MULTISTEP MECHANICAL ANALYSES OF CENTRIFUGAL BARREL POLISHING BARREL AND CAVITY *

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Abstract

Fermilab has successfully demonstrated the ability to improve the performance of damaged 1.3 GHz single cell and 9-cell Tesla–type cavities by using a modified centrifugal barrel polishing (CBP) process that leaves a mirror finish on the inside of the cavity. Fermilab now is developing and constructing a new CBP machine which can handle both 650 MHz and 1.3 GHz cavities. The new machine will have a larger moment arm and therefore impart more force on the cavity and machine. Because of these increased forces the effects on cavity supports and machine design were examined. This paper will document the multistep mechanical analyses for the CBP barrel and cavity, calculations of the fatigue life and the requirements for the structural welds.

INTRODUCTION

Centrifugal barrel polishing (CBP) is an alternative processing technique that polishes the inside of superconducting radio frequency cavities by rotating the cavities at high speeds while filled with an abrasive media [1]. CBP has received great interest at Fermilab because of its ability to produce mirror like finishes, reduce amount of chemistry needed, and repair defects that could not be repaired with standard processing techniques [2]. Excellent superconducting properties resulted after initial process optimization, with quality factor of 3×10^{10} and accelerating gradient of 43 MV m^{-1} being attained for a single-cell TESLA cavity, which are both close to practical limits [3].

Current CBP machine in Fermilab has two barrels with 18 inches arm. The barrel rotates around a central shaft at 115 rpm and also spins around its own axis at the same speed in the opposite direction. In order to process 650 MHz cavity which has larger diameter than 1.3 GHz cavity (from 9 inches to 16 inches), Fermilab has designed a new CBP machine which can handle both 650 MHz and 1.3 GHz cavities. The main differences between current machine and new machine are:

1. Two vs. Four barrels.
2. Arm length (18 inches vs. 24 inches).
3. Rotate speed (115 rpm vs. 120 rpm).
4. Barrel structure (enclosed vs. welded sheet metal).

Since media weight is proportional to the cavity volume, 650 MHz cavities will experience more centrifugal force than 1.3 GHz cavities. There are concerns on 650 MHz cavity strength when polishing, and fatigue life for the barrels. Therefore multistep static analyses were performed with ANSYS workbench to predict cavity stresses and deformations and the operational life of the barrel.

MULTISTEP STATIC ANALYSES

The main forces applied on the cavities and barrels are gravity, centrifugal forces due to the rotation around the main shaft and eccentric self- rotation. The centrifugal forces will have different magnitudes and directions in different rotating positions. In order to understand which position is the worst case and how the cyclic loads affect the barrel's life, ANSYS's multistep static analysis method is adopted. Multiple steps allow a series of static analyses to be set up and solved sequentially. The end time can be used as a counter/tracker to identify the load steps and substeps. Results can be viewed step by step. Load values for each step can be entered in the tabular data [4].

Multistep Setup

Eight load steps are used to represent different positions of the barrel and cavity when they rotate around the main shaft. Each position is 45 degrees apart. Eight steps are considered as one cycle. Standard earth gravity of 9.81 m/s^2 is applied to all bodies and all positions. Rotational velocity of 12.566 r/s is also applied to all bodies and all positions. Centrifugal acceleration of 96.258 m/s^2 (a = arm length time square of rotational velocity) is divided to Y and Z components according to the barrel position. Since the media weight is always in the far side of the rotating body when polishing, 115.7 kg of the media is considered as centrifugal force (F=ma) to be applied normally to the corresponding inner surface region of the cavity or supporting frame in each position. Figure 1 is the schematic of eight load steps. Table 1 is tabular data for each load steps.

