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Author
Meuser, R B

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Lawrence Berkeley Laboratory

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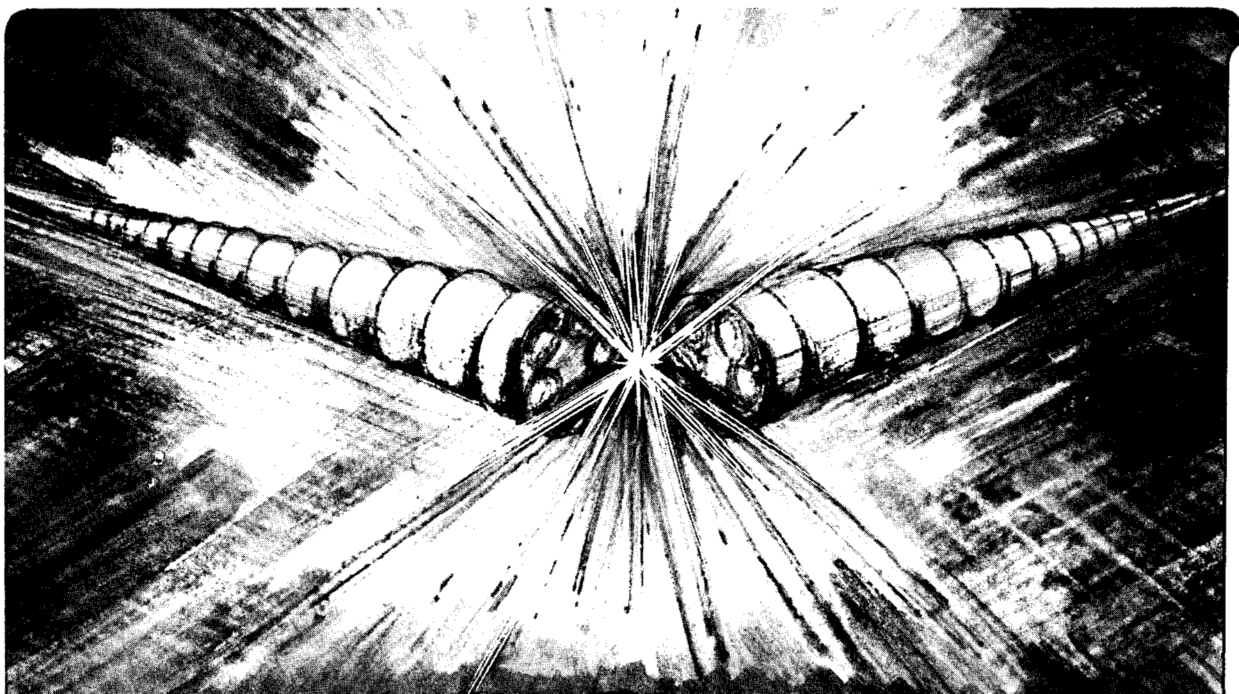

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Robert B. Meuser

Lawrence Berkeley Laboratory
University of California
1 Cyclotron Road
Berkeley, CA 94720

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SHELL HOOP PRESTRESS GENERATED BY WELDING*

Robert B. Meuser

Lawrence Berkeley Laboratory
1 Cyclotron Road, 47-112
Berkeley, CA 94720

ABSTRACT

For some magnet designs it is desirable to generate a prestress, approaching the yield strength, in the shell surrounding the yoke. If that prestress can be generated by weld shrinkage, then more expensive methods of prestressing can be avoided. Shell-to-yoke friction can reduce the prestress, so it is desirable to minimize it. A quick-and-dirty test was performed to address these matters. While the scatter of the data was large, it appears that weld shrinkage can indeed generate the required prestress. The scatter was too large to give any information about the friction, however. The experiment raised more questions than it answered.

INTRODUCTION

For a magnet design being considered it is necessary to develop hoop stresses of about 30 kpsi in the shell surrounding the yoke. If weld shrinkage alone can develop sufficient stress then more expensive mechanical methods can be avoided.

The goals of the tests reported here were:

1. To determine the hoop stress generated in the shell by welding,
2. To determine the effect of friction at the shell-yoke interface under several extreme conditions, and
3. To learn something about the experimental techniques involved.

