Subcritical Crack Growth Under Intermittent Overloading in Cold-Rolled Steel

by L. G. Vargas [1] and R. I. Stephens [2]
1.) LASPAU Fellow, Mech. Eng. Dept., U. of Iowa, Iowa City, Iowa, USA
2.) Professor, Mech. Eng. Dept., U. of Iowa, Iowa City, Iowa, USA

The effect of single or intermittent peak tensile overloads on fatigue crack growth life is extremely complex. To further clarify this behavior, cyclic strain softening cold-rolled SAE 1020 steel was subjected to various tensile overload patterns as indicated schematically to the right in Figures 1 and 2. Compact tension fatigue specimens 1/4 x 4 x 3.94 in. were cut from 1/4 in. rolled strip. Loads were applied in the direction of rolling. A chevron starter notch was used to initiate a precrack and all crack growth monitoring was begun with a crack length, a, of 1.0 in. Side grooves 0.0125 in. deep with a 1/16 in. radius were milled on both sides of the specimens to control the plane of crack extension. The side grooves were polished to facilitate crack monitoring at 36X. All tests were performed on a MTS test system. Tests were run with $R = P_{min}/P_{max} \approx .06$. Constant steady-state loads, ΔP_s, applied at 15 Hz were 2.5, 3.0 and 3.5 kips which resulted in a stress intensity, ΔK_s, of 37, 44.5 and 52 ksi$\sqrt{in.}$ respectively for a = 1.05 in. Tensile overloads, ΔP_o, were 5 and 6 kips and were always first applied at a = 1.05 in. These overloads resulted in an initial stress intensity, ΔK_o, of 74 and 89 ksi$\sqrt{in.}$ respectively. Fracture toughness, K_c, for the material was 95 ksi$\sqrt{in.}$ The number of cycles between overloads, ΔN, was 2, 5, 10 and 20 thousand cycles. Fatigue fracture surfaces were flat and therefore in plane strain. Most intermittent overloaded specimens fractured during an overload and macroscopic crack extension was rarely observed during an overload except at fracture. The maximum stress intensity at fracture was usually greater than 130 ksi$\sqrt{in.}$

RESULTS: Table 1 gives the delay in crack growth, N_f-N_i, resulting from all overload tests, where N_f is the number of cycles to failure with overloads and N_i is the number of cycles to failure with no overloads. It is evident in Table 1 that all tensile overload conditions resulted in increased fatigue life and that all intermittent overloads had greater life than just single overloads (S.O.). It is also evident that for a given ΔP_s greater fatigue life or delay occurred with the larger ΔP_o for all ΔN. Fig. 1 shows crack growth behavior for no overloads (N.O.) and single overloads for ΔP_s = 3.5 and 2.5 kips. Fig. 2 shows crack growth behavior under intermittent overloads for ΔN = 10,000 cycles. Open data points indicate crack length and applied cycles for each overload. Fig. 3 shows the effect of varying ΔN for a given ΔP_s and ΔP_o. Fig. 4 indicates the influence of overload period ΔN on the fatigue life of all intermittent overload conditions. The normalized fatigue life was obtained by dividing N_f by N_i. It is evident in Fig. 4 that for each combination of ΔP_s and ΔP_o an optimum value of ΔN occurred for maximum fatigue life.

DISCUSSION: In Figures 1-3 it is seen that immediately after overload the crack growth rate is maximum and decreases as the crack extends with further steady-state cycling. This high crack growth rate has been called delayed retardation. A quantitative measurement of delayed retardation, a_{dr}, is illustrated in Fig. 1 and the number of applied cycles during delayed retardation has been labled ΔN_{dr}. Values of a_{dr} for single overloads are given in Table 1. Also shown in Table 1 are plane strain plastic zone sizes, $2r_y$, which were .075 and .11 in. for ΔP_o = 5 and 6 kips respectively at a = 1.05 in. For

single overloads, delayed retardation varied from 0 to 36% of the overload plastic zone size. The number of applied cycles during this delayed retardation was always less than 7,000 cycles. Larger values of a_{dr} and ΔN_{dr} occurred at higher values of ΔP_o and lower values of ΔP_s. With ΔP_s = 3.5, no macroscopic delayed retardation was observed. It is difficult to quantitatively compare a_{dr} and $2r_y$ for intermittent overloads because of interaction effects of prior overloads.