Table 1: Summary of Loads

	Media Force		Acceleration	
Steps	Y [N]	Z [N]	Y [m/s²]	Z [m/s²]
1	11137	0	-96.258	0
2	7875	7875	-68.065	-68.065
3	0	11137	0	-96.258
4	-7875	7875	68.065	-68.065
5	-11137	0	96.258	0
6	-7875	-7875	68.065	68.065
7	0	-11137	0	96.258
8	7875	-7875	-68.065	68.065

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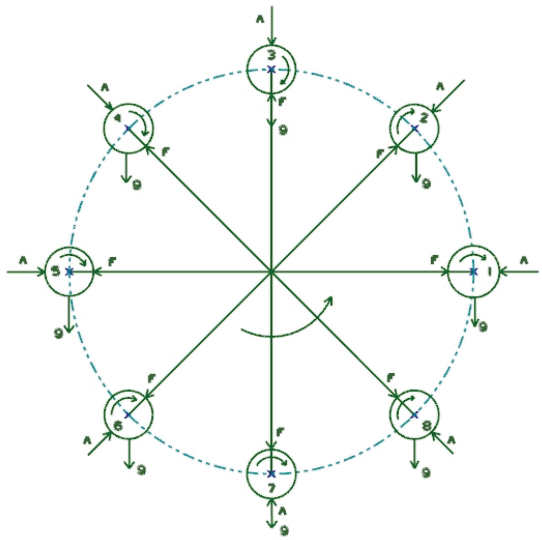

Figure 1: Schematic of eight load steps. g is standard earth gravity; A is centrifugal acceleration; F is media weight force.

Cavity Polishing Simulation

The cavity is secured in the barrel by special designed supporting frame. The material used for 650 MHz cavity is niobium. The following physical properties of niobium are used for the simulations:

- Density ρ=8570 kg/m^3
- Young's modulus E=1.05x10^{11} Pa
- Poisson's ratio ν=0.38

A yield strength of 37.92 MPa is used for the room temperature niobium. The cavity is fixed in all directions on four frame holding locations and two end flanges. The inner surfaces of the cavity are divided to eight regions for media force. The maximum stresses happened in the end of load step seven where the direction of centrifugal force in coincident with the gravity. The maximum equivalent stress is 11.2 MPa and the safety factor is 3.39. The maximum total deformation is 0.019 mm which is acceptable. Figure 2 shows the simulation result.

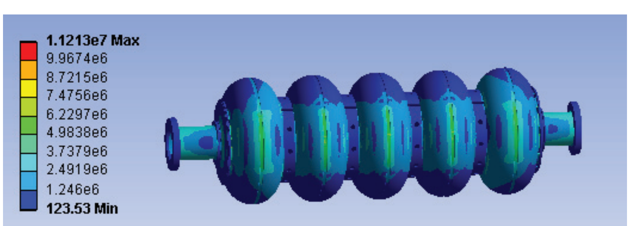

Figure 2: Equivalent stress of 5-cell cavity

Barrel Fatigue Calculation

The barrel is subject to repeated variation of live load due to its rotation. The designed new centrifugal polishing machine is expected to work for both 650 MHz cavities and 1.3 GHz cavities. Each cavity CBP process will take about 54 - 94 hours depending on the initial surface conditions. If the machine rotates at 120 rpm, in one hour it will rotate 7200 times (cycles) and one cavity process will at least take 3.888 x10^5 cycles. Thirty cavity processes will reach 1.166 x10^7 cycles. So the barrel design must have an operating life of above 10^7 cycles which means the fatigue stress of the barrel must be lower than the fatigue limit in the S-N curve.

The material used for the barrel is mild steel A36. The physical properties of A36 are listed below:

- Density ρ=7850 kg/m^3
- Young's modulus E=2.0x10^{11} Pa
- Poisson's ratio ν=0.3

The lowest yield strength of 250 MPa is used for the yield criteria. The ultimate tensile strength S_u is 400 MPa. S-N curves showed on Figure 3 [5] are used for the fatigue criteria. The solid line is for weld as is which has a fatigue limit of 175 MPa. The dashed line is stress relieved after weld which has a fatigue limit of 220 MPa.

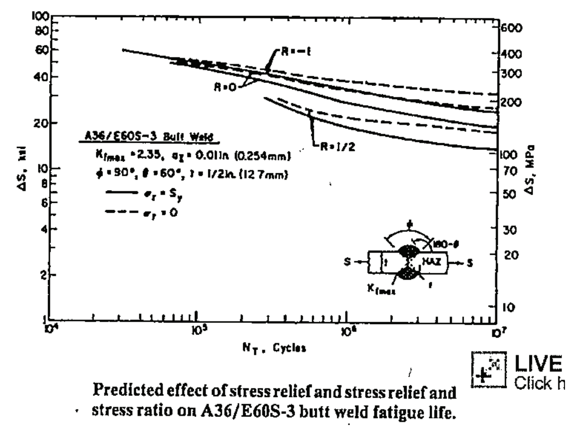

Figure 3: S-N Curves for A36 with welds.