This was intended to be a quick-and-dirty, shotgun experiment; it turned out to be less quick and more dirty than intended.

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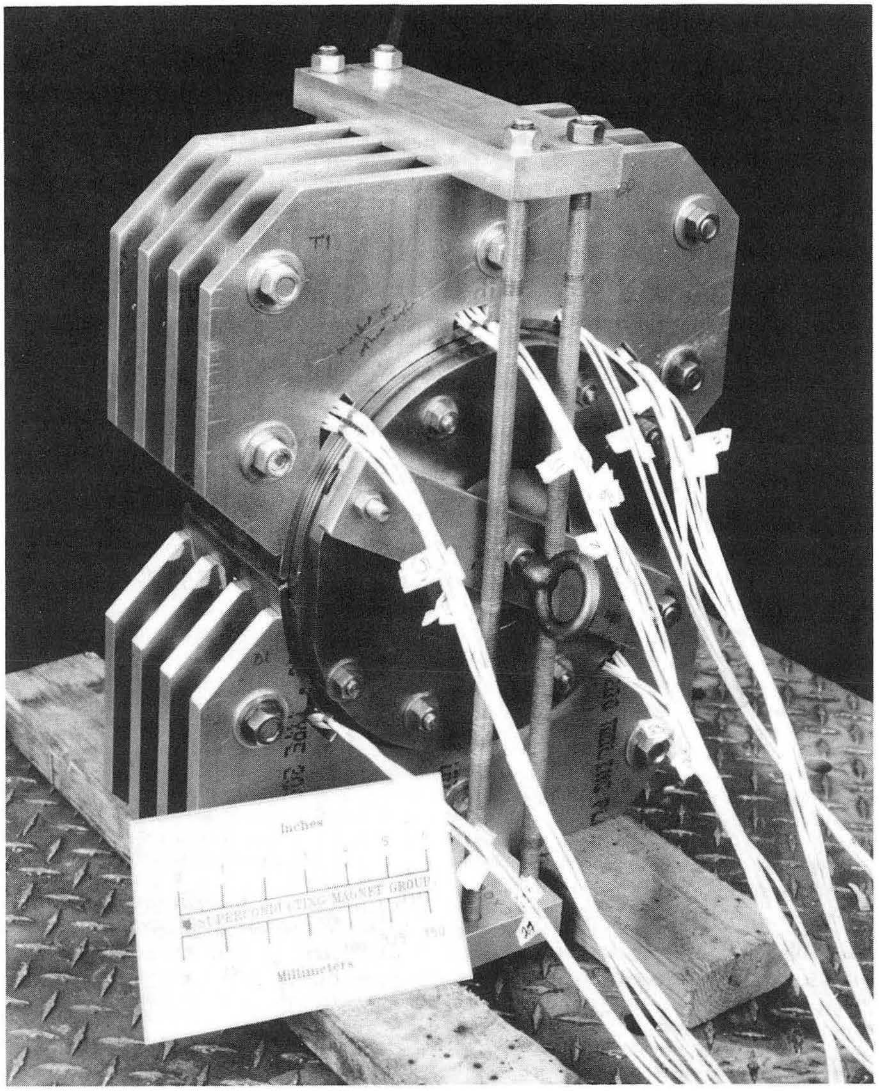

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Fig. 1 The test setup. Aluminum plates clamp the shell pieces against the yoke for welding.

TEST SETUP

Annealed Type 304 stainless steel shell halves 5 in. long and 1/4 in. thick, to which strain gages were applied (Figs. 1 and 2), were clamped over 6 in. long by 10.5 in. diameter dipole yoke blocks. For the first of the two tests, welds were made simultaneously on both sides in two passes using TIG welding. After strain measurements were taken, the welds were cut apart. For the second test the yoke was slicked up with emery paper, and molybdenum disulfide powder was applied to both the yoke and the shell. The joints were then re-welded in a single pass.