Figures 5-7 represent micro and macro crack extension following overload as shown by the two dashed vertical lines in Fig. 3 for ΔP_s = 3, ΔP_o = 6 and ΔN = 20,000. Fig. 5 shows the micro crack extension for this overload at 60X magnification and Fig. 6 gives the macro and micro crack growth rates following overload. Micro rates were obtained by analyzing the fracture surface with a scanning electron microscope (SEM) at 12,500X. SEM fractographs of data points, A, B and C in Fig. 6 are shown in Fig. 7. It is evident that delayed retardation has occurred both macroscopically and microscopically.

Shown in Fig. 1 and Table 1 are measurements labeled a_{ag} and ΔN_{ag} which represent crack extension and applied cycles respectively following a single overload when the crack growth rate again begins to increase. These values in general increased with larger ΔP_o or smaller ΔP_s. a_{ag} varied from .04-.06 in. or 36-67% of $2r_y$ and ΔN_{ag} varied from 3,000 to 40,000 cycles. Values of ΔN_{ag} agree quite well with values of ΔN which resulted in maximum fatigue life under intermittent overloading as shown in Fig. 4. It is hypothesized that maximum fatigue life under intermittent overloading for a fixed ΔP_o, should occur when $\Delta N \approx \Delta N_{ag}$. If ΔN is either less than or greater than ΔN_{ag} maximum crack growth life should not occur.

Table 1 Delay in Crack Growth Resulting from Intermittent Tensile Overloading ($N_f - N_i$)

ΔP_s	ΔP_o \ ΔN	S.O	20,000	10,000	5,000	2,000	a_{dr}	a_{ag}	$2r_y$	ΔN_{ag}
2.5	5	19,700	38,000	48,200	77,000	55,700	.02	.04	.075	10,000
	6	57,500	138,000	107,800	92,300	59,500	.04	.06	.11	40,000
3.0	5	2,400	8,300	13,400	24,500	14,300	.02	.05	.075	7,000
	6	14,900	35,400	53,400	34,200	28,200	.02	.04	.11	10,000
3.5	5	1,300	——	2,000	6,200	6,950	0	.04	.075	3,000
	6	4,800	——	12,700	18,300	12,200	0	.05	.11	4,000