The barrel is supported in two end shafts. Total of 79.925 kg mass is equally distributed to the supporting frame to simulate the cavity weight. All other loads are the same as in the cavity simulation.

The maximum stresses happened in the end of load step one and step five where the Y component of centrifugal acceleration is maximum. It may indicate the barrel design is weaker in subjecting Y direction load than in Z direction. The maximum equivalent stress is 88.63 MPa which is well below the yield strength of 250 MPa. Figure 4 shows the simulation result.

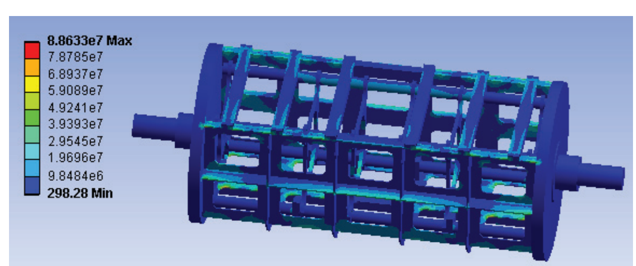

Figure 4: Equivalent stress of processing barrel.

A couple of weld locations with the highest stresses are examined. All stresses of eight load steps in these locations are manually recorded. Mean stresses and strange ranges are calculated as:

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$S_m = ½*(S_{max} + S_{min})$
$\Delta S = S_{max} - S_{min}$ [6]

The Goodman equivalent stress range is calculated as:

$\Delta S_e = (S_u*\Delta S)/(S_u – S_m)$ [6]

The calculated Goodman equivalent stress ranges are compared to the S-N curves. The safety factor for the stress relieved barrel is 3.07. If not stress relieved after weld the safety factor would be reduced to 2.44. Table 3 is the results of the analysis and calculation.

Table 2: Results of Analysis and Calculation

Load steps	Steps	Location 1 Stress (MPa)	Location 2 Stress (MPa)
	1	64.5	-0.912
	2	39.1	-1.5
	3	-1.06	-1.03
	4	-1.52	39.4
	5	-0.95	63.9
	6	0.23	51.9
	7	11.6	10.4
	8	53	0.266
Mean stress		31.49	31.2
Stress range		66.02	65.4
Equivalent stress range		71.66	70.93

REQUIREMENT OF WELDS

From the finite element analysis, the maximum stress in welds happened at the connection between the top plate and the end flange. Since the weld is not explicitly included in the finite element model it is necessary to scale the stress range at the weld area by the ratio of the minimum thickness of the weld and the plate thickness. This gives:

$\Delta\sigma_w = \Delta\sigma_p *t_p/t_w$ [7]

Where:
$\Delta\sigma_w$ = stress range in the weld
$\Delta\sigma_p$ = stress range in the plate = 71.66 MPa
t_p = plate thickness = 6.35 mm
t_w = weld equivalent thickness
= 2*8mm/√2 = 11.3136 mm

All the welds are double side fillet welds with 8 mm weld size. For this case the weld stress range $\Delta\sigma_w$ is 40.22 MPa. According to AISC Manual of Steel Construction 9th Edition, when the welds subjecting cyclic loading the allowable stress range for fatigue shall not exceed 8000 psi which equals to 55.158 MPa [8]. So 8 mm fillet welds in both sides satisfy the fatigue strength requirement.

CONCLUTIONS

Finite element models have been used to predict the stress levels of centrifugal polishing barrel and 650 MHz SRF cavity. The multistep simulation provides a means of applying cyclic loads to predict the fatigue life of the barrel. The weld strength is also examined and stress relief after welding is highly recommended. With the mechanical analysis Fermilab has the confidence to build a bigger CBP machine to handle both 1.3 GHz and 650 MHz cavities. The machine is under construction now in Mass Finishing, Inc., USA.

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