EFFECTS OF SHOT PEENING ON FATIGUE-DAMAGED HIGH STRENGTH ALUMINUM ALLOY —APPLICABILITY OF REJUVENATION ON FATIGUE-DAMAGED COMPOPENTS—

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ABSTRACT

It is well established that the shot peening can prolong the fatigue lives and enhance the fatigue strengths as well. Many components and equipment operating currently were not shot peened at their initial installation. If the x-ray fatigue damage assessment method (previously reported by Y.O.) is applied to such components, one can estimate extent they are fatigue damaged. Extending the remaining fatigue lives of these existing components will be one of the most interesting demands among industry engineers. Therefore, it is the objective of the present study (i) to find effects of shot peening on fatigue damaged high strength aluminum alloy for rejuvenating fatigue-damaged materials, and (ii) to study the rejuvenating mechanisms by x-ray diffraction parameters including dislocation densities through the diffraction line analyses and residual stress development.

Rejuvenating factor, newly proposed in this study, can be defined as N_F^{SP}/N_F^{UP} where N_F^{SP} is the number of cycles-to-failure of shot-peened pre-fatigued condition and N_F^{UP} is N_F of un-peened non-damaged condition of the material. It was found that the remaining fatigue life can be prolonged to $N_F^{SP'}$ (N_F of shot-peened but un-fatigued condition) if 50% or less of the N_F^{UP} has been consumed during the previous fatigue stressing of un-peened condition.

KEYWORDS : Al 7050-T7651, pre-fatigue stressing, four-point reversed bending fatigue test, shot-peening, rejuvenating factor, residual stress, surface and interior dislocation densities, dislocation density ratio.

INTRODUCTION

It is well established that the shot peening can prolong the (corrosion) fatigue lives and enhance the fatigue strength as well. Recently this improvement is recognized in retarding susceptibility to stress corrosion cracking [1,2,3,4,5].

Shot peening induces a high magnitude compressive residual macrostress which reduces the mean stress in the surface, retarding the initiation and early fatigue crack growth [6,7,8]. In our previous work on shot-peened Al 7050-T7651 [9], the surface compressive residual stress (σ_{rs}) as well as the interior peak compressive σ_{rs} (situated at ca. 100 μm below the surface) relaxed continuously throughout the entire fatigue life with different rates. At the same time, the work hardening generated by the shot peening results in an increased dislocation density. This high dislocation density hinders dislocation movement due to the fatigue load and suppresses localized plastic deformation [10], or accelerates the growth rate of small surface cracks [11]. Therefore, the effect having compressive residual stress in the surface layer is generally believed to be positive. On the other hand, the highly densed dislocation density possesses positive [10] or negative [11] effects on fatigue behavior.

It was also found, in our previous work, that surface dislocation density, ρ_S, obtained by using CuK_α radiation decreased by increasing degree of fatigue damage; while the interior dislocation density, ρ_I, measured by using MoK_α radiation increased during the fatigue process. It was, therefore, concluded that the ratio of ρ_I/ρ_S served as a fatigue damage indicator for the shot-peened Al alloy [9].

In this study, the shot peening was employed on pre-fatigued specimens of Al 7050-T7651. The shot-peened pre-fatigued specimen was further subject to the fatigue stressing under the same stress amplitude as used for the previous fatigue cycling. Then x-ray diffraction parameters including residual stresses and dislocation density through the diffraction line analyses were utilized to evaluate the rejuvenating effect of the shot peening on pre-fatigued un-peened specimens.

