

The Effect of Hole Drilling on Fatigue and Residual Stress Properties of Shot-Peened Aluminum Panels

J. Chaudhuri, B.S. Donley, V. Gondhalekar, and K.M. Patni

The effect of hole drilling after shot peening on the fatigue life and residual stress state of selected aluminum alloys was investigated. Compared to the unpeened condition, the hole drilling after shot peening reduced the fatigue life of the 2024-T351 and 2324-T39 alloys to a small extent. On the other hand, the fatigue life of 7150-T7751 decreased considerably due to hole drilling after shot peening.

A compressive residual stress was at the surface of the shot peened specimens. Hole drilling reduced the compressive residual stress by 60%. The excess dislocation density was mostly concentrated at the surface of the specimens.

Keywords
dislocation density, effect of hole drilling after shot-peening, residual stress, shot-peened aluminum panels, x-ray rocking curves

1. Introduction

SHOT-PEEN forming improves the fatigue life of metals in general due to the introduction of favorable compressive residual stresses at and near the exposed surface (Ref 1-3). Similar benefits are expected in the shot-peen forming fabrication process of aircraft wing skin panels. This process is extensively used to contour form the wing panels of high-performance general aviation aircraft. Holes are drilled in the shot-peen formed panels to assemble items called spar caps and stiffeners. Hole drilling causes changes in the residual stress state in the material adjacent to the hole. The altered state of residual stress may detrimentally affect the fatigue life as well as the damage tolerance performance of the wing structure. To this date, there are no studies on the effect of hole drilling after shot peening on the fatigue behavior and residual stresses of metal alloys.

This study investigates fatigue properties and residual stresses of the aluminum alloy plate materials, which were hole drilled after shot peened. The residual stresses were measured on the surface as well as in depth. The x-ray diffraction analysis offers an excellent possibility to measure residual stresses (Ref 4, 5). It is a sensitive, fast, and nondestructive method. In the present study, a double crystal x-ray diffractometry method was used to measure residual stresses (Ref 6, 7). The excess dislocation density on the surface and in depth was also monitored using this x-ray technique.

2. Experimental

2.1 *Fatigue Test*

For the advance aircraft wing panels, potential materials are 2024-T351, 2324-T39, and 7150-T7751 aluminum alloy sheet materials. These three materials were used for a fatigue test evaluation. The fatigue test specimen geometry is shown in Fig. 1. Two identical sets of specimens were fabricated from each material. Only one set of specimens was then shot peened on one side to 0.018 Almen 'A' intensity while the other side was shot peened to make the specimens flat. Cast steel shot of size 330 was used for shot peening. A hole was drilled in each specimen. A constant-amplitude, sinusoidal-loading fatigue test was run at a frequency of 10 or 20 Hz, stress ratio of 0.05, and two different stress levels of 140 and 172 MPa (20 and 25 ksi). Each test was repeated three times. All specimens were subjected to fatigue testing to failure by fracture (i.e., separation of the specimen into two pieces).

2.2 *Measurement of Residual Stress*

For the residual stress measurement, two identical sets of specimens of dimensions 101.6 × 101.6 mm^2 (4.0 × 4.0 in.^{2}) of each of the three alloys were fabricated. All the specimens were shot peened using the same procedure used for the fatigue test specimens. A hole was drilled in only one set of specimens. An x-ray double crystal diffractometry method was used to measure the residual stress on the shot-peened surface. A Blake industries x-ray double crystal diffractometer tuned for the CuKα radiation was used. A germanium (111) crystal was used as the first crystal. All the three alloy plate materials were highly tex-

