Demarcation of Fatigue Crack Cumulative Damage (Initiation + stage I) of Aluminum Alloy under Combined Loading

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Abstract: Fatigue crack initiation behaviors of casting aluminum alloys are viewed mainly on the basis of experimental results. Fatigue strength and crack initiation of the representative AA320 (UNS#03200) are also summarized with respect to surface temperature effects. Cumulative damage data is used to identify the two different regimes named as initiation and propagation. Load sequence effect is successfully applied to notify initiation phase life. Crack initiation at notch root and fatigue life is calculated under single step mechanical loading (ML) in phase I experiments and multistep ML and combined thermal cycling (CTC) is applied respectively in phase II & III experiments. From a comprehensive experimental details of each phase, the S-N curves are plotted and a comparison is made between crack lips segregation (initiation + stage I propagation) & propagation leading to failure under different ML with & without thermal loading (TL).

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1. Introduction:

Aluminum is the tested material in the present work for its vast used in different industries. It is an emerging material used in aerospace and other advanced scientific fields due to its useful properties. The use of cast aluminum alloys in automotive structural applications is growing rapidly because of the need to reduce weight.[1]

Possibly the most important and not clearly solved problem in the area of fatigue is the accumulation of the damage produced during each cycle of fatigue and its mathematical relationship with failure criteria. At one end it is tried to add up damage components resulting from random loadings and on the other side it is required to evaluate how damage adds up while the loading is constant. The Palmgren [2] and Miner's equation [3] explains only linear damage accumulation with a low summation factor and yield S-N curve. Langer [4], Grover [5], Manson [6] modify the Palmgren-Miner methodology by changing the load sequence from high to low rather than from low to high to made the summation factor greater than unity, however they gained unsafe results with conventional load sequence. They also summarized that damage accumulation is different at different stages of fatigue crack. Bui Quoc Thang et al. [7][8] give a theory when loading levels are far away, Corton and Dolan [9] states about the stress interaction factors but unsafe results prediction is not eliminated by any theory. Resultantly it is said that Palmgren-Miner approach is still a rule with some limitations in damage accumulation most likely for high temperature situations.

Fatigue failure is initiation and propagation of a crack up to a critical stage. The propagation stage is divided into two sub regimes named as stage I and stage II based upon the varying growth styles, along a plane of shear strain and perpendicular to the direction of maximum tensile strain respectively, which makes the damage accumulation different in different zones. The rupture of the material is started due to tensile stress at macro or microscopic flaw [10]. Once rupture started, the edge behave as stress concentrated area and assist in crack propagation until the reduced section bear no imposed load anymore[11]. In engineering applications most structures and components contain notches, holes or some other stress raisers. They often experience cyclic loading, and therefore crack initiation and propagation start [12]. Designers cannot avoid the existence of notches in engineering components. A notch is simply a geometrical discontinuity possibly introduced accidentally or deliberately [13]. Stress concentration is the result of the presence of such notches. It has also been noted repeatedly that heating exists in working environment of engineering materials e.g. when shafts are used in industries etc. these work under mechanical as well as thermal loading [14]. Therefore, a sound knowledge of fatigue behavior of notched specimens under mechanical and thermal loading is necessary while designing [13]. In this paper specimens were subjected to combined thermal cycling (CTC) and mechanical loading (ML), and its effect has been seen on crack propagation behavior. This research also reveals the varying ML during experimentation, the ML is shifted from low to high; if reciprocal sequence is performed then the strain hardening disturbs the results. The TL during the step ML has an accelerating effect on crack initiation and resultantly shrinking the total fatigue life of the specimens. The temperature cycling was made between 170˚C and 570 ˚C and at heating and cooling rates of 3 or 5 ˚C /min. Extraction of data for prediction of isothermal conditions was made using a temperature interval of 20 ˚C. It is clear that there is a relatively strong dependence of the temperature on the crack growth rate. In this research work the TL is provided by an electric rod of 1000W fixed exactly on the loaded work pieces and 2mm GI sheets are installed on both side of the rod to protect the bearings. A Multi-Meter having a built in temperature sensor is used to measure the temperature range. No work has been reported in the literature that attempts to ascertain the damage accumulation in terms of fatigue life prediction of first two stages with respect to total fatigue life under different types of stresses. This paper attempts to understand and quantify the accumulation of damage in the initiation and stage I propagation phase.

2. Experimental Work

The composition of casting alloy used for this research is expressed in Table 1.

