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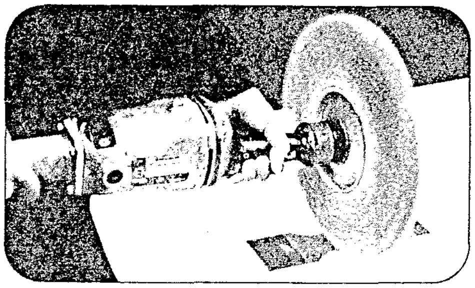
Improving the Fatigue Performance of Welded Aluminum Alloys

is accomplished with postweld brush shot peening and suggests using rotary brush peening for aluminum ship hull construction in postweld treatment of areas subject to localized cyclic loading



Brush peening of 5086-H116 butt-weld test specimen

BY T. W. MONTEMARANO AND M. E. WELLS

An investigation was conducted to develop suitable methods to improve the fatigue performance of welded 5086 alloy aluminum for high performance ship construction. A previous study showed that the high cycle fatigue performance of 5086 aluminum alloys was seriously degraded by welding as shown in Fig. 1. Degradation was attributed to softening of the weld bead and the presence of weld microporosity, levels of which were either undetectable by radiography or allowable by current standards.[1]

Concern over the potential performance of aluminum welds subjected to cyclic loading resulted in an investigation to develop methods to improve the fatigue performance of butt- and fillet-welded 5086 aluminum welds. Methods investigated for improving fatigue performance included welding procedure modifications, improvements in weld quality and postweld treatments. Of the methods investigated, postweld brush shot peening was shown to significantly improve the fatigue strength of butt and fillet welds.

This paper presents the results of postweld brush shot peening on the fatigue performance of butt- and fillet-welded 5086 alloy aluminum.

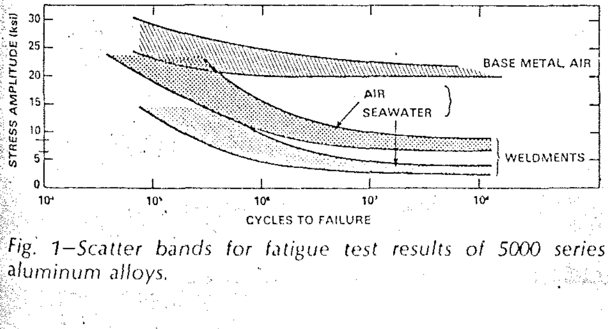


Fig. 1—Scatter bands for fatigue test results of 5000 series aluminum alloys.

Experimental Procedure

Materials

The materials of primary consideration for high performance ship construction are exfoliation-resistant grades of 5086 and 5456 aluminum alloys. These alloys are nonheat-treatable, strengthened primarily by work hardening and have essentially the same fatigue performance.[2] The base metal chosen for this study was ¼ and ⅝ in. (6.4 and 15.9 mm) thick alloy 5086 in the H116 exfoliation-resistant temper.[3] Aluminum alloy 5356 filler metal wire was used in fabrication of butt and fillet weldments.[4]

Weldment Preparation and Testing

Weldments were fabricated automatically in the flat position by the GMAW process in the spray mode. The welding parameters employed are shown in Table 1. After welding, the weldments were subjected to radiographic inspection. Test blanks were removed from unwelded base plate and weldments and machined into the fatigue specimens shown in Fig. 2. Specimens were prepared so that all welds were transverse to the long specimen axis.

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Table 1—Welding Parameters Employed in Fabrication of 5086-H116 Weldments

Weldment identification	Voltage, V	Current, A	Travel speed		Heat input	
			ipm	mm/s	kJ/in.	kJ/m
S5-2	25	230	19	8.0	18	70.9
S5-4	24	230	21	8.9	16	70.0
S5-5	25	240	23	9.7	16	70.0
S5-8	28	265	24	10.2	19	74.8
S5-9	27	265	21	8.9	20	78.7
S5-10	28	300	24	10.2	21	82.7
S5-17	31	245	21	8.9	22	86.6
S5-18	30	230	22	9.3	19	74.8
Average	27	250	22	9.3	19	74.8
Range	24-31	230-300	19-24	8-10.2	16-22	70.0-86.6

After machining, the test sections of the specimens were given a rotary wire brush finish. Specimens were tested in air in completely reversed bending fatigue (stress ratio: R = minimum stress/maximum stress = −1) using a Sonntag testing machine at a cycle test frequency of 1800 cpm until complete fracture occurred.

Shot Peening

Shot peening studies were conducted using two types of commercially available peening brushes. The first type of brush consisted of cast steel shot uniformly distributed and bonded to nylon cloth flaps which are mounted on a rigid hub. These brushes were used in either 8 or 12 in. (20.3 or 30.5 cm) diameter by 1 in. width and were mounted on conventional electric hand grinders as shown in Fig. 3A.

The other type of brush, described in Military Specification MIL-W-81840,[5] consists of tungsten carbide shot bonded in one or two rows along the outer edges of two small nylon reinforced polymeric flaps. The flap assembly is held in a mandrel mounted in a hand-held grinder or flexible shaft tool as shown in Fig. 3B.

In use the brushes are rotated rapidly with peening occurring as the shot strikes the workpiece. This type of peening, rather than conventional shot or hammer peening, was investigated because of its potential for use as a portable, manual or automatic method of controlled peening.