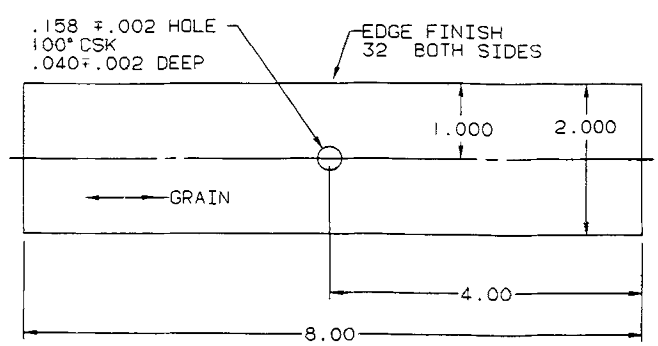

Fig. 1 Test specimen geometry

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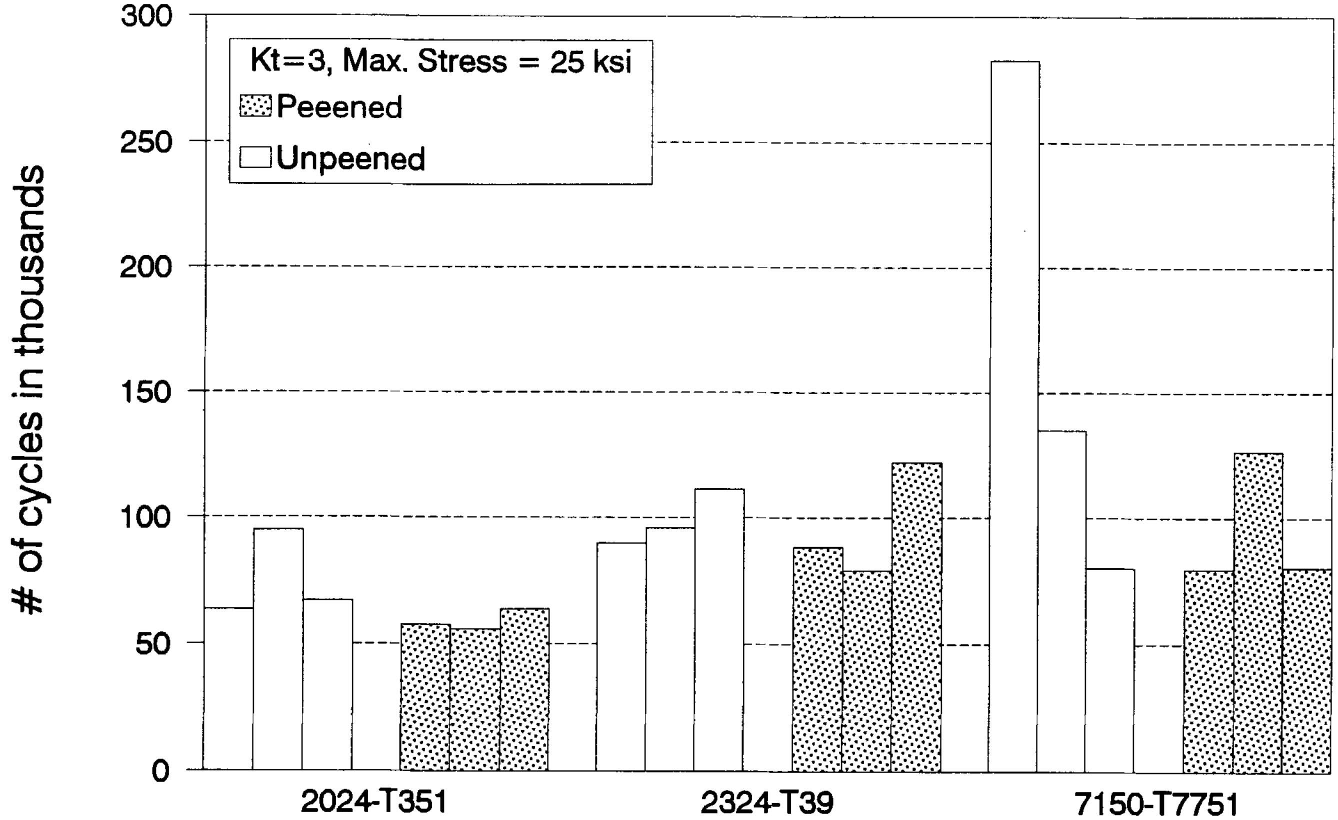


Fig. 2 Fatigue life comparison of peened and unpeened specimens at a maximum stress level of 172 MPa (25 ksi)