MATERIAL AND TEST PROCEDURES

Fatigue test specimen were machined from a high strength aluminum alloy sheet (Al 7050-T7651; Cu 2.0~2.6, Mn<0.10, Mg 1.9~2.6, Ti<0.06, Si<0.12, Zr 0.08~0.15, Cr<0.04, Zn 5.7~6.7, Fe<0.15, Al bal.). Specimen's configuration for fatigue tests is shown in Figure 1. The fatigue tests were conducted at a four-point reversed bending mode (R=-1) with the Sonntag Universal Fatigue Tester operating with the frequency of 30 Hz in air. Selected maximum applied stresses were 30 ksi (stress ratio, σ_{app}/σ_Y, is 0.43), 40 ksi (σ_{app}/σ_Y=0.57), and 50 ksi (σ_{app}/σ_Y=0.71). In order to find any possitive effects of subsequent shot-peening on remaining fatigue lives of pre-fatigued specimen, the fatigue cyclings were interrupted at certain pre-determined cycle ratios (i.e., N/N_F^{UP} = 25%, 50%, 75%, 90%, and 95%, where N_F^{UP} is the number of cycles-to-failure of un-peened Al 7050 alloy) for having a rejuvenating shot-peening. Four sides of test sections of these pre-fatigued specimen were shot-peened under controlled conditions (performed at Metal Improvement Company, USA) to the following specification; shot size: MI 230, intensity: 0.005A, and coverage: 100%, verified by PEEN SCAN.

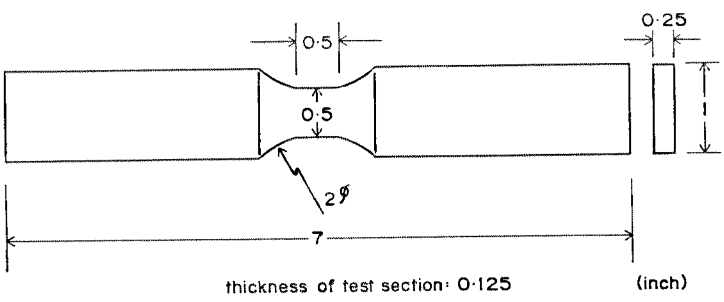


Figure 1. Specimen's Configuration for Fatigue Tests

Shot-peened pre-fatigued specimen was further subject to fatigue cyclings at the same stress ratio, at which the identical specimen was conducted for the previous fatigue cycling, until the fatigue failure. Meanwhile, the fatigue cyclings were again interrupted several times for x-ray studies. X-ray studies included residual stress measurements by CuK_α radiation and diffraction line profile analyses by both CuK_α and MoK_α radiations for computing dislocation densities. Detailed procedures for the x-ray diffraction studies can be found elsewhere [9,12].

RESULTS AND DISCUSSIONS

Pre-Fatigue Cycling

Figure 2 shows the ratio of the interior surface dislocation density, ρ_I, to the surface dislocation density, ρ_S, as a function of cycle ratio, N/N_F^{UP}. Since MoK_α radiation having a shorter wavelength can penetrate deeper (ca. 100 μm beneath the surface layer) than CuK_α radiation (ca. 20 μm), ρ_I was observed by MoK_α radiation nondestructively while ρ_S was measured by using CuK_α radiation. It was clearly defined previously that if the dislocation density ratio, ρ_I/ρ_S, exceeds 1.0 (in other words, the interior dislocation builds up at the equivalent level to that of the surface dislocation) the un-peened specimen is fatigue failed [12], as shown with parallel dotted lines. As seen from Figure 2, marked data points (results of this study) are found within these two dotted lines and none of pre-fatigued specimen was failed, although each was already fatigue-damaged to respective extent.

Shot-Peening on Pre-Fatigued Specimen

Figure 3 shows a progressive development of x-ray residual stresses during the pre-fatigue cycling, shown at upper portion of the figure. After shot-peening on these pre-fatigued specimen, the residual stresses show all compressive within a reasonable scatter band (i.e., σ_{rs} = - 27.32±1.35 kg/mm^2), as shown in the bottom portion of the figure. This result agrees very well with that was previously reported [9]. Consequently, all specimen now shot-peened can be considered to possess equal initial conditions as far as surface residual stress is concerned, although the material at subsurface layer was subject to a fatigue damage to different extent.

Similarly, the dislocation density ratio between the interior layer (ca. 100 μm below the surface) and the surface layer of each pre-fatigued specimen is related to the pre-determined cycle ratio, N/N_F^{UP} (see Figure 4). In our previous paper [9], it was reported that if the ratio, $\rho_{I(Mo)}/\rho_{S(Cu)}$, for shot-peened specimen is over 1000, 98% or more ($\sim N_F^{SP}$) of the fatigue life is already consumed or the specimen is fatigue-failed ($=N_F^{SP}$). Therefore, although each of the specimen was even already fatigue-damaged prior to the shot-peening, it is clear that none of them was fractured yet, since the ratio is even less than 100. Closed marks at N/N_F^{UP} = 0 were obtained in the previous work.