The degree of peening (known as almen intensity) is determined by measuring the curvature, in terms of arc

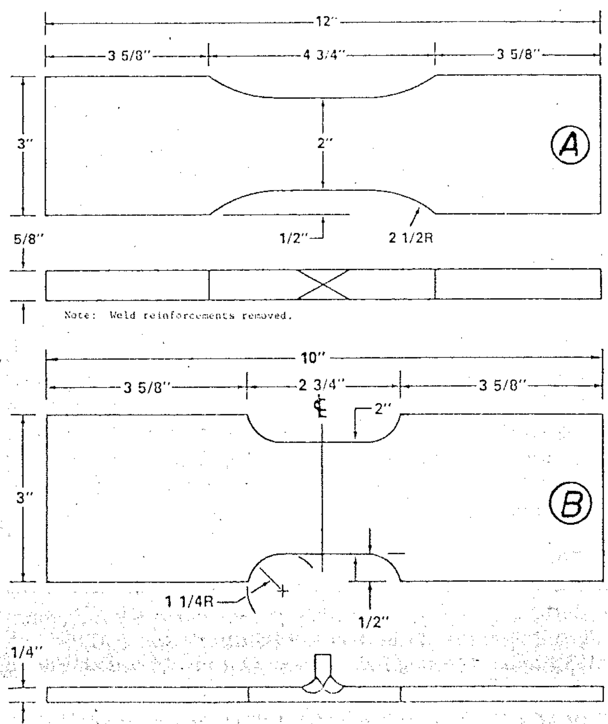


Fig. 2—Fatigue test specimens: A—butt welded; B—tee fillet welded

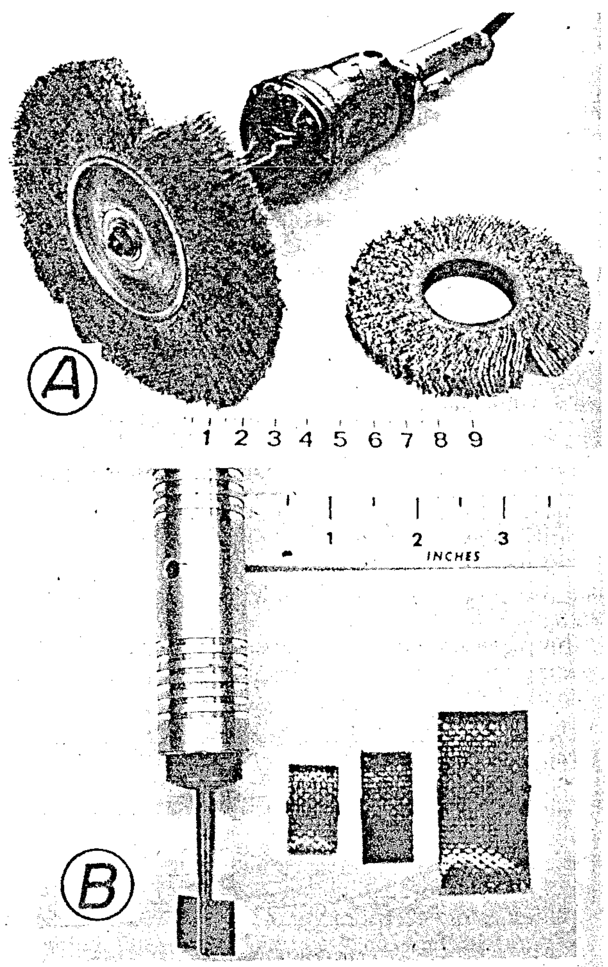


Fig. 3—Peening brushes. A—cast steel shot brushes; B—tungsten carbide shot brushes

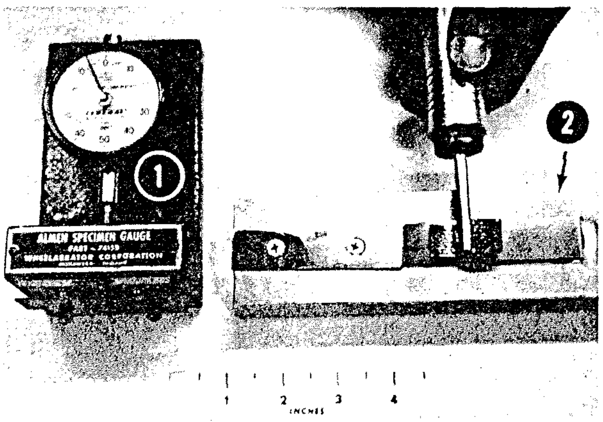


Fig. 4—Apparatus for determining peening intensity

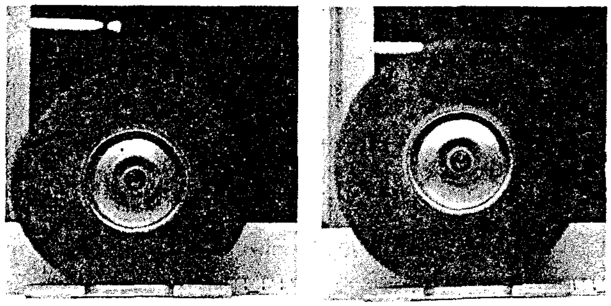


Fig. 5—Flap deflection range for ⁹⁄₁₆ × 1 in. (14.3 × 25.4 mm) flap brush and 12 in. (30.5 cm) diameter flap brush

height, induced in an originally flat standard steel strip. The almen intensity is dependent on the force with which the shot impacts the workpiece and the time of peening. The impact force is dependent on the type of shot, brush diameter and rotational speed.

A standard almen strip and almen gage used for determining almen intensity are shown in Fig. 4. The procedures used for determining almen intensity are described in military specification MIL-R-81841 and are excerpted below:[6]

1. With a new almen strip placed on the almen gage, set zero curvature on the gage dial.
2. Position the almen strip on magnetic strip holder.
3. Brush peen the strip at a fixed speed and for a given time so as to fully cover the strip with peening impressions.
4. Determine the strip arc height (almen intensity) by placing the peened strip in the almen gage.
5. The strip is peened for additional periods of time and the intensities measured to generate peening time/intensity curves.