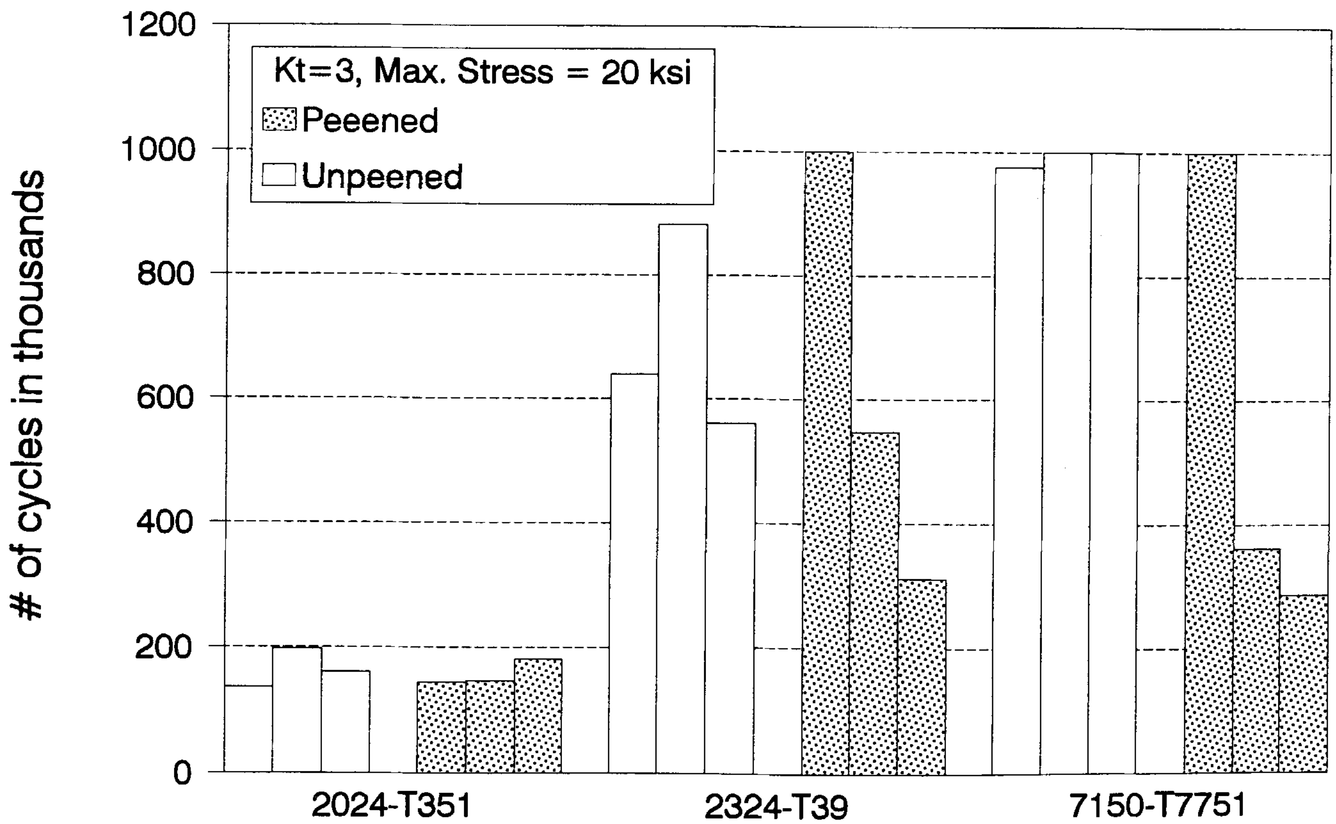


Fig. 3 Fatigue life comparison of peened and unpeened specimens at a maximum stress level of 140 MPa (20 ksi)

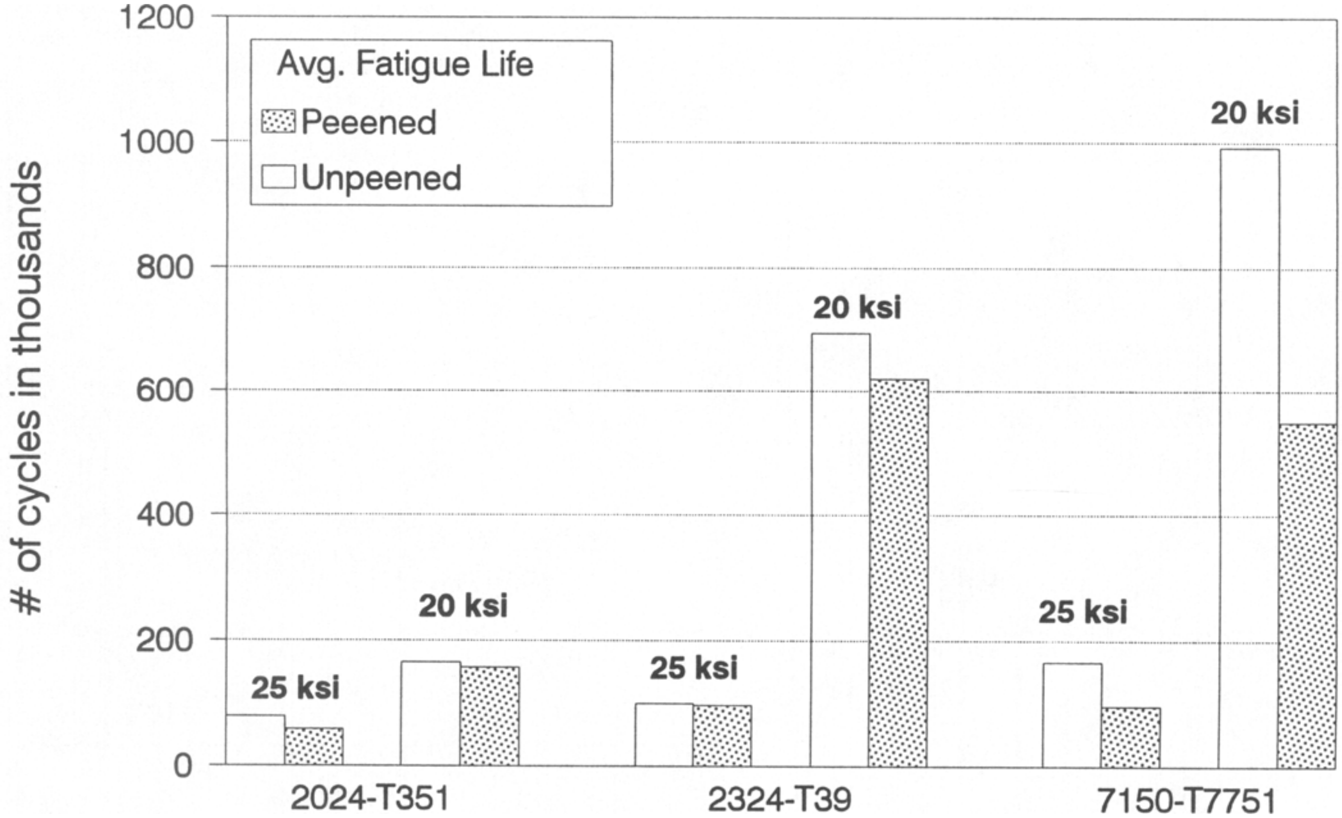
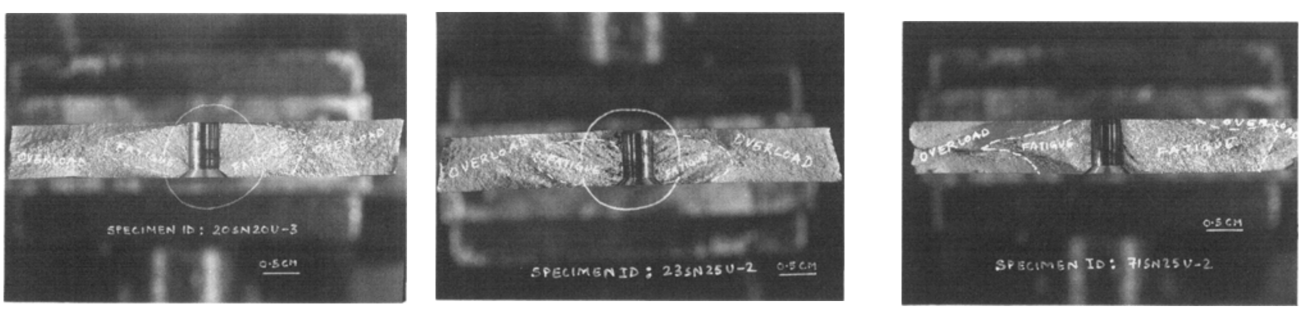