Table 1. Longitudinal vs. Circumferential Strain

	Circumferential		Longitudinal	
Gage no.	28	24	27	25
Micro-strain	781	1130	-377	-409

Avg. longitudinal / avg. circum. = -0.41

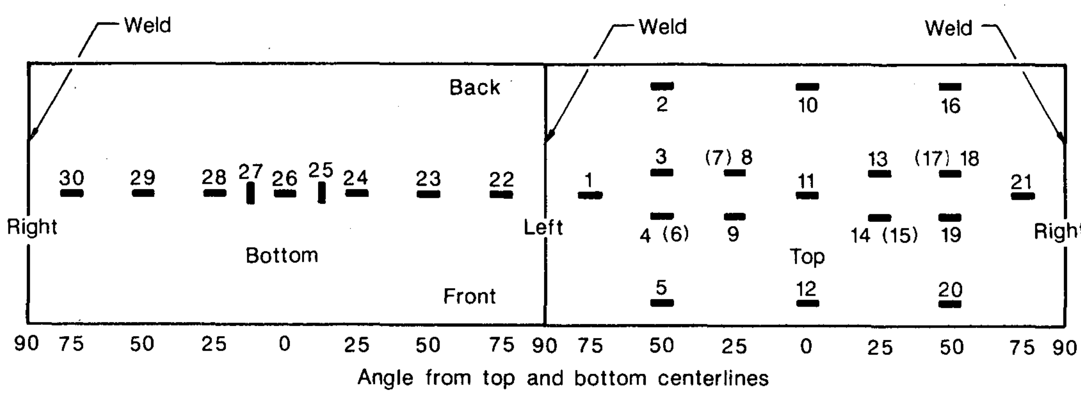

Fig. 2. Schematic development of the shell showing strain gage positions and nomenclature. Numbers in parentheses represent gages on the inside surface; all other gages were on the outside.

Table 2. Stresses Measured Using Inside/Outside Gage Pairs Compared With Those Using Only Outside Surface Gages

Location		Gage #	Stress (kpsi)	Stress ratio	
				Inside/Outside of pair	Average, pair/outside only
R 50	Inside Outside Outside	17 18 19	35.1 16.5 19.7	2.13	1.31
R 25	Inside Outside Outside	15 14 13	31.1 17.9 22.4	1.74	1.09
L 25	Inside Outside Outside	7 8 9	34.9 19.3 25.5	1.81	1.06
L 50	Inside Outside Outside	6 4 3	30.0 21.5 28.4	1.40	0.91

Table 3. Front-to-Back and End-to-Center Stress Variation

Location		Front	Center	Back	Stress Ratios	
					Front/Back	End/Center
0	Gage No.	12	11	10		
	Stress (kpsi)	34.9	21.0	30.5	1.14	1.56
L 50	Gage No.	5	3	2		
	Stress (kpsi)	37.2	28.4	43.5	0.86	1.42
R 50	Gage No.	20	19	16		
	Stress (kpsi)	31.8	19.7	33.2	0.96	1.65

Ideally, the experimental setup should duplicate a real magnet as closely as possible. My setup was far from ideal. The welds were done by hand rather than by machine. Neither of the welders was left-handed, so one had to work "backwards". The section of shell was only 5 inches long, so there was the danger that the test does not represent conditions in a longer cylinder.

RESULTS

Despite thorough checking at every stage, some of the results were inconsistent, and in some instances totally ridiculous. Some of this can be explained, some remains a mystery.

I have interpreted the measured circumferential strains as stresses using simply stress = strain x modulus. That implies a linear stress-strain relationship, which is not correct for stresses greater than the yield strength[+], and also implies zero longitudinal stress, a good assumption as it turned out. Two gages were oriented to respond to longitudinal strain (Table 1). They indicated compressive strains of about 41 percent of the circumferential strain. That corresponds to a compressive longitudinal stress of 12 percent of the circumferential stress, and a 6 percent effect on interpreted stresses. Longitudinal compression near the poles where longitudinal strains were measured is consistent with longitudinal weld shrinkage.

A number of gages were not operable in the second test, and because of space limitations, the tables of results do not include all of the results of the second test. There were no glaring differences between the results of the two tests, however, despite the different welding procedures and surface treatments.

Local kinks in the shell create local bending stresses, which could cause the strains measured at one surface to be different from the pure hoop stress. The usual way to mitigate that is to apply strain gages to both surfaces, and average the results. But that creates other problems. The leads from the inner gage must be brought through holes in the shell (as I did it) or through grooves in the yoke, and the yoke must be relieved so as to not touch the gage, so the cost is more than doubled. And, those reliefs cause local distortion of the shell, which can affect the accuracy of the measurements.

