FORM 367

MEMORANDUM

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DATE: July 31, 1964

TO: D. J. McPherson

FROM: J. P. Sheehan

SUBJECT: B1000B1 - Report No. 4 - July 2, 1963 to July 31, 1964

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INTRODUCTION

There has been an increasing demand in recent years for ultra-high strength, light-weight pressure vessels for applications that require 100% reliability in service. Two examples of these requirements are solid fuel missile motor cases and high-pressure gas cylinders for rocket boosters and aircraft. Such pressure vessels are manufactured with utmost care, and yet, because they contain weldments and possibly other undetectable metallurgical flows that could lead to catastrophic fracturing, they must be overdesigned to ensure reliability in service. Super high strength steels capable of being heat-treated to strength levels in excess of 300,000 psi are available for these applications, but because of their marginal or poor fracture toughness, they are generally heat-treated to strength levels far below their maximum capability.

Shot peening is a process that has been used commercially for many years for improving the strength and fatigue resistance of gear teeth, drive shafts, axles, and other heavily stressed components. In shot peening, the surface layers of the material are heavily cold worked to a predetermined depth, and this produces a state of residual compressive stresses on the surface which helps to resist the applied service stresses.

In pressure vessels, the majority of failures that occurred in service or in proof testing were found to originate at the surface where perhaps some type of mechanical or metallurgical flaw caused a stress concentration or weakness in the metal. It has been suggested that surface decarburization might be helpful in preventing these failures by providing an increase in toughness and ductility at the region where flaws are likely to exist. However, this process has been subject to dispute because it is difficult to control and can cause a serious loss of strength if carried too far.

It is suggested that shot peening might also be helpful in improving the reliability of pressure vessels. Generally, the higher the strength of the vessel, the smaller is the size of flaw required for catastrophic failure; also, the lower is the applied stress to initiate failure. Therefore, with shot peening, because of the residual compressive stress, a surface flaw will "see" a smaller applied stress than is actually present, and for this reason larger flaws can be tolerated than in a vessel that has not received a shot peening treatment. To determine how much improvement can be obtained in the strength and service reliability of pressure vessels by shot peening treatments, the following program was conducted. This is the final report and covers the work carried out from July 2, 1963 to July 31, 1964.

II. EXPERIMENTAL PROGRAM

Pressure vessels approximately 7 in. in diameter and 24 in. long were fabricated from seamless tubing of 4142 steel, a structural alloy grade capable of attaining about 200,000 psi yield strength after heat treatment. The tubing was machined inside and out to produce a wall thickness of about 0.1 in. Flanges were also machined on the ends of the tubes to provide for end closures for pressure testing. Eight such tubes were machined and heat treated by Lindberg Heat Treating Co. Fixtures were used during heat treatment to minimize distortion. The tubes were austenitized at 1550°F in a neutral atmosphere to prevent decarburization and then quenched in molten salt at 400°F. After cooling to room temperature each tube was tempered at 400°F for 1 hour to a hardness of Rc 56-57. Of the eight heat treated tubes two were shot peened on the outside only, two on the inside only, two on both the inside and outside and two were left in the as-heat treated condition. Shot peening was carried out by the Metal Finishing Service Co. using Almen strips to control the depth of cold work penetration.

Strain gages were affixed to the vessels to measure circumferential strain during pressure testing. Pressure was raised in increments of 500 lbs d strain gage readings taken at each increment until the yield strength was proached whereupon the strain measurements were made at 200 lb increments pressure until failure of the vessel occurred.

RESULTS

Table I gives the strain measurements as a function of pressure for ch of the eight vessels. These data are plotted as strain-pressure curves in gures 1-8. In several cases (Figures 3, 5, and 7) the strain gage ceased to function either before or just as the yield strength was reached and it was impossible to determine the yield strength of these vessels. In another instance vessel No. 2 (Figure 2) failed prematurely before the yield strength was reached. Vessel No. 3 (Figure 3) may also have been a premature failure but this cannot be said with certainty because the strain gage also failed early.

The results are summarized in Table II. These results clearly show that the vessels that were shot peened on the inside surface and on the inside and outside surfaces had distinctly higher burst strengths than any of the other vessels. On the other hand, the elastic limit and other yield strength criteria are lower for these vessels than for the ones that were not shot peened.

Of the two vessels that were not shot peened, one failed prematurely before the elastic limit was reached and the other failed at a rather low value of stress (217,000 psi) and total strain. The two vessels that were shot peened on the outside surface also displayed low burst strengths and low total strain values. Of the four vessels that were shot peened on the inside or both inside and outside surfaces the two on which the strain gages held up showed very large values of total strain to failure, and, as mentioned earlier, also had high burst strengths. The other two vessels on which the strain gages failed also had high burst strengths and had the strain gages held they probably would have demonstrated high values of strain at fracture.

In all of the vessels the origin of failure was on the inside surface. A small flat fracture initiated at this surface and grew under plain strain through the wall thickness and upon reaching a critical length the crack propagated rapidly in shear causing complete rupture of the vessels, as shown in Figures 9 and 10.

It is apparent that the shot peening was highly beneficial in retarding crack growth and permitting the vessels to attain higher values of strain and therefore higher burst strengths before complete failure occurred. Since the cracks always initiated on the inside surface only those vessels that were peened on the inside surface benefited from the peening treatment. Those that received no treatment or were peened only on the outside surface failed prematurely because the crack was free to grow rapidly after it initiated on the inside surface.