Fig. 4 Average fatigue life comparison of peened and unpeened specimens at a maximum stress level of 172 and 140 MPa (25 ksi and 20 ksi), respectively



(a) (b) (c)

Fig. 5 Typical fracture surface of unpeened specimens. See Fig. 6 for the magnified view of the circled area showing the primary crack origin. (a) 2024-T351 alloy. (b) 2324-T39 alloy. (c) 7150-T7751 alloy

tured along the (111) direction, so the [111] reflection was used for x-ray measurements. The residual stress and dislocation density were measured at the center part of the specimen. The depth of CuKα x-ray penetration, in aluminum, $x = \mu/\sin\theta$, where θ is the Bragg angle for the [111] reflection and μ is the mass absorption coefficient of CuKα radiation in aluminum, is 0.025 mm (0.001 in.). Thus the x-ray measurement was taken from a depth of 0.025 mm (0.001 in.). Then the center part of each specimen was electropolished to remove 0.05, 0.1, 0.015, 0.25, and 0.5 mm (0.002, 0.004, 0.006, 0.010, and 0.020 in.), respectively, from the shot-peened surface. The residual stress and dislocation density were measured after each electropolishing step. The electropolishing technique does not alter the residual stress pattern (Ref 7).

3. Results and Discussions

3.1 *Fatigue Test Results*

The fatigue test data are shown in Table 1 and Fig. 2 through 4. The average fatigue life of the shot-peened specimens of 2024-T351 and 2324-T39 was slightly lower than the unpeened ones at both stress levels. However, for 7150-T7751, the reduction in fatigue life was approximately 42% and 45% as compared to the unpeened specimens at the 172 and 140 MPa (25 and 20 ksi) maximum stress levels, respectively.

At the 172 MPa (25 ksi) maximum stress level, the fatigue life of 2324-T39 and 7150-T7751 shot-peened specimens was approximately 63% longer as compared to that of 2024-T351. At the 140 MPa (20 ksi) maximum stress level, the fatigue life of the 2324-T39 shot-peened specimens was approximately 300% longer, and that of the 7150-T7751 shot-peened specimens was approximately 250% longer as compared to the fatigue life of the 2024-T351 shot-peened specimens.