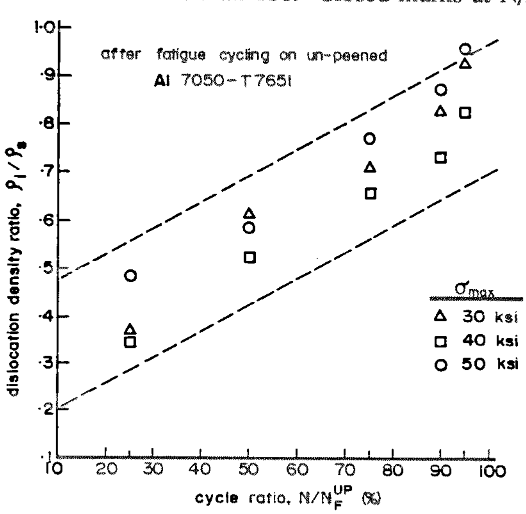


Figure 2. Dislocation Density Ratio vs. Cycle Ratio, after Fatigue Cycling on Un-Peened Al 7050

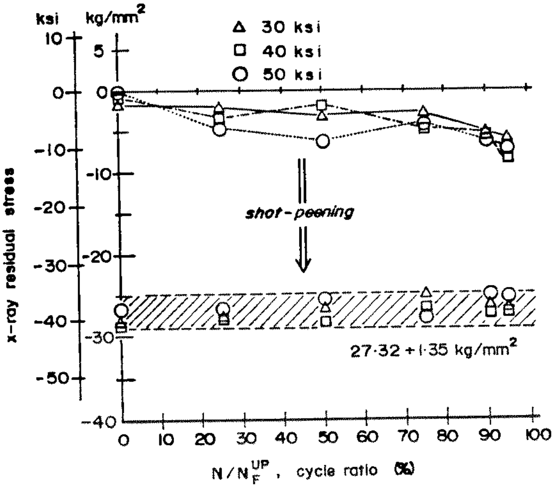


Figure 3. Changes in X-Ray Residual Stress during Fatigue Cycling and Residual Stress after Shot-Peening on Fatigued Specimens

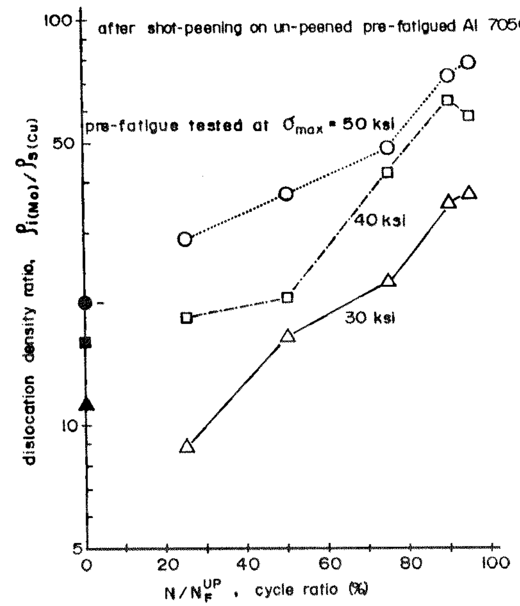


Figure 4. Dislocation Density Ratio after Shot-Peening on Un-Peened Pre-Fatigued Al 7050