Manufacturers' literature concerning these brushes states that sufficient brush flap deflection must be obtained for optimum peening results.[7] Minimum and maximum brush deflections to be used for the small ⁹⁄₁₆ × 1 in. (14.3 × 25.4 mm) tungsten carbide shot brush and the 12 in. (30.5 cm) diameter cast steel shot brush are shown in Fig. 5.

Preliminary peening tests were run with the operator applying sufficient pressure to cause flap deflections equivalent to both the minimum and maximum limits of the range shown in Fig. 5. (During subsequent discussions the minimum and maximum limits are referred to as light and heavy peening pressure, respectively.) The rotational speed of the peening brushes was controlled through the use of a variable speed drive motor and a strobe light.

Using a practice plate, the brush speed was set by an assistant adjusting the variable speed control while the operator maintained the proper peening pressure. The operator could then vary peening pressure, as necessary, to maintain a constant speed as indicated by the stationary image of an index mark on the brush when illuminated by the strobe light set at the desired speed of the drive motor. This technique controlled both the brush speed and peening pressure and was not difficult to master.

Results and Discussion

The results of Sonntag fatigue tests performed on 5086-H116 base plate, transverse butt weldments with reinforcement removed, and transverse tee fillet weldments (shown in Fig. 6 and Table 2) indicate that the fatigue strength of this alloy is seriously degraded by welding. In the butt-welded specimens, fatigue cracks initiated in and propagated through the weld metal. Cracks in the fillet-welded specimens initiated at the weld toes and propagated through the HAZ of the continuous member (flange). To effect an improvement

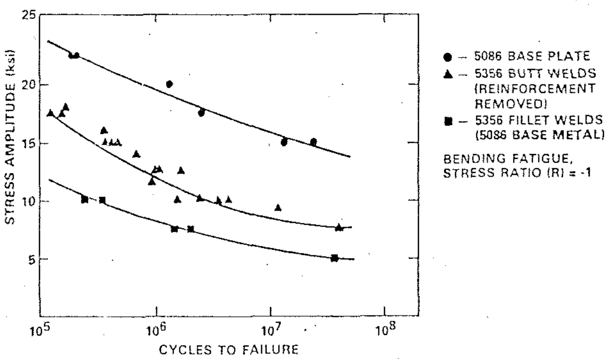


Fig. 6—Fatigue performance of 5086-H116 base metal and unpeened weldments

Table 2—Comparison of Fatigue Performance of Unpeened and Peened Specimens From the Same Butt Weldments

	Unpeened Specimens			Peened Specimens			
Weld identification	Stress ksi	Stress MPa	Cycles to fracture $\times 10^6$	Peening intensity	Stress ksi	Stress MPa	Cycles to fracture $\times 10^6$
S5-2	15.0	103.4	0.37	0.0065	15.0	103.4	12.54
S5-4	10.0	68.95	1.52	0.0065	15.0	103.4	10.62

in the fatigue performance of 5086-H116, preliminary brush peening studies were performed.

To determine initial peening intensities for use on the fatigue specimens, sections of ⅝ in. (15.9 mm) thick 5086-H116 plate were brush peened using the 8 and 12 in. (20.3 and 30.5 cm) diameter brushes. The effect of different combinations of brush diameter, brush rpm, peening time and operator pressure on peening intensities is plotted in Fig. 7. During the preliminary peening tests, the maximum brush deflection (heavy peening pressure) was found to be the easiest for the operator to maintain. It is evident from Fig. 7 that increases in the value of any one of the peening variables, while maintaining the others constant, will result in increases in the peening intensity.

Typical surface appearances of peened aluminum plates with the peening parameters and peening intensities used are shown in Fig. 8. Examination of the peened surfaces revealed two types of general surface appearance. Light peening pressure gave the appearance of overlapping circular spots. This spotted surface (Figs. 8A and 8C) would normally be expected when using conventional shot peening in which the steel or carbide shot strikes normal to the surface of the workpiece. Heavy peening pressure produced a spot appearance, superimposed on a background of waves running in the direction of peening (Figs. 8B, 8D, and 8E). The wave pattern is felt to be unique to rotary brush peening and is caused by lateral plastic flow of the surface in the direction of brush rotation.

Based on the amounts and types of surface deformations obtained during the preliminary studies, peening parameters were selected for fatigue screening. Almen (A) scale intensities from 0.0015 to 0.0065 in. (0.03 to 0.17 mm) and peening conditions which result in both spot- and wave-type surface patterns were chosen for initial fatigue evaluation.