Table 4. Circumferential Variation of Stress

Angle**	Gate No.				Stress (kpsi) First Test				Second Test			
	Top		Bottom		Top		Bottom		Top		Bottom	
	L	R	L	R	Left	Right	Left	Right	Left	Right	Left	Right
At mid-length of shell												
0	11		26		21.0		72.9		--		15.4	
25	9	13	24	28	25.5	22.4	31.6	21.9	25.5	22.6	25.1	17.5
50	3	19	23	29	28.4	19.7	28.8	34.7	25.8	20.5	22.5	32.2
75	1	21	22	30	133.0	90.2	104.6	113.0	69.3	54.4	--	60.2
At Front of shell												
0	12		--		34.9		--		--		--	
50	5	20	--	--	37.2	31.8	--	--	--	33.8	--	--
At back of shell												
0	10		--		30.5		--		--		--	
50	2	16	--	--	43.5	33.2	--	--	28.4	20.4	--	--

**Measured from top and bottom centerlines; welds are at 90°.

There were no kinks higher than about .0025 in., which could give only about a 5 percent error from bending, so I was pretty sure that in-and-out gage pairs were not required. However, I installed four such pairs; barely enough to determine whether they were really necessary, and also barely enough to give some minimal useful data in case they turned out to be necessary. I made the reliefs in the yoke as small as I could, 0.5 by 0.8 in. Rough calculations indicated that local effects would be negligible; nevertheless, the test results indicated that they were not.

For the paired gages, the ratio of inside-to-outside strain was from 1.4 to 2.1 (Table 2). That would be consistent with a bump in the shell of .017 to .047 in. There were no such bumps. Also, if local kinks had been the cause of the difference, then it seems highly unlikely that it would have occurred with the same sign and nearly the same magnitude on all four gages. My conclusion is that that the difference is an artifact of the reliefs cut into the yoke. The average of the inner and outer members of a pair was 16 to 24 percent lower than that measured by an adjacent outside-only gage; I am inclined to believe the latter.

Temperature indicators were placed near the gages nearest the welds, at 75°, to determine whether their allowable temperature was exceed. None got too hot. Nevertheless, the strains measured were anomalously high. My guess is that the tension generated at the weld was greater on the outside than on the inside, which caused local bending.

Gages were placed near the ends and at the center at several azimuthal positions to determine center-to-edge and edge-to-edge effects (Table 3). There was essentially no edge-to-edge difference. However, the strains at the ends were some 42 to 65 percent higher than those at the center. I have no explanation.

Shell-to-yoke friction causes an azimuthal variation in shell hoop tension. One of the goals was to determine the coefficient of friction for the as-delivered condition, and to see how much friction effects were reduced by smoothing up the yoke and applying Molykote. The results were too inconsistent for that, however (Table 4). No consistent left-right or top-bottom trends are apparent.

MECHANISM OF WELD SHRINKAGE

The following mechanism for weld shrinkage is postulated. During welding, regions of the shell nearest the weld get hot and expand. After the weld solidifies, regions far from the weld continue to get hotter for a time as heat flows into them from the weld region, then finally the whole works cools off, tries to shrink which it can't do because the circumference is fixed, and so hoop stresses are generated. However, temperature indicators only 1.4 in. from the weld never got above about 350 F. Calculations of the shrinkage based on the above mechanism can only account for about a fifth of the shrinkage of .018 in. per weld required to generate a stress of 30 kpsi. The change in volume of the weld metal resulting from changing from the liquid to the solid state cannot play a significant role in the process. Or can it? Nevertheless, it seems apparent that the greater the total heat applied, the greater the stress induced. Preheating of the weld region, or possibly the entire shell, would enhance the effect, but that might not be practical.

CONCLUSIONS

Unless the shell has local kinks so severe as to be unacceptable for other reasons, paired strain gages, applied to both shell surfaces, are not only unnecessary but are also likely to create more problems that they solve, in addition to being expensive.

Despite the many inconsistencies in the results, it seems clear that hoop stresses of the order of 30 kpsi can be generated by the welding process.

The data are not sufficiently consistent to allow determination of a shell-to-yoke coefficient of friction.

LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
INFORMATION RESOURCES DEPARTMENT
BERKELEY, CALIFORNIA 94720