Table 1 Fatigue test results

Alloy	Shot peen condition	Maximum stress MPa	Maximum stress ksi	Number of cycles to failure	Average number of cycles to failure
2024-T351	Unpeened	140	20	136,536	164,741
				197,200	...
				160,488	...
		172	25	63,554	78,195
				94,979	...
				76,053	...
	Peened	140	20	144,134	157,000
				146,005	...
				180,863	...
		172	25	57,402	58,993
				55,762	...
				63,816	...
2324-T39	Unpeened	140	20	639,944	694,150
				881,903**	...
				560,604**	...
		172	25	89,786	99,062
				95,946	...
				111,454	...
	Peened	140	20	1,000,000	619,382
				547,510**	...
				310,637**	...
		172	25	88,415	96,468
				78,931	...
				122,057	...
7150-T7751	Unpeened	140	20	976,080	992,027
				1,000,000	...
				1,000,000**	...
		172	25	282,888	165,928
				134,847	...
				80,049	...
	Peened	140	20	1,000,000**	549,015
				361,363**	...
				285,682**	...
		172	25	79,646	95,477
				126,474	...
				80,311	...

** The fatigue test was run at a frequency of 20 Hz.

3.2 *Fractographic Examination*

The fractographic examination was performed on the fracture surfaces of both the unpeened and shot-peened specimens of the three alloys to examine the crack origins and other fracture features. The crack origination site can be well guessed even at low magnification; however, it is clearly visible at larger magnification (Fig. 5a, b, and c through 8a, b, and c). For the 2024-T351 and 2324-T39 alloys, fracture surfaces of both the unpeened and shot-peened specimens showed the primary crack origin at the base of the countersink, and the final failure was due to the overload. For the 7150-T7751 alloy, the primary crack originated at the edge of the hole away from the countersink in both the unpeened and shot-peened specimens. This could be attributed to the lower damage tolerant properties of the 7150 alloy and/or the surface defects produced due to the metal fold and broken shot, which possibly acted as primary crack origin sites. Microstructural examination of specimen surfaces revealed that dimples formed by shot peening were almost similar in all three alloys (Fig. 9a, b, and c).

3.3 *Residual Stress Analysis*

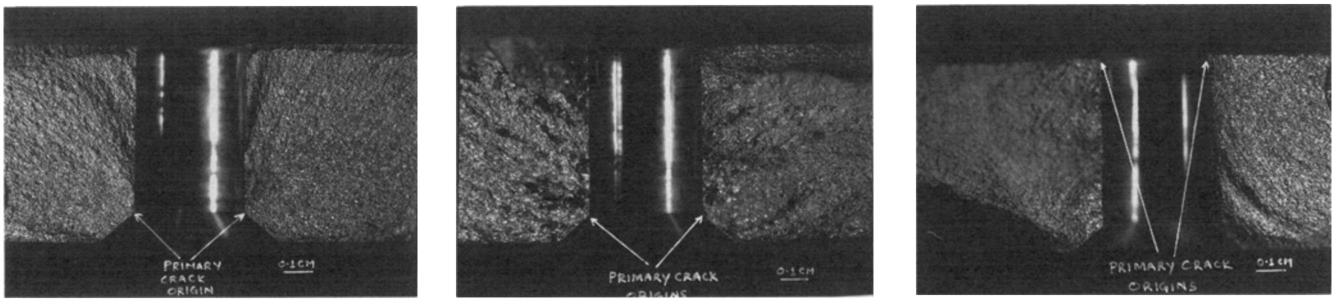
The details of the residual stress analysis method can be obtained elsewhere (Ref 4). From the shift of the Bragg peak position, $\Delta\theta$, the residual strain, $\Delta\varepsilon$, can be measured as:

$$\Delta\varepsilon = \frac{\Delta d}{d} = -cot\theta\Delta\theta \qquad \text{(Eq 1)}$$

where d is the interplanar spacing, Δd is the change in interplanar spacing, and θ is the Bragg angle. The results on residual stress measurement are listed in Table 2 and plotted in Fig. 10. Both the shot-peened, and shot-peened and hole-drilled specimens had a compressive residual stress at the surface. The residual stress reached a zero value at approximately 0.25 mm (0.01 in.) depth from the surface and became tensile in nature at larger depths. The tensile residual stresses may be responsible for the lower fatigue life of the shot-peened specimens. The

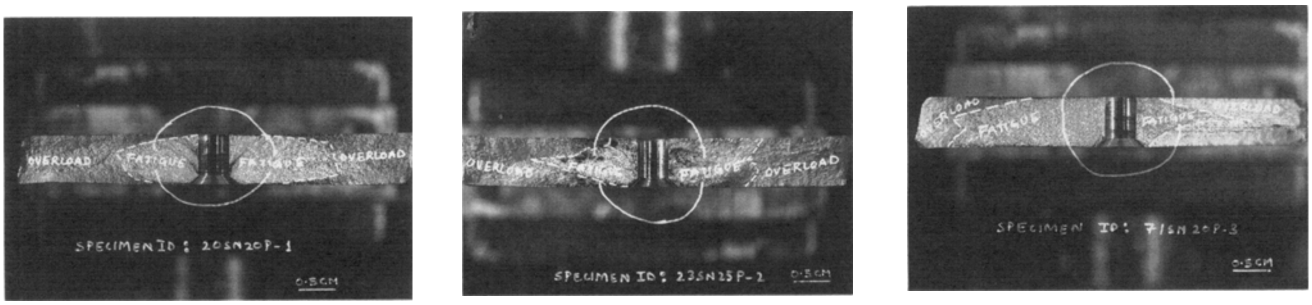
Table 2 Residual stress values for indicated alloys and conditions

