages 1.275 mm (on long straightforward parts) and 1.175 mm (on short straightforward parts). After the pancake shaping the overall dimensions met all requirements of the drawings. After the heat treatment and the pancake liberation the value of residual deformation was determined by a measurement of the pancake sides spring back. It was equal to 12 mm, that is less than the calculated value - 17 mm.

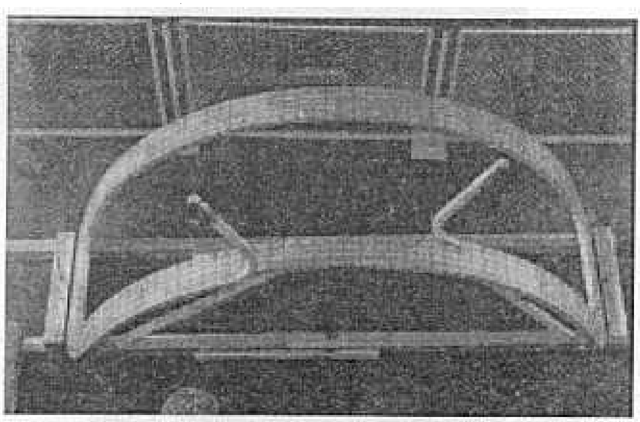

Figure 6: The model pancake prepared for electric tests

The pancake insulated surfaces after the heat treatment had uniform colour except of minor areas where the anti-adhesive covering KO-916 was applied. Besides the chamfers between neighbouring turns were found not filled with the insulation.

The measured value of the insulation resistance was not less than $1.5\times10^{10}$ Ohm at different test voltages (the accepted one is $10^9$ hm). The absorption factor was not less than 1.25 at different test voltages (the accepted one is 1.2). The model pancake sustained tests by an increased direct voltage, pulse voltage and check for an absence of turn short circuits.

Electrical tests demonstrated that the prototype pancake satisfied the accepted criteria.

# 6. Conclusions

The presented technology process of the Dipole Magnet ALICE coil manufacturing has never been used before.

The main aim of the prototyping work was the production of a coil model pancake of a simplified design, which would be as close as possible to a real construction.

The questions of the general dimensions fidelity, turn-to-turn insulation quality, the substantial spring back shift value of the shaped and cured pancake were answered as outcomes of a prototype manufacturing and tests.

The correctness of the chosen technology of the manufacturing of coils of the ALICE Dipole Magnet is confirmed. It was proven that the chosen manufacturing technology is applicable for the coil production.

Electrical tests demonstrated that the prototype pancake satisfied the accepted criteria.

The feasibility of the constructing of large aluminum conductor coils with the proposed technology was shown.

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