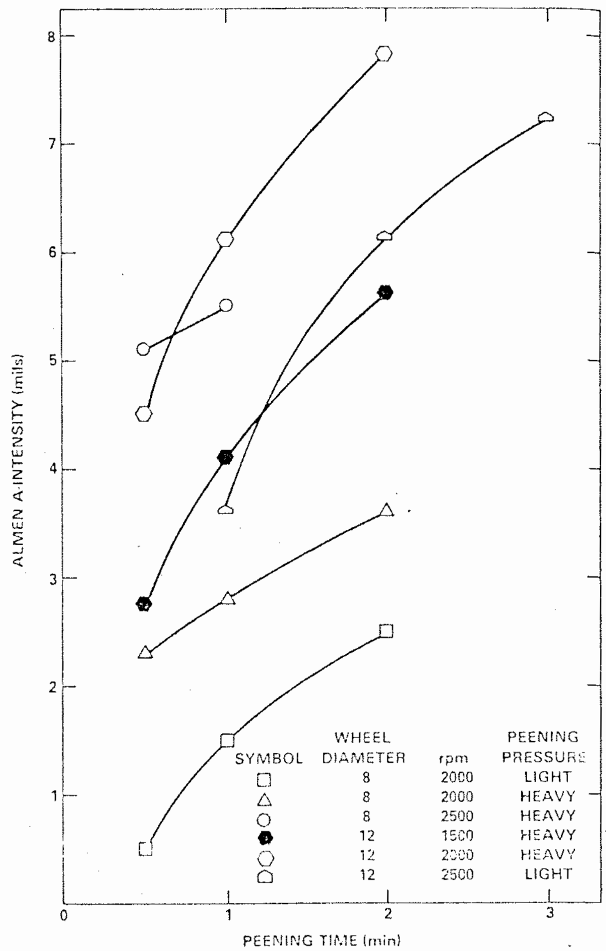


Fig. 7—Effect of peening variables on peening intensity

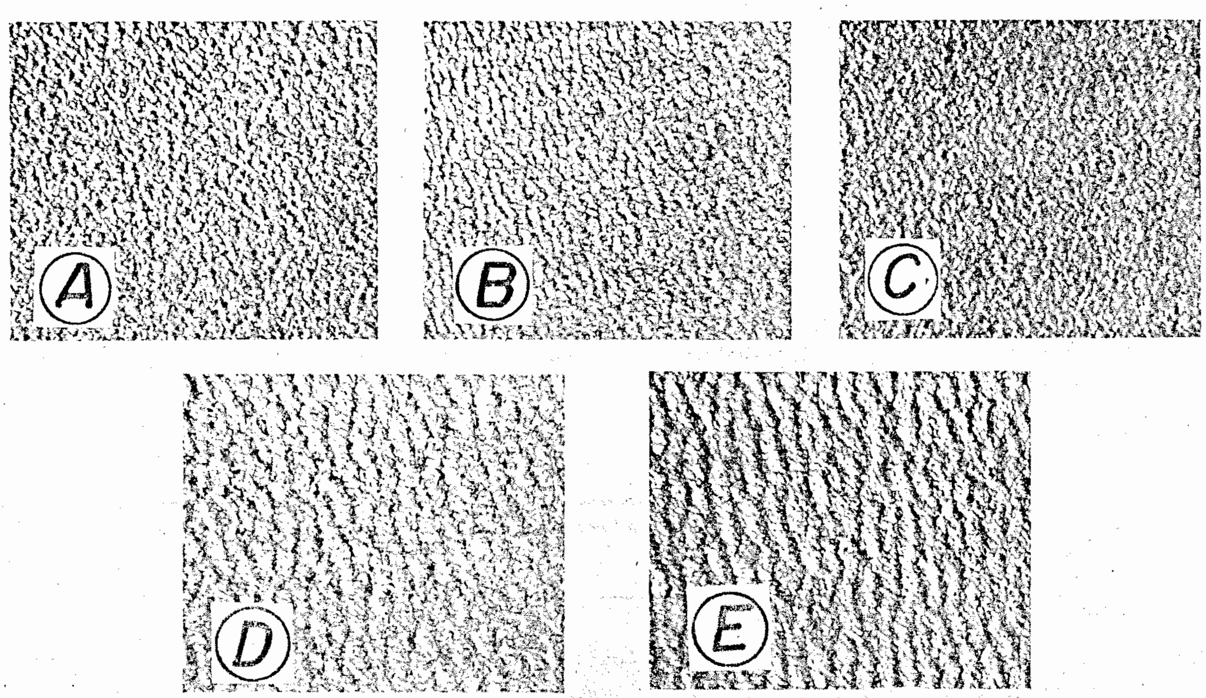


Fig. 8—Surface appearance of peened 5086-H116 base plate. Almen (a) intensity = AL; peening pressure = PP: A—AI = 0.0015; PP = light. B—AI = 0.0025; PP = heavy. C—AI = 0.0035; PP = light. D—AI = 0.0060; PP = heavy; E—AI = 0.0080; PP = heavy

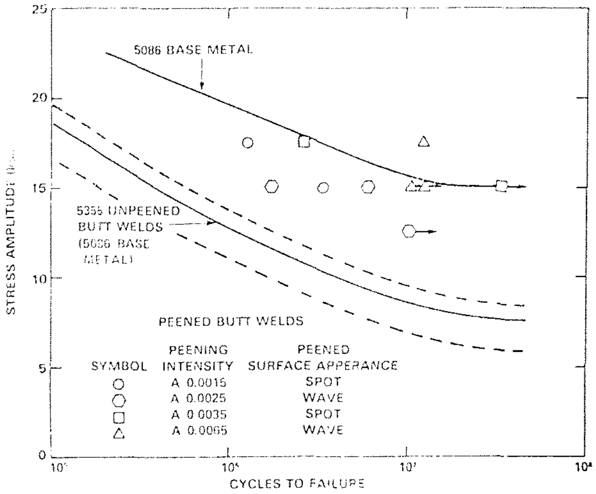


Fig. 9—Screening fatigue test results of brush peened 5086-H116 butt welds

Butt-Weld Peening

With weld reinforcements removed, butt-welded ⅝ in. (15.9 mm) thick fatigue specimens were peened using the 8 and 12 in. (20.3 and 30.5 cm) diameter peening brushes to almen (A) scale intensities of 0.0015, 0.0025, 0.0035 and 0.0065 in. (0.038, 0.064, 0.089 and 0.17 mm). Peening was performed on both plate surfaces only in the weld area. To assure that peening intensities were accurate, an almen strip was peened along with each fatigue specimen. The specimens peened at intensities of 0.0015 and 0.0035 in. (0.038 and 0.089 mm) exhibited a spotted surface while the other specimens showed wavy patterns. A typical butt-weld specimen undergoing peening is shown in the lead photograph.