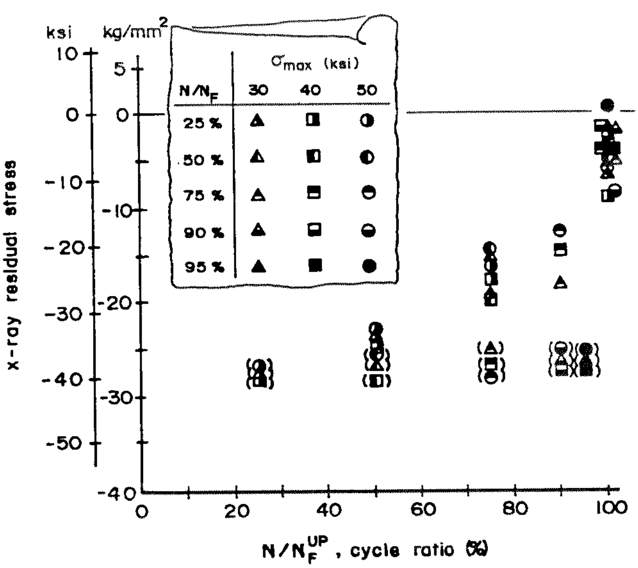


Figure 5. Progressive Changes of Residual Stress of Shot-Peened Pre-Fatigued Specimen

Fatigue Damage Evaluation of Shot-Peened Pre-Fatigued Specimen

Figure 5 shows a development of surface residual stresses measured by CuK_{α} x-ray diffraction through the $\sin^2\Psi$-2θ method. Data points with parentheses are identical to those shown at bottom portion of Figure 3. Shot-peened pre-fatigued specimen shows a continuous relaxation of the surface residual stresses which were introduced by the shot-peening. The general trend is very similar to that was observed from the shot-peened un-fatigued specimen [9].

Bathias et al. [13], studying Al 2024-T351 and Al 7075-T7351, found that (i) a rapid evolution of σ_{rs} in shot-peened surface layer was followed by its stabilization, (ii) the first onset of the microcracks did not alter σ_{rs}, and (iii) final macrocarcks completed relaxation. The relaxation of surface σ_{rs} seecems to be dependent of the applied stress amplitude. For example, Bergstroem et al. [14], examining σ_{rs} relaxation of quenched and tempered AISI 4140 steel during the fatigue cycling (R=-1), reported that any specimen did not change their initial compressive σ_{rs} to the tensile σ_{rs}. However, the relaxation rate during the fatigue cycling increased by increasing the normal stress amplitude [14,15]. McClinton et al. [16] investigated on σ_{rs} relaxation of normalized and shot-peened SAE 1040 steel during the R=0 fatigue stressing and demonstrated that compressive σ_{rs} changed to tensile σ_{rs} when being subject to fatigue stressing at or more than 94% of the material's yield strength; while no changes in σ_{rs} for the entire fatigue life under fatigue cycling conducted at 62% of σ_Y although it relaxed monotonically but never changed to tensile σ_{rs} under 79% of stress ratio. Nevertheless, from the present work (see Figure 5) it was observed that (i) all shot- peened pre-fatigued specimen relaxed compressive σ_{rs} but did not change to tensile σ_{rs}, and (ii) the relaxation rate of σ_{rs} seems to be independent of the stress ratio (σ_{app}/σ_Y) ranging from 43% to 71%.

Figure 6 shows progressive changes in dislocation density ratio for each shot-peened pre-fatigued specimen as a function of subsequent cycle ratio, N/N_F^{UP}. Again it is found that dislocation density ratios of all failed specimens are close to or more than 1000, as found from shot-peened un-fatigued specimens [9]. Data points with parentheses are dislocation density ratio of specimens which were pre-fatigued and shot-peened prior to further fatigue cycling. An envelope defined by two parallel dotted lines indicates the dislocation density ratio of specimen - which was pre-fatigued to some extent -, followed by the shot-peening. Another band defined by solid lines show the scatter band of the dislocation density ratio obtained from shot-peened un-fatigued specimen, as previously reported [9]. The present data agree well with the previous results.

The work hardening by a shot-peening causes increase of dislocation density. Bergstroem et al. [10], studying various x-ray parameters including dislocation density during fatigue cycling of AISI 4140 steel, stated that the degree of cold work caused by shot peening process can be estimated from the ratio of dislocation density at the surface (ρ_S) to that of the bulk (ρ_B) and found that the dislocation density ratio (ρ_S/ρ_B) is 15. The bulk dislocation density (ρ_B) reported by Bergstroem et al. [10] was obtained from approximately 400 μm beneath the surface, which is much deeper than the peak position (ca. 100 ~ 150 μm from the surface) for the maximum compressive σ_{rs} and the maximum interior dislocation density which both were observed by the present authors [10]. According to our previous work [9], as shot-peened condition of Al 7050, ρ_S/ρ_I (at about 400 μm below the surface) was found be in unity.