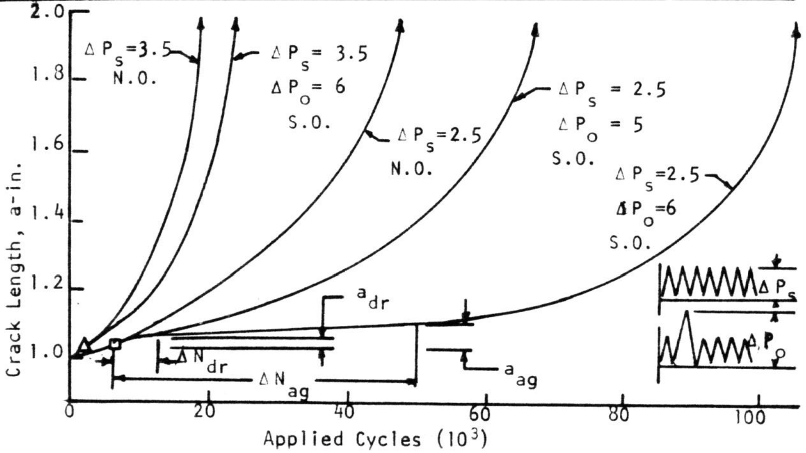

Fig. 1 No overloads and Single Overloads

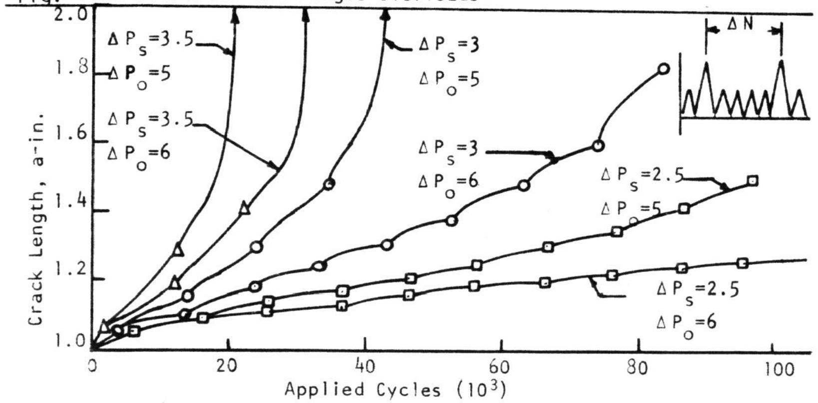

Fig. 2 Intermittent Overloads Applied with ΔN = 10,000

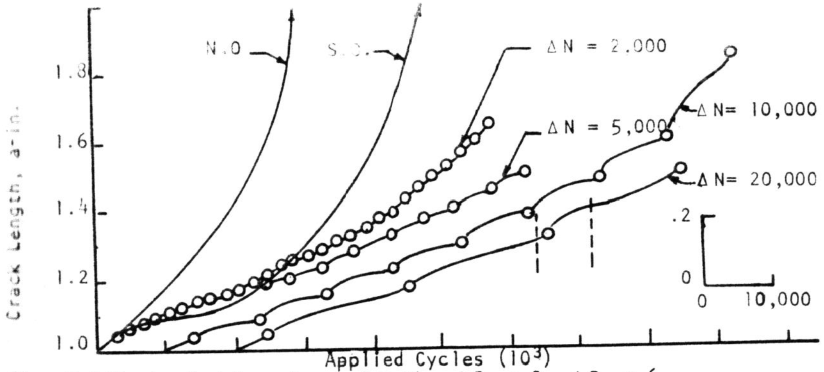

Fig. 3 Effect of ΔN on Crack Growth, $\Delta P_s = 3$, $\Delta P_o = 6$

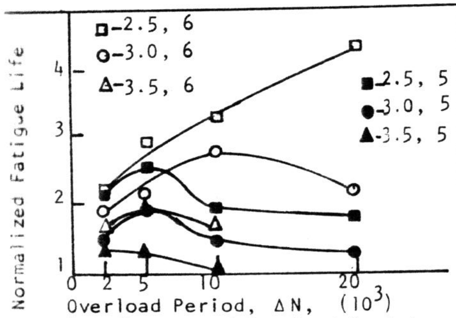

Fig. 4 Influence of Overload Period

Fig. 5 Overload Crack Extension, 60X

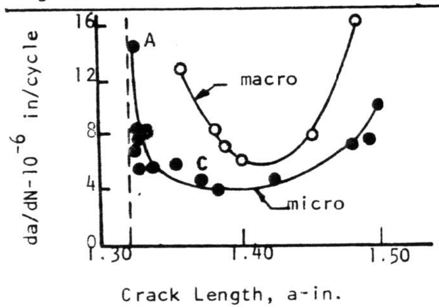

Fig. 6 Delayed Retardation

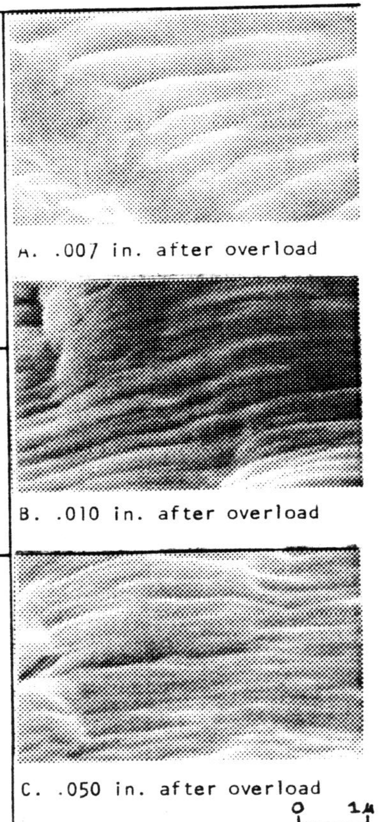

Fig. 7 Striation Spacing Following Overloading, 12,500X

V-325