After peening the specimens were fatigue tested. The results of these screening tests were compared to the results of unpeened butt welds in Fig. 9. Although some peened specimens exhibited surface discontinuities such as dents and machining marks (Fig. 10) from previous handling, peening caused the fracture to occur away from the defect locations.

A comparison of fatigue results for unpeened and peened specimens taken from the same weldments (S5-2, S5-4) is shown in Table 2. Radiographs of weldment S5-4 had revealed extensive lack of fusion defects in the specimens used for fatigue testing. This defect can be seen in the fracture surface of the unpeened specimen S5-4A—Fig. 11. However, the peened specimen taken from this weldment, S5-4C (Fig. 11), lasted significantly longer when tested at a higher stress level and did not fracture through the defect area.

Analysis of the screening fatigue data did not reveal any deleterious effects from the type of peened surface, neither wave nor spot, on fatigue performance. Based on these results, additional butt-welded specimens were

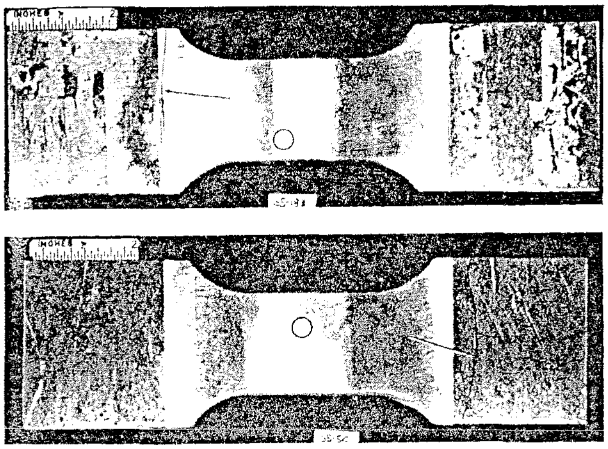


Fig. 10—Fatigue tested peened butt-weld specimens

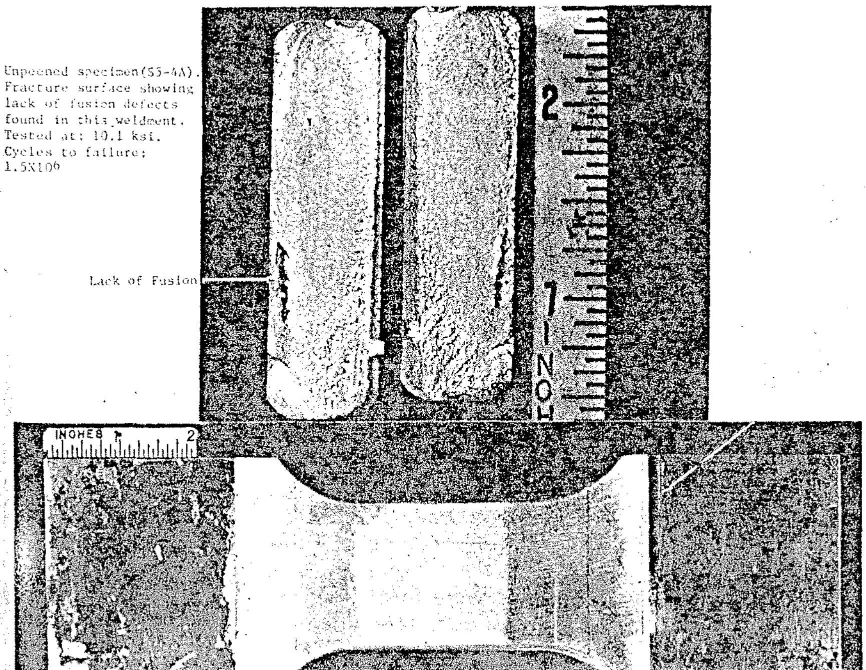


Fig. 11—Fracture location in peened specimen taken from a weldment having extensive subsurface lack of fusion defects

Table 3—Fatigue Performance of Postweld Peened 5086-H116 Butt Welds[a]

Peening intensity (Almen A)	Stress ksi	Stress MPa	Cycles to failure × 10^6	Surface appearance
0.0035	15.0	103.4	33.4[b]	Spot
0.0035	17.5	120.6	2.7	Spot
0.0065	15.0	103.4	10.6[b]	Wave
	15.0	103.4	12.5[b]	
	17.5	120.6	1.4	
	17.5	120.6	2.1	
	17.5	120.6	2.7	
	17.5	120.6	12.2	
	20.0	137.9	0.2	
	20.0	137.9	0.5	
0.0065	22.5	155.1	0.1	Wave
0.0080	15.0	103.4	12.0[b]	Wave
0.0080	17.5	120.6	3.0	Wave

[a] All tests in air; bending fatigue ($R = -1$); reinforcement removed; 5356 filler metal; peening performed by 12 in. (30.5 cm) diameter brush.
[b] No failure.

peened to generate a full S-N curve. Tests were also run to determine if it were possible to overpeen the butt welds and cause a degradation of fatigue performance by peening to almen (A) scale intensity of 0.0080 in. (0.2 mm). The results of the fatigue tests performed on the specimens are listed in Table 3.