Moreover, it was reported that the dislocation density, ρ_S, decreased in the shot-peened layer due to the fatigue loading under both R=-1 and R=0 conditions [10]. Our previous work on shot-peened Al7050 and the present study on shot-peened pre-fatigued Al 7050 indicate also the same trend, showing that the surface dislocation density, ρ_S, observed by CuK_{α} radiation decreases by increasing the cycle ratio, N/N_F^{UP}. However, of the most important and significant in this study is to verify the dislocation density ratio (ρ_I/ρ_S) criterion, which was proposed in our previous work [9], for evaluating fatigue damage process and for predicting the remaining fatigue life. It should be restated here that the interior dislocation density, ρ_I, was observed from approximately 100 μm from the surface, not 400 μm beneath the surface.

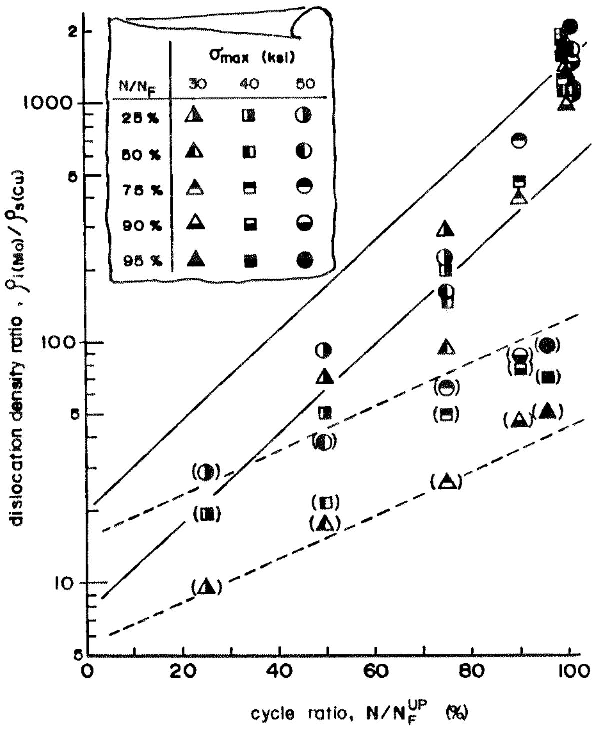
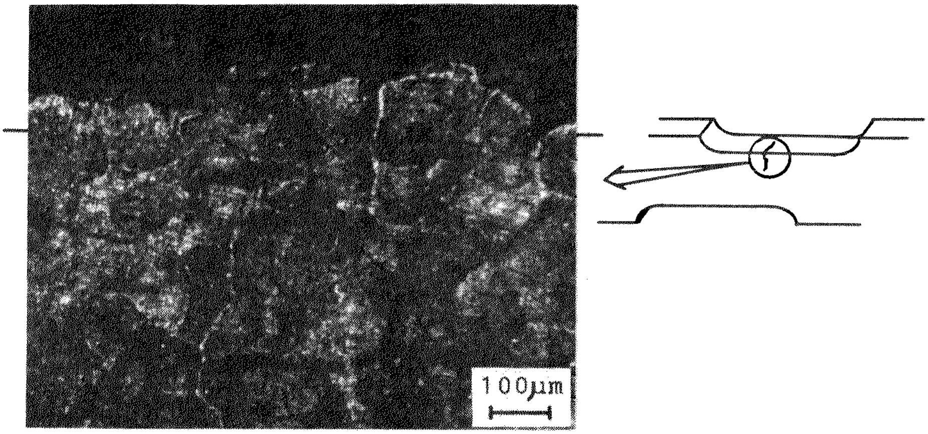


Figure 6. Changes in Dislocation Density Ratio of Shot-Peened Pre-Fatigued Specimen during Subsequent Fatigue Cycling

Figures 7 and 8 are optical microstructures of failed specimen which was previously fatigue cycled for 2.25 x 10^4 cycles (i.e., N/N_F^{UP} = 0.5), shot-peened and further fatigue cycled until N_F^{SP} = 8.34 x 10^4 cycles. Figure 7 shows as failed condition; while Figure 8 (a) and (b) are microstructures after about 100 μm surface layer (a) 150 μm surface layer (b) were removed. It seems to be that the major crack was initiated at approximately 100 μm below the surface which is close to the location where the interior dislocation density and compressive σ_{rs} show their maximum values.