Condition or etch depth		2024-T351 Alloy				2324-T39 Alloy				7150-T7751 Alloy			
		Without a hole		With a hole		Without a hole		With a hole		Without a hole		With a hole	
mm	in.	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi
Shot peened	...	−291	−42	−318	−46	−318	−46	−291	−42	−352	−51	−365	−53
Hole drilled	...	...	...	−69	−10	...	...	−110	−16	...	...	−117	−17
0.05	0.002	...	...	−48	−7	...	...	−62	−9	−172	−25	−83	−12
0.1	0.004	−110	−16	−41	−6	−124	−18	−41	−5.6	−110	−16	−55	−8
0.15	0.006	−25	−3.6	−11	−1.6	−47	−6.8	−13	−1.9	−58	−8.4	−43	−6.2
0.25	0.010	0	0	0	0	0	0	0	0	0	0	0	0
0.5	0.020	+14	+2.0	+11	+1.6	+32	+4.6	+15	+2.2	+42	+6.1	+15	+2.2



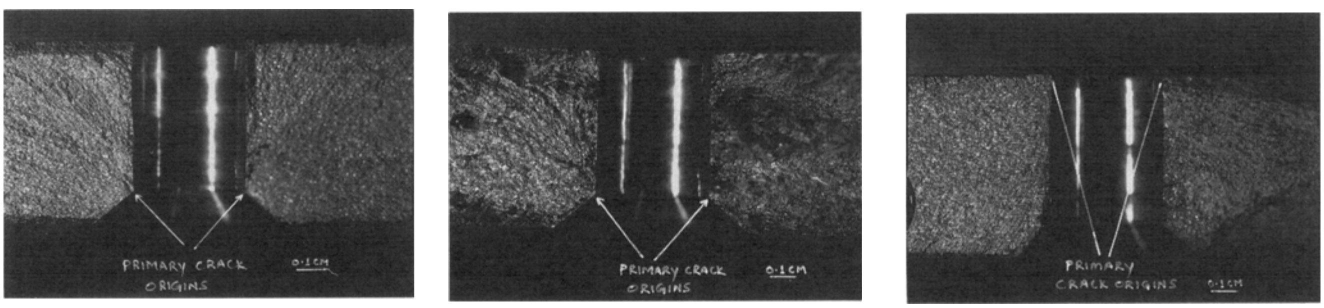
(a) (b) (c)

Fig. 6 Magnified view of the typical primary crack origin in unpeened specimens. (a) 2024-T351 alloy; the cracks originated at the base of the countersink. (b) 2324-T39 alloy; the cracks originated at the base of the countersink. (c) 7150-T7751 alloy; unlike the 2*xxx* series alloys, the cracks originated at the edge of the hole away from the countersink



(a) (b) (c)

Fig. 7 Typical fracture surface of peened specimen. Figure 8 gives the magnified view of the circled area showing the primary crack origin. (a) 2024-T351 alloy. (b) 2324-T39 alloy. (c) 7150-T7751 alloy



(a) (b) (c)

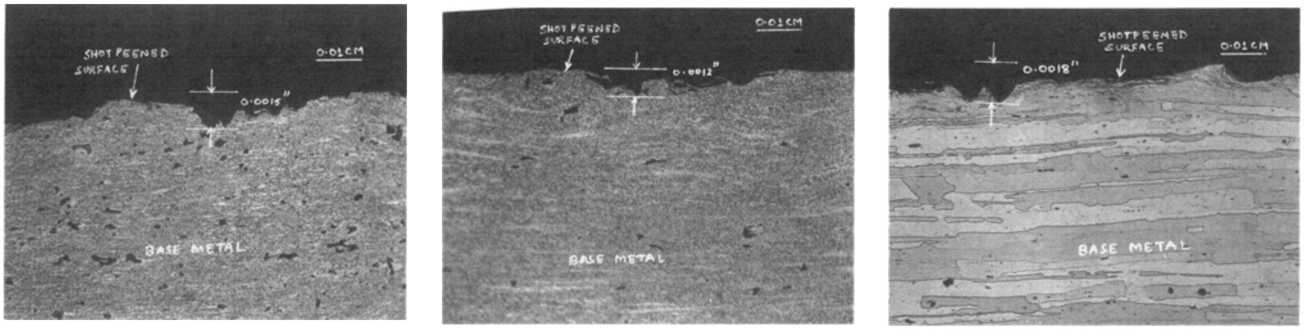
Fig. 8 Magnified view of the typical primary crack origin in peened specimens. (a) 2024-T351 alloy; the cracks originated from the base of the countersink as in the unpeened specimen. (b) 2324-T39 alloy; one of the multiple crack origin locations was at the base of the countersink like in the unpeened specimen. (c) 7150-T7751 alloy; the cracks originated at the edge of the hole away from the countersink similar to the unpeened specimen

compressive residual stress at the surface was found to decrease by ~60% due to hole drilling.