Figure 12 shows the fatigue test results for all of the peened butt weldments. These data show that peening in the range of 0.0035 to 0.0080 in. (0.089 to 0.2 mm) (the maximum peening intensity that could be obtained using the 8 or 12 in., i.e., 20.3 or 30.5 cm diameter brushes) significantly improves the fatigue strength of butt-welded 5086-H116. At the high-cycle to failure end of the curve, the peened specimen fatigue performance is equal to or possibly higher than the base metal performance. In the low-cycle, high-stress region, peened specimens, while performing better than unpeened welds, are only slightly lower in fatigue strength than the base metal. It is also significant that the maximum intensity, which could be obtained with the 8 or 12 in. (20.3 or 30.5 mm) brushes, did not result in any deleterious overpeening. This factor, along with the overall wide range of optimum peening intensities that improve fatigue performance, 0.0035 to 0.0080 in. (0.089 to 0.2 mm) almen (A), makes the brush peening process relatively insensitive to operator error.

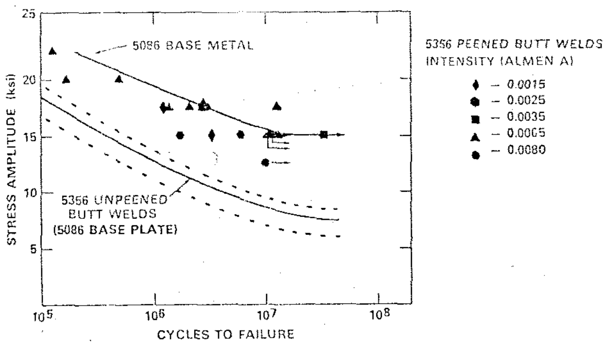
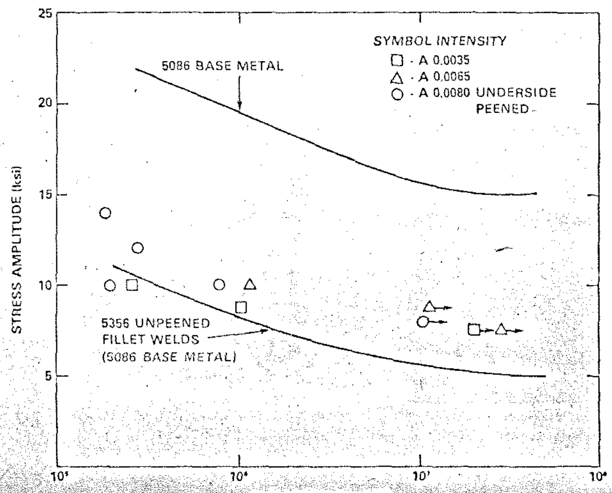


Fig. 12—Effect of brush shot peening on fatigue performance of butt-welded 5086-H116.



Fillet-Weld Peening

The effects of postweld peening on fillet-weld fatigue performance were screened using the optimum butt-weld peening intensities. Peening was performed using the 12 in. (30.5 cm) diameter brush rotating parallel to the stiffener length direction. Areas further than ⅜ in. (9.5 mm) away from the toes of the welds were masked, using glass cloth adhesive tape to prevent inadvertent peening of these areas. Fillet specimens were fatigue tested in two conditions. In the first, only the toes of the welds were peened; in the other, both the weld toes and the plate surface opposite the stiffener (underside) were peened.

The initial peening had a somewhat erratic effect on fillet-weld fatigue performance, as shown in Fig. 13. Some specimens, peened at 0.0035, 0.0065 or 0.0080 in. (0.089, 0.17 or 0.2 mm) almen (A) scale intensity, showed a 50% improvement over the as-welded fatigue strength at 10^7 cycles, whereas other specimens fractured at stress levels and cycles-to-failure equivalent to unpeened welds.

Examination of the fractured specimens revealed the presence of rolled lips that formed on the specimen edges during peening, as shown in Fig. 14. By peening parallel to the stiffener into a free edge of the specimen, rolled lips were formed and sometimes acted as crack initiation sites. Crack initiation sites were also located in

Fig. 13—Screening fatigue test results of brush peened 5086-H116 fillet welds

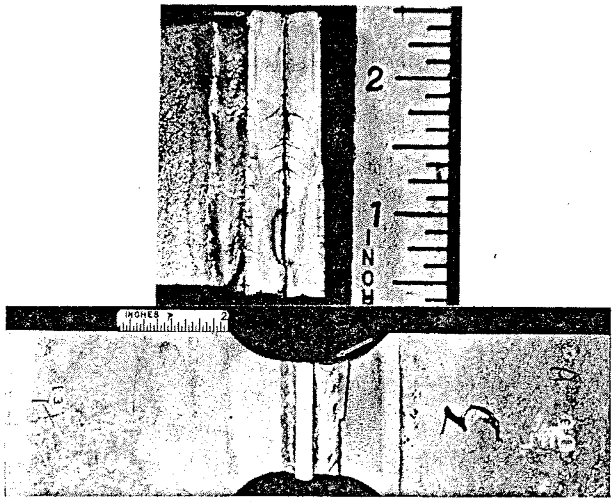


Fig. 14—Fatigue tested peened fillet weld

regions where local weld irregularities had, in effect, masked the weld toes from the 12 in. (30.5 cm) peening brush. It was also observed that peening only the weld toes forced fatigue initiation to the back or unwelded side of the flange.

Further peening tests showed that the small tungsten carbide peening brushes, which were designed for peening in restricted areas, were the most effective method for obtaining 100% peening coverage, while avoiding excessive specimen edge deformation. The 9/16 by 1 in. (14.3 × 25.4 mm) flap brush could easily be manipulated to allow for peening irregularities at the weld toe while peening parallel or perpendicular to the stiffener.

