Prototyping of radial plates for fusion relevant superconducting magnets

M Ghate¹, D Bhavasar¹, A Panchal¹, S Udgata² and S Pradhan¹

¹Institute for Plasma Research, Near Indira Bridge, Bhat, Gandhinagar 382 428, India
²DESIGN Engineering Solutions Ltd., Wagholi, Pune 412207, India

E-mail: mghate@ipr.res.in

Abstract. The fabrication trials for prototype radial plate to support its conceptual design and development for fusion relevant superconducting magnet have been discussed in this paper. The simulation approach with CAD has been presented for prototyping of radial plates. Extensive trials have been done on SS316LN plates to estimate and establish machining sequences, machine parameters, machining tools to achieve required tolerances. The critical machining operation and parameters has been discussed in this paper. Inspection procedures with articulated arm coordinate measuring machine for prototype radial plate has been conceptualized and verified.

1. Introduction

“Magnet technology Development Division” is responsible for the development and fabrication of fusion relevant superconducting magnet (FRSM) and associated technologies at Institute for Plasma Research (IPR) in India. FRSM has been designed for magnetic field of 5.5 T / 12 T with maximum current carrying capacity of 30 kA. It consists of five insulated double pancakes stacked together to form winding pack. FRSM has been conceptualized considering the use of Niobium-Titanium (NbTi) or Niobium-Tin (Nb₃Sn) based cable in conduit conductor (CICC) with designed operating parameters [1,2]. Radial plate is primarily structural component of superconducting magnet required to transmit large electromagnetic forces on coil case, to enhance electrical and mechanical reliability of insulation, to support large electromagnetic force on conductor and to provide structural integrity and stability. The critical design drivers for conceptualization and development of radial plates are CICC configuration and its shape, configuration of superconducting magnet, operational field and operating current, electromagnetic stresses, manufacturing requirements, and assembly tolerances. SS 316LN material is widely used for manufacturing of radial plates due its high yield stress, machinability, weldability and its compatibility with cryogenic temperature.

Radial plate and cover plate for FRSM has been conceptualized considering CICC of Ø 30 mm as shown in figure 1 with respect to design drivers mentioned earlier. An arrangement of one double pancake for FRSM winding pack with radial plate is shown in figure 1. It consists of CICC with insulation, radial plate, cover plate and ground insulation. The conceptual design of radial plate and cover plate has been carried out considering SS316LN as structural material. Further design refinement with assembly considerations and FEM simulations needs to be carried out for optimization of radial plate configurations. Before going for final design and optimization, it is decided to evaluate manufacturing feasibility by prototyping of radial plates to achieve required tolerances.

Content from this work may be used under the terms of the Creative Commons Attribution 3.0 licence. Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI. Published under licence by IOP Publishing Ltd
2. Prototyping of Radial Plate

The dimensions for prototype radial plate are shown in figure 2a. It is scaled down from actual size to demonstrate feasibility of manufacturing with available machines and tools. It consists of 10 cylindrical grooves and slots of 500 mm length with tolerances as shown in figure 2a. Some of the sectors of radial plate are curved as shown on figure 2b.

2.1. Machining procedure & Parameters

The important objective of these prototyping trials was selection of appropriate tools, machines, machining parameters and machining sequence. An extensive survey for appropriate tools and machine has been carried out. Ball end milling cutter (⌀10 mm with 3 numbers of carbide inserts for roughing and ⌀ 8 mm with 3 number of carbide inserts for finishing) and vertical machining center has been selected for this prototyping activities. The visual simulation for optimization of machining process to reduce deformation during machining has been carried out in commercially available CAD software as shown in figure 2b. Numbers of fabrication trials were performed for manufacturing of prototype radial plates on SS316LN. The machining sequences, procedures and parameters were optimized by number of trials as shown in Table 1. Typical machining processes include facing operation, slotting operation and milling operation. For facing operation of SS316LN plates, face milling cutter with carbide inserts of 45° entering angle has been used. Ball end milling cutter with 3 number of carbide inserts has been used for slotting operation. Typical sequence for slotting operation of prototype radial plates is shown in figure 3. The slotting operation was initiated from left side (1) of plate and alternatively from right side (2) of plate. The typical sequence as shown in figure 3 has been optimized and followed to reduce deformation during machining process.
Table 1. Final parameter for prototyping trials by SS316LN

| Machining Pass | Cutter speed (rpm) | Feed rate (mm/min) | Depth of cut (mm) | Longitudinal tool travel (mm) |
|----------------|-------------------|--------------------|------------------|-----------------------------|
| Roughing Pass  | 2000              | 1800               | 0.1 - 0.15       | 520                         |
| Finishing Pass | 3200              | 1500               | 0.1              | 520                         |

Figure 3. Typical machining sequence for slotting operation of prototype radial plates

2.2. Inspection and Validation

The number of prototypes for radial plate has been manufactured to optimize machining parameters and machining sequence. Dimensional metrology of these prototypes has been carried out with measurement equipment’s, go – no go gauges (figure 4a) as well as with articulated arm coordinating machine (AACMM) (figure 4d). The suitability of AACMM and its probe for inspection of critical components has been demonstrated and reported [3]. During inspection, manufactured radial plate has been inspected with AACMM using contact probes. The wire frame model has been generated using collected data and analyzed with reference to datum surface of radial plate and its CAD model. Few initial samples during optimization of manufacturing process have been rejected due to dimensional variation with respect to the drawings. The subsequent prototypes after appropriate fixturing and optimize machining parameters were found to be satisfactory.

Figure 4. (a) Go- No go gauges, (b) Prototype radial plate-1, (c) Prototype radial plate-2 (d) AACMM
Detailed inspection of prototypes has been carried out by AACMM for its flatness, perpendicularity, linear variation, groove dimensions using contact probes as shown in figure 5. The average rib thickness was found to be 2.24 mm while average diameter of slots was found to be 16.11 mm. The perpendicularity of various surfaces was ranging from 0.07 mm – 0.18 mm. Three surfaces were found to be out of tolerance limit of flatness (0.2 mm).

3. Summary
- Survey for machining tools and cutter along with machining process sheet has been carried out. Ball end milling cutter mounted on vertical milling machine has been selected for this activity.
- Prototyping of radial plate on SS 316LN has been carried out for optimization of machining tools, procedure and machining parameters.
- Detail evaluation of prototype radial plate during trials has been carried out by gauges, measuring tool, and by AACMM.
- The prototyping trials for radial plate are found to be satisfactory as per all dimensional requirements. Manufacturing feasibility within stringent tolerance with prototypes has been demonstrated.

Acknowledgement
This work has been done under “Magnet Technology Development Programme”. We are thankful to colleagues at MTDD, IPR for their assistance in this prototyping activity.
References

[1] Ghate M et al 2014 Cryogenics 63 166

[2] Raj P, Ghate M et al., “Design and fabrication of indigenous 30 kA Nh3Sn CICC for fusion relevant superconducting magnet”, March 2016, 26th International Conference on Cryogenic Engineering and Cryogenics Materials, New Delhi, India

[3] Ghate M, Bhavsar D et al, “Application of AACMM for Quality Control in Fabrication of Superconducting Magnet Components”, December 2013, Proceedings of National Symposium on Plasma Science & Technology, KIIT University, Bhubaneswar, India.