In addition to the shift of the x-ray rocking curve, a broadening of the rocking curve was also observed. Thus the dislocation density per cm^2 (in.^{2}), D, was assessed from the full width at half maximum of the rocking curve, β, as (Ref 8, 9):

$$D = \frac{\beta^2 - \beta^2_{particle}}{9b^2} \quad \text{(Eq 2)}$$

where b is the Burgers vector and β_{particle} is the full width at half maximum for the particle size or grain size. The excess dislocation density, i.e., the ratio of the dislocation density to that in the unpeened surface, are reported in Table 3 and plotted in Fig. 11. As shown, the excess dislocation density is concentrated within only 0.1 mm (0.004 in.) depth from the surface for all three alloys. It reaches, from a high value at the shot-peened surface (4.08 to 2.28 times the dislocation density of the unpeened surface), to the dislocation density value of the un-



(a) (b) (c)

Fig. 9 Microstructure of the peened specimen showing impressions due to broken shot and/or metal folds. (a) 2024-T351 alloy. (b) 2324-T39 alloy. (c) 7150-T7751 alloy

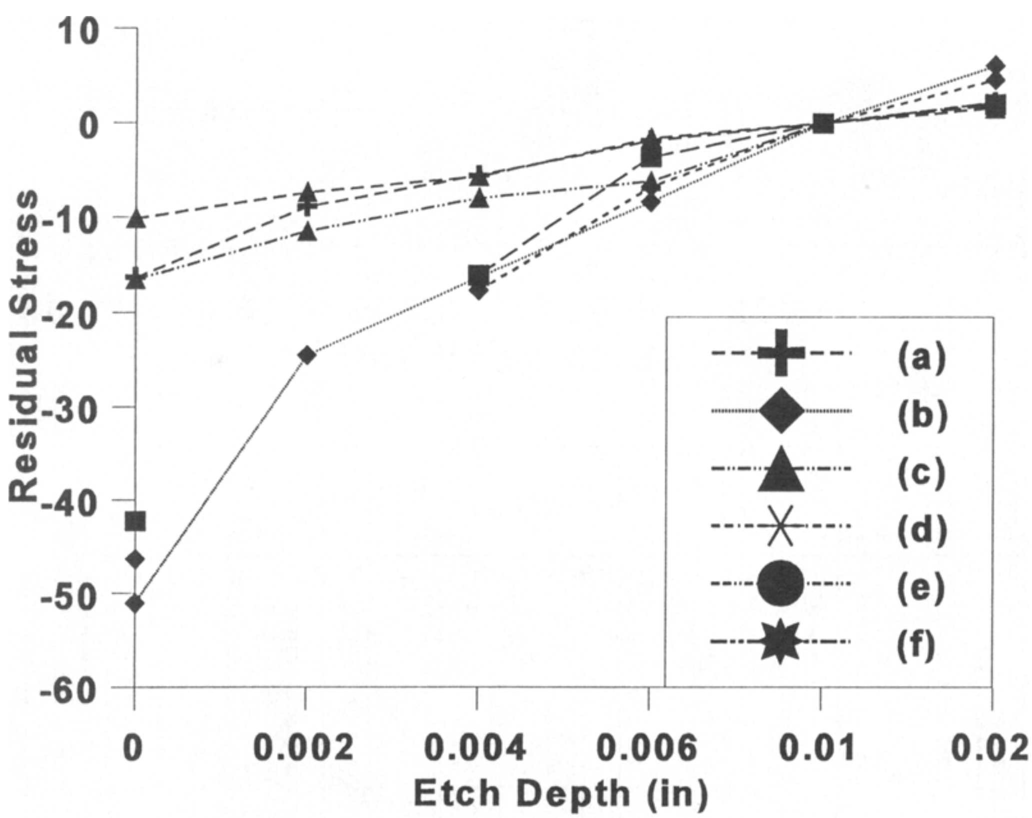


Fig. 10 Residual stress of shot-peened samples with or without a hole is plotted against the etch depth.

peened surface at that depth. The hole drilling did not change the general dependence of the excess dislocation density on the distance from the surface; it only increased the amount to some extent. Also, the excess dislocation density is less in the 2024 alloy compared to the other two alloys.