IV. CONCLUSIONS

1. Weld-free pressure vessels made of 4142 steel heat treated to the highest possible strength level and hardness (Rc 55-57) failed under pressure testing at relatively low stress levels and with very little plastic strain to fracture.

2. When similar vessels were shot peened after heat treatment on the inside surface the burst strength was increased by about 25% and the total strain to fracture by about 50%.

3. Inside surface shot peening was beneficial because failure always initiated on the inside surface as a small flat crack and the effects of shot peening retarded the growth of the crack and thereby permitted the vessel to sustain higher loads before the crack reached critical size and rupturing ensued.

4. Outside surface shot peening was not beneficial because it had no retarding influence on cracks that initiated on the inside surface.

5. The yield strength of shot peened vessels was no higher and, in fact, appeared to be lower than in vessels tested in the as-heat treated condition. No explanation can be offered for this anomoly.

V. RECOMMENDATIONS

Although the results of this investigation are not completely clear and conclusive, it is suggested that shot peening might be beneficial to the reliability of high strength thin-walled pressure vessels particularly if weldments are present. Failures in such vessels usually initiate in the weld zone due to existing microcracks and/or poor fracture toughness of the weld metal and heat affected zone. Residual compressive stresses resulting from the shot peening might help overcome the service tension stresses and retard crack growth and premature failure.

Respectfully submitted,

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TABLE I

PRESSURE AND STRAIN MEASUREMENTS

Pressure, psi	Strain, μin/in.
Vessel No. 1 (Not Peened)	
0	0
500	910
1,000	1,310
1,500	1,870
2,000	2,390
2,500	2,910
3,000	3,570
3,500	4,180
4,000	4,730
4,500	5,320
4,750	5,650
5,000	5,920
5,200	6,250
5,500	6,790
5,750	7,350
6,000	8,290
6,200	8,930 Failed
Vessel No. 2 (Not Peened)	
0	0
500	840
1,000	1,280
1,500	1,880
2,000	2,310
2,500	2,870
3,000	3,280
3,500	3,780
4,000	4,460
4,500	5,020
5,000	5,560
5,300	- Failed
Vessel No. 3 (Shot Peened on Outside)	
0	0
500	830
1,000	1,290
1,500	1,770
2,000	2,290
2,500	2,810
3,000	3,220
3,500	3,730 Strain gage failed
5,250	- Vessel failed

TABLE I (Cont'd)

Pressure, psi	Strain, μin/in.	
Vessel No. 4 (Shot Peened on Outside)		
0	0	
500	940	
1,000	1,560	
1,500	2,190	
2,000	2,780	
2,500	3,160	
3,000	3,870	
3,500	4,400	
4,000	5,200	
4,500	5,910	
5,000	6,830	
5,500	8,160	
5,700	9,120	
5,900	-	Failed
Vessel No. 5 (Shot Peened on Inside)		
0	0	
500	780	
1,000	1,330	
1,500	1,870	
2,000	2,360	
2,500	2,880	
3,000	3,510	
3,500	3,990	
4,000	4,580	
4,500	5,210	
5,000	-	Strain gage out
7,350	-	Failed
Vessel No. 6 (Shot Peened on Inside)		
0	0	
500	890	
1,000	1,460	
1,500	1,940	
2,000	2,530	
2,500	3,060	
3,000	3,600	
3,500	4,180	
4,000	4,740	
4,500	5,380	
5,000	6,090	
5,500	7,150	
6,000	8,330	
6,300	9,350	
6,500	10,610	
7,000	12,750	
7,010	-	Failed

TABLE I (Cont'd)

Pressure, psi	Strain, μin./in.
Vessel No. 7 (Shot Peened Inside and Outside)	
0	0
200	660
500	960
1,000	1,520
1,500	1,940
2,000	2,560
2,500	3,160
3,000	3,740
3,500	4,230
4,000	4,860
4,500	5,460
5,000	6,240
5,200	- Gage out
6,500	Failed
Vessel No. 8 (Shot Peened Inside and Outside)	
0	0
500	880
1,000	1,420
1,500	1,970
2,000	2,550
2,500	3,070
3,000	3,450
3,500	4,230
4,000	4,810
4,500	5,450
5,000	6,250
5,200	6,620
5,500	7,320
6,000	8,720
6,350	10,090
6,600	11,040
7,000	13,460
7,350	- Failed

TABLE II

No.	Treatment	Elastic Limit, psi	.05% Strain, psi	[illegible] Strain, psi	Burst Strength, psi	Comments
1	Not peened	178,500	210,000	*	217,000	
2	Not peened	*	*	*	185,500	Premature failure
3	Shot peened on outside	**	**	**	183,500	Probable premature failure
4	Shot peened on outside	157,500	192,500	201,000	206,000	
5	Shot peened on inside	**	**	**	257,000	
6	Shot peened on inside	161,000	198,000	220[illegible]	245,000	
7	Shot peened on inside and outside	147,000	**		227,000	
8	Shot peened on inside and outside	142,500	192,500	214,000	257,000	

* Vessel failed before reaching this level of strain.

** Strain gage failed within elastic limit.