Table I summerizes fatigue test data conducted for the present studies, where N_F^{UP} indicates the number of cycles-to-failure of un-peened specimen, N_F^{SP} the number of cycles-to-failure of shot-peened but not pre-fatigued specimen, and $N_F^{SP'}$ the number of cycles-to-failure of shot-peened pre-fatigued specimen. Here two types of the rejuvenating factors, $N_F^{SP'}/N_F^{SP}$ and $N_F^{SP'}/N_F^{UP}$, are proposed. Since, however, N_F^{UP} can serve as a rather baseline for evaluating positive effects of the shot-peening, the rejuvenating factor defined as $N_F^{SP'}/N_F^{UP}$ is preferrably adopted.

Figure 9 shows S-N curves for un-peend and shot-peened Al 7050 [9]. Fatigue lives of shot-peened pre-fatigued specimens tested in this study are shown with respective marks. It was found that (i) all of specimens, which were previously fatigue damaged to some extent and shot-peened later, possessed their fatigue lives between these two curves, and (ii) more significantly, the fatigue lives of shot-peend specimens - which were previously fatigue-damaged up to 50% - were very close to those of specimens which were shot-peened at the beginning (see the legend in Figure 6 for each mark). On the other hands, if the degree of previous fatigue damage exceed more than 50 ~ 60% or more there seems to be no remarkable positive effects of having shot-peening on the pre-fatigued material, since all data points are close to the N_F^{UP} curve.



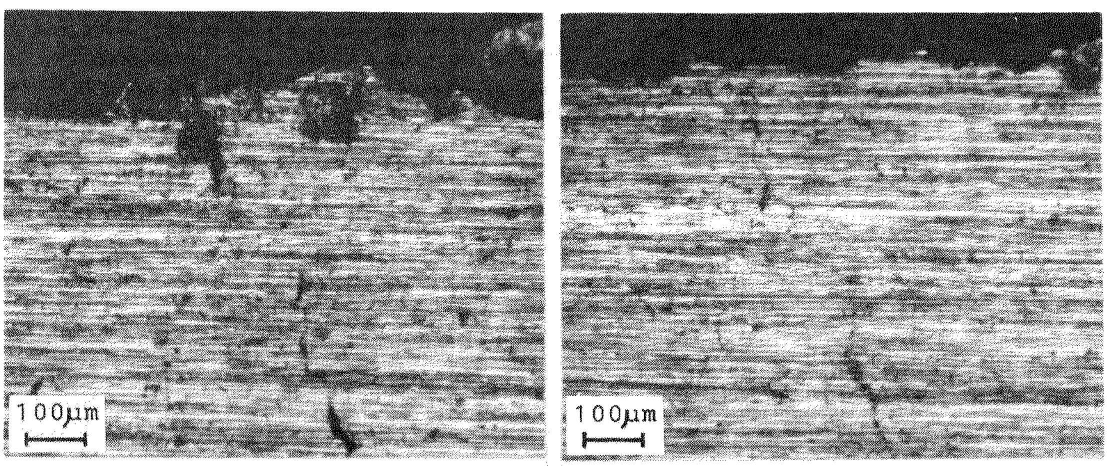
initial fatigue cycling → shot peening → further fatigue cycling