4. Conclusions

For the 2024-T351 and 2324-T39 alloys, the average fatigue life of the shot-peened samples decreased very little when compared to the unpeened samples at both 140 and 172 MPa (20 and 25 ksi) maximum stress levels. However, the fatigue life reduction due to shot peening was significant for the 7150-T7751 alloy. At the 140 MPa (20 ksi) maximum stress, both the shot-peened and unpeened specimens of the 2324-T39 and 7150-T7751 alloys exhibited much longer fatigue life as compared to that of the 2024-T351 alloy.

The primary crack origin site was at the base of the countersink in the 2024-T351 and 2324-T39 alloys. On the other hand, the primary crack was generated at the edge away from the countersink in the 7150-T7751 alloy.

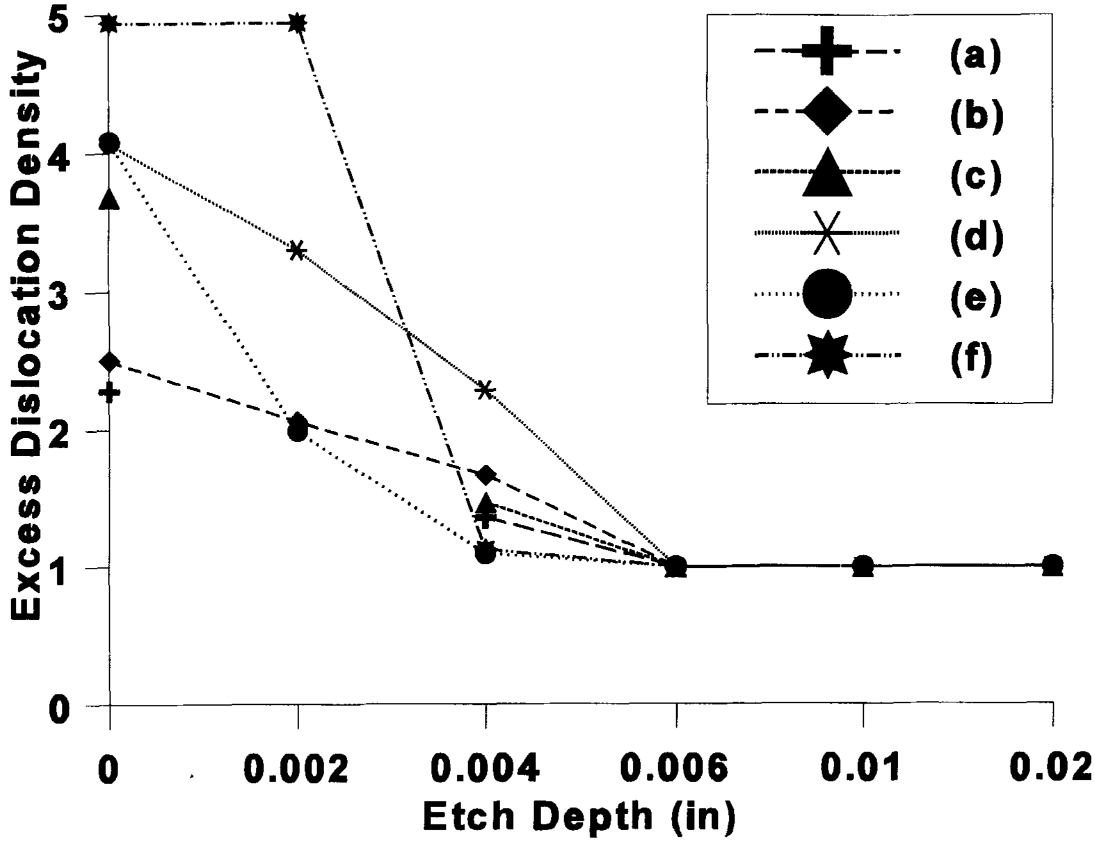


Fig. 11 Excess dislocation density in shot-peened samples with or without a hole is plotted against the etch depth.

Table 3 Excess dislocation density

Condition or etch depth		2024-T351 Alloy		2324-T39 Alloy		7150-T7751 Alloy	
mm	in.	Without a hole	With a hole	Without a hole	With a hole	Without a hole	With a hole
Shot peened	...	2.28	...	3.68	...	4.08	...
Hole drilled	...	...	2.5	...	4.07	...	4.94
0.05	0.002	...	2.06	...	3.3	1.99	4.94
0.1	0.004	1.36	1.67	1.47	2.29	1.1	1.13
0.15	0.006	1.0	1.0	1.0	1.0	1.0	1.0
0.25	0.010	1.0	1.0	1.0	1.0	1.0	1.0
0.5	0.020	1.0	1.0	1.0	1.0	1.0	1.0

The residual stress was found to be compressive at the surface of both shot-peened, and shot-peened and hole-drilled specimens. The stress changed from a compressive to a tensile value at about 0.25 mm (0.01 in.) depth. The compressive residual stress at the surface decreased by 60% due to hole drilling. The excess dislocation density was mostly concentrated at the surface. The hole drilling increased the amount of excess dislocation density slightly.

Acknowledgment

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