Fillet-welded, ¼ in. (6.4 mm) thick specimens were peened on the weld toes and on the back of the flange to almen (A) scale intensities of 0.0040 and 0.0070 in. (0.1 and 0.18 mm), using the 9/16 × 1 in. (14.3 × 25.4 mm) flap brush. After peening, the specimens were fatigue tested. Results of these tests (Fig. 15) show that peening with this type of brush improves the fatigue strength of 5086 fillet welds from an as-welded strength of 5,500 to 10,000 psi (37.9 to 68.9 MPa) at 10^7 cycles.

Process Variables

Since brush shot peening was shown to significantly improve the fatigue performance of 5086 butt and fillet weldments, the characteristics of the peening process were further investigated. This discussion is confined to the small tungsten carbide shot peening brushes, since these flap brushes were the easiest for the operator to manipulate in restricted areas, and to obtain 100% peening coverage of irregular surfaces and in restricted areas.

Brush shot peening is a cold-work process which plastically deforms and strain hardens the soft aluminum and induces residual compressive stresses into the weld area. The increased hardness and residual compressive stress act to improve fatigue strength by retarding the initiation and growth of fatigue cracks. The hardness of the material relative to depth from surface for different peening intensities is shown in Fig. 16. Since the effect of work hardening on the surface extends approximately ¼ in. (6 mm) deep, such a peened surface should be resistant to damage or removal by subsequent surface treatments or grinding.

The operating time intensity curves used for fillet-weld peening are shown in Fig. 17. The small size of the 9/16 by 1 in. (14.3 × 25.4 mm) flap and the use of only a single row of shot on each flap results in lower peening intensities when used at the same rotational speeds as the large brushes. However, the construction of the small flaps allows peening at speeds up to 15,000 rpm. The higher rotational speed and the use of dense tungsten carbide shot, rather than steel shot, can ultimately give much higher intensities than the 8 and 12 in. (20.3 and 30.5 cm) brushes.

Figure 18 compares the peening intensities obtained by two operators using the 9/16 by 1 in. (14.3 by 25.4 mm) brush. Each operator made three separate test strips at different times. The range of intensity values obtained for each operator is also shown. The differences in the intensity curves are due to different brush manipulation

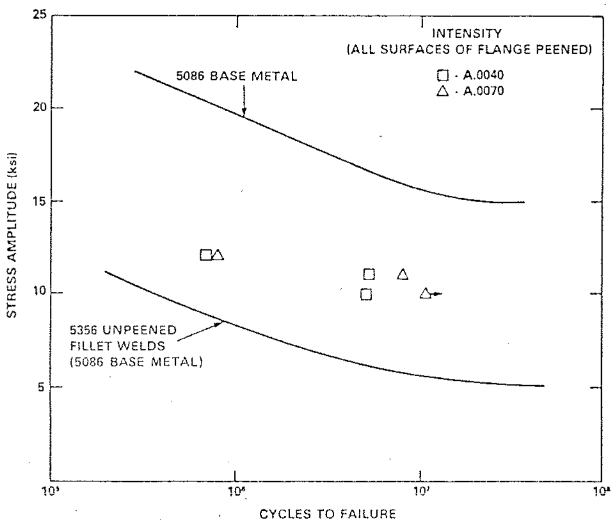


Fig. 15—Effect of brush shot peening of fatigue performance of fillet-welded 5086-H116

techniques and amounts of pressure applied by each operator.

The curves of Fig. 18 illustrate the need for "calibrating" each operator to determine the brush rpm and peening time required to yield the specified peening intensity. Published curves should be used only as a guide for establishing actual peening parameters. The military specification for peening (MIL-R-81841) calls for a repeatability of intensities for a particular operator to be less than ±0.001 in. (±0.025 mm).[6] In the tests run to generate the curves of Fig. 18, the maximum range of intensities for an operator at a particular peening time was 0.0006 in. (0.015 mm).