$\sigma_{max} = 40$ ksi — $\sigma_{max} = 40$ ksi

$N = 2{\cdot}25 \times 10^4$ cycles — $N_F^{SP} = 8{\cdot}34 \times 10^4$ cycles

$N/N_F^{UP} = 50\%$ — $N_F^{SP}/N_F^{UP} = 1{\cdot}85$

Figure 7. Microstructure of Fatigue-Failed Specimen



(a) after 100 μm removed   (b) after 150 μm removed

Figure 8. Internal Microstructures of Fig.7

Table I. Results of Fatigue Tests

σ_{max} (ksi)	N_F^{UP} (cycles)	N/N_F^{UP} (%)	$N_F^{SP'}$ (cycles)	$N_F^{SP'}/N_F^{UP}$	N_F^{SP} (cycles)	rejuvenating factor $N_F^{SP}/N_F^{SP'}$	N_F^{SP}/N_F^{UP}
30	1·5 x 10⁵	0	6·0 x 10⁵	4·0			
		25			6·00 x 10⁵	1·00	4·00
		50			5·78	0·96	3·85
		75			1·61	0·27	1·07
		90			1·65	0·28	1·10
		95			1·45	0·24	0·97
40	4·5 x 10⁴	0	8·5 x 10⁴	1·9			
		25			8·57 x 10⁴	1·01	1·90
		50			8·34	0·98	1·85
		75			4·95	0·58	1·10
		90			4·41	0·52	0·98
		95			4·35	0·51	0·97
50	1·7 x 10⁴	0	2·5 x 10⁴	1·5			
		25			2·32 x 10⁴	0·93	1·36
		50			2·41	0·96	1·42
		75			1·62	0·65	0·95
		90			1·62	0·65	0·95
		95			1·65	0·66	0·97

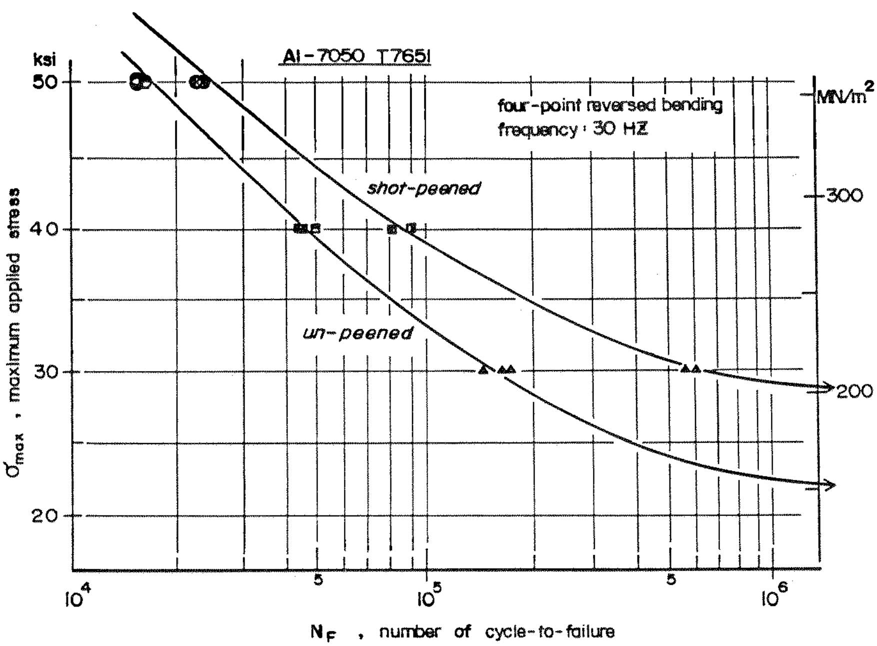


Figure 9. S-N Curves of Shot-Peened and Un-Peened Al 7050 Alloy

The latter finding is more clearly demonstrated by Figure 10. As described early, the newly proposed Rejuvenating Factor is introduced here to evaluate the beneficial effects of shot-peening on pre-fatigue damaged material. If the RF is unity or less, there were no positive effects of having the shot-peening on pre-fatigued material. Namely, the fatigue damage has been accumulated close to its critical level in the near surface zone, so that the subsequent shot-peening did not show any rejuvenating effect, although there should be some but they might be small. According to Table I, the effective factor of shot-peening on un-fatigued condition of Al 7050 , N_F^{SP}/N_F^{UP} is 4.0 for σ_{max} = 30 ksi, 1.9 for 40 ksi, and 1.5 for 50 ksi, respectively. These are also plotted at N/N_F^{UP} =0 in Figure 10. From Figure 10, it can be concluded that if the pre-damage factor is over 50 ~ 60%, there is a little chances left for the shot-peening to rejuvenate the fatigue-damaged material. Hence, if one can estimate the degree of previous fatigue damage by using the Failure Probability curve on un-peened material [12] and if it shows approximately 50% or less, according to the present finding, one can expect to prolong the remaining fatigue life of the pre-fatigued material by applying the rejuvenating shot- peening up to that of the material which was originally shot-peened.

The positive effect of re-shot-peening on pre-fatigued shot-peened material on prolonging its remaining fatigue life will be another important concern among engineers. This is now under progress.

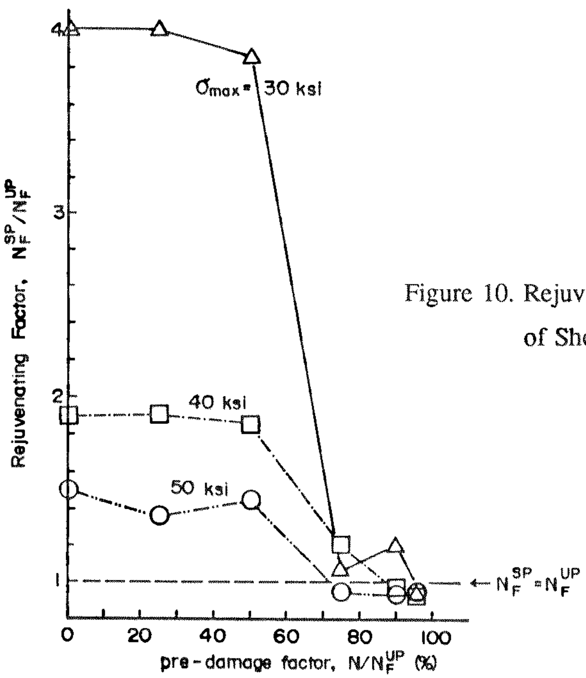


Figure 10. Rejuvenating Factor vs. Pre-Damage Factor of Shot-Peened Pre-Fatigued Al 7050 Alloy

CONCLUSIONS

Pre-fatigued un-failed specimen of Al 7050-T7651 was shot-peened, followed the subsequent fatigue cycling under a four-point reversed bending mode (R=-1) until its failure. A rejuvenating effect of the shot-peening on pre-fatigued un-peened condition was studied by x-ray diffraction techniques. Within the limited numbers of test results, the following can be concluded.
(1) Being independent of degree of previous fatigue damage and applied stress amplitude, the surface residual stresses caused by shot-peening on pre-fatigued specimen showed all compressive with 27 kg/mm^2, which was a similar level to that observed on the shot-peened un-fatigued specimen.

(2) After shot-peening on un-peened pre-fatigued specimen, the dislocation density ratio, $\rho_{I(Mo)}/\rho_{S(Cu)}$ increases by increasing the previous fatigue damage factor (N/N_F^{UP}) and the magnitude of the ratio ρ_I/ρ_S is higher by increasing applied stress amplitude.
(3) Continuous relaxation of surface compressive residual stress of shot-peened pre-fatigued specimen was recognized by a further fatigue stressing.
(4) Progressive changes in the ρ_I/ρ_S ratio increases until the fatigue failure at which the dislocation density ratio is near/above 1000.
(5) Rejuvenating factor, N_F^{SP}/N_F^{UP}, newly proposed in this study, can serve as an indicator to evaluate the positive effect of having the shot-peening improvement on pre-fatigued material. For Al 7050-T7651, under R=-1 fatigue cycling, the observed rejuvenating factor indicates that if the material was previously fatigue-damaged less than 50%, the subsequent shot-peening can prolong the remaining fatigue life to that of the shot-peened but un-damaged material; while about a half (or more than) of the original un-peened fatigue life is already consumed, it seems to be no remarkable rejuvenating effect by shot-peening.

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