Potential problems with operator reproducibility are

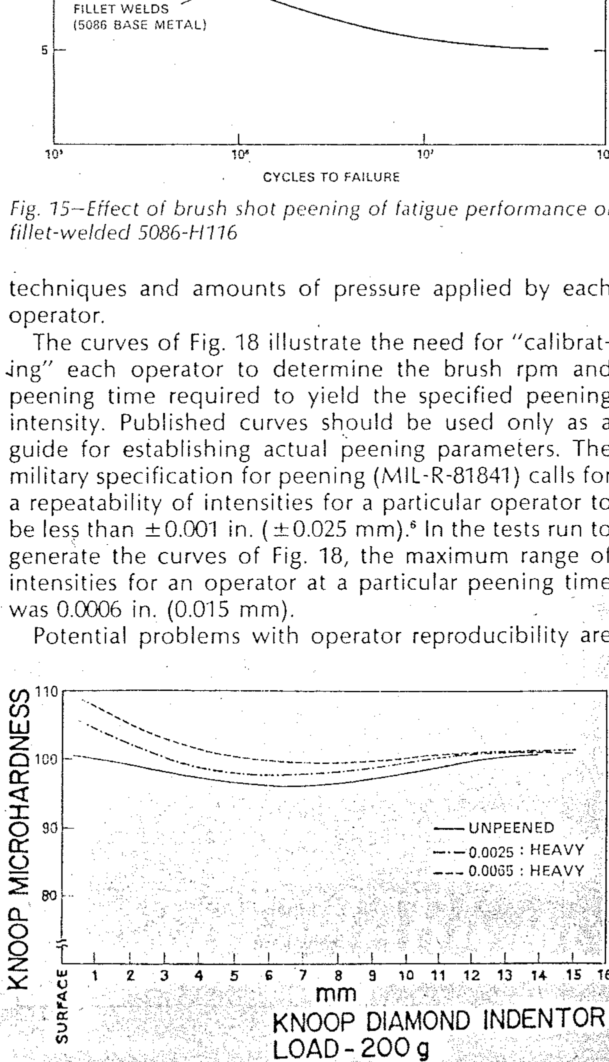


Fig. 16—Effect of peening on base plate hardness

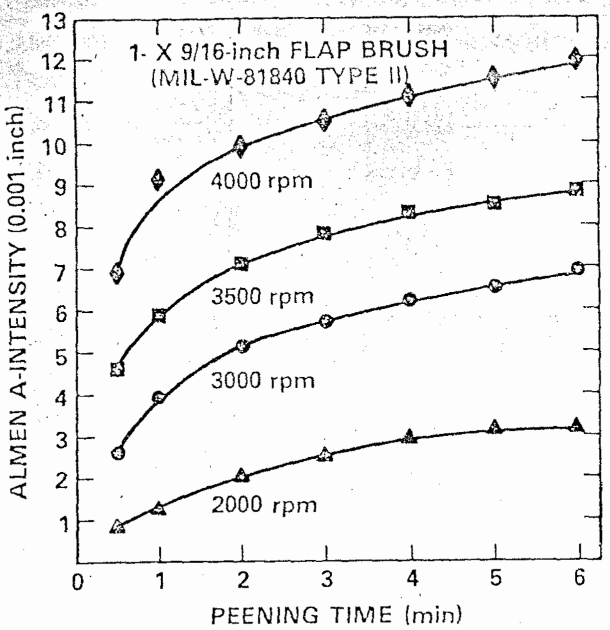


Fig. 17—Operating time/ intensity curves for tungsten carbide shot brush

minimized by following the specification, which requires that during production peening a test strip be run every 30 minutes to verify the actual peening intensity used. The size of the effective peening almen range, 0.0045 in. (0.11 mm), for aluminum welds will also minimize the effects of operator variation. Reasonable quality control procedures, such as those in MIL-R-81841, should assure that effective peening is performed.

Ship Application

Based on the results reported herein, brush shot peening was performed as part of the procedure for weld repair of locations on an aluminum-hulled, high-performance craft which had experienced repetitive occurrences of fatigue cracking. Peening was performed using the $^{9}/_{16}$ by 1 in. (14.3 by 25.4 mm) tungsten carbide flap brushes.

The area to be peened was laid out in grids with each grid corresponding to the size of an almen strip. Peening parameters were chosen to yield the desired range of peening intensities (0.0035 and 0.0080) on each grid in from 30 to 240 seconds(s). Grid layout was done so the operator could concentrate on providing a uniform surface coverage.

Flap speed and peening pressure was controlled by the variable speed motor/strobe light technique previously described. When the operator felt that complete coverage had been achieved, he stopped and noted the peening time. The peened surface was then examined at ×10 for visible evidence of plastic flow to indicate complete coverage. For accessible, smooth areas the average peening time for each grid was 45 s. Irregular surface areas in locations of poor accessibility required up to 120 s of peening time. When peening flat surfaces the peening brushes remained intact up to 1 hour but lasted only 5 to 10 minutes when peening sharp edges.

After the repair and brush peening treatment, the test craft underwent high-speed trials for over one year. There was no reoccurrence of the cracking.

Conclusion

The following conclusions and recommendations are derived from this investigation on developing methods to improve the fatigue performance of welded 5086-H116 alloy aluminum:

1. Postweld brush shot peening improves the fatigue performance of butt-welded 5086-H116 (with the weld reinforcement removed) to the level of unwelded base metal and can increase the fatigue strength of 5086-H116 fillet welds from 5,500 to 10,000 psi at 10^7 cycles.

2. Due to the degree of improvement in fatigue performance of butt-welded 5086 and the relative insensitivity of fatigue life to operator process variables, rotary brush peening should be considered a potential method to be used in aluminum hull construction for postweld treatment in areas subjected to localized cyclic loading.

3. The ability to conduct the peening operation in an aluminum ship structure makes brush peening an attractive method for treating areas susceptible to fatigue cracking both in new construction and during repair of aluminum hull surface effect ships and other high-performance craft.

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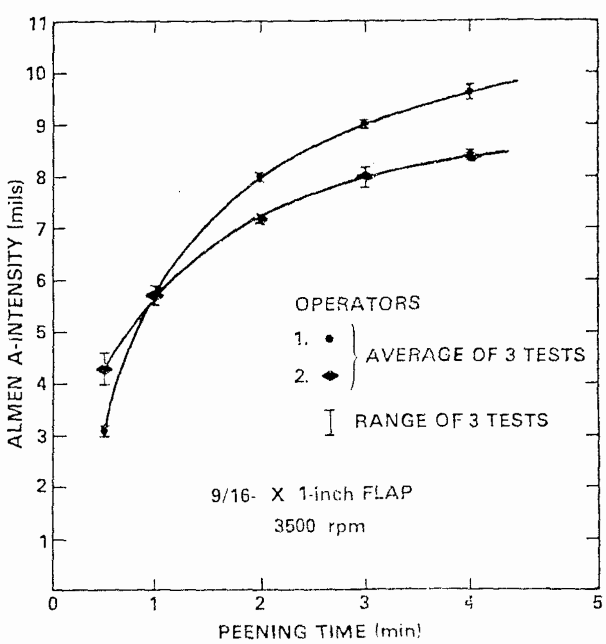

Fig. 18—Operator effects on peening intensity