Table 1. Chemical composition of alloy

Elt.	Al	Cu	Si	Fe	Mn	Mg
%	89.5	1.5	5.5	1.3	0.32	0.36
Elt.	Zn	Ni	Cr	Pb	Sn	Ti
%	1.28	0.056	0.064	0.080	0.02	0.05

The bars of aluminum are used for specimen preparation having dogbone shape. The dimensions of the specimens are confined to fatigue testing machine limitations. Lath is used to figure the specimen, centers are punched on both sides of pieces for proper circular rotation on machine, and appropriate coolant and tool speed is maintained to avoid the excessive residual stresses [15]. In Figure1 at the center of the dogbone a notch of 0.45 radius is made by using CNC. The fatigue testing machine of model PQ-6 shown in

Figure 2. having a motor power of 0.75 kW rotates the test specimen at 3000 r/min.

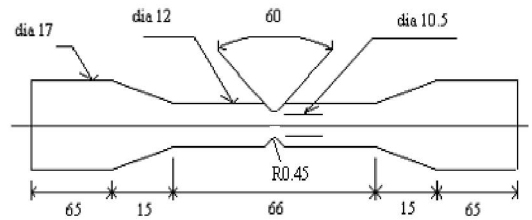

Figure 1 (Dogbone specimen)

Figure 2 (Rotary bending fatigue testing

The work pieces are installed in collets of machine having maximum internal temperature greater than 30^0 C in case of CTC. The bending load of ML is directly applied on the load bearing of the machine ranging from 160N to 250N sequenced with a difference of 10N. In phase I experiments the load applied in the hanger remain constant during the crack initiation, propagation and failure of the specimen. Then thermal loading is applied in single step ML and results are taken. The temperature of upper notch root is measured 90-100 ˚C while the lower notch root is at 60-70 ˚C. The cross sectional temperature after the failure of specimens is measured nearly 55-60 ˚C. In phase II experiments the load applied on specimen is changed before the failure and increased it and view the results of crack initiation at low load and its propagation at high load. Low load level is started from 160N and increasing with a difference of 10 N in successive experiments but the high load level of 220N is kept constant in all multistep loading experiments. In phase III the set up keep same as in phase II additionally applying the TL. The notch root temperatures remain constants in all phases.

3. Results & Discussion

The experiments are conducted to investigate crack initiation phase in fatigue life of aluminum alloy under fully reversed stress at constant amplitude loading. The load applied on specimens is converted into stresses by using Eq.1 and resultantly multiplied by Kt to attain alternating stresses used while plotting S-N curves.

$$\sigma = 509.3\frac{Q}{d^3} \tag{1}$$

As all tested specimens are notched, stress concentration factor Kt has to be applied to calculate stress at the notch root.[16] According to specimens dimensions Kt is taken 2.45. In phase I experiments during the CTC & ML the number of cycles that a specimen can endure before the crack starts are drastically decreases than the case of only ML supports the fact of early crack lips segregation in CTC assistance along with ML resulting a short fatigue life depicting from S-N curve shown in Figure3.[17]

It is observed that deflection and the bending moment of the material under this research is not effected appreciably while applying the CTC. It remains nearly same as in ML as shown in table 2.

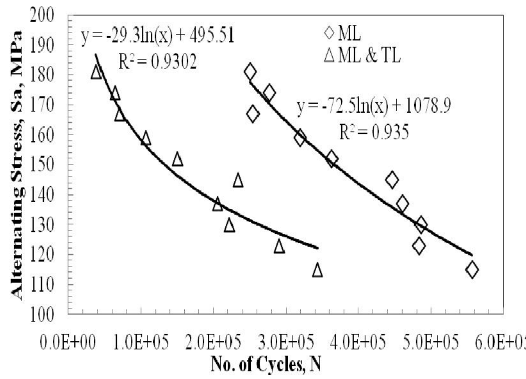

Figure3 (S-N Curves of constant amplitude)

Table 2 (Deflection & bending moment during all phases)

Load [N]	Moment [Nmm]	Deflection [mm]	Load [N]	Moment [Nmm]	Deflection [mm]
160	8000	0.1312	210	10500	0.1722
170	8500	0.1394	220	11000	0.1804
180	9000	0.1476	230	11500	0.1886
190	9500	0.1558	240	12000	0.1968
200	10000	0.1641	250	12500	0.2051

Nomenclature
N_i = Cycles to initiate a fatigue crack
N_p= Cycles for crack to propagate to final fracture
S_2 = Low Load
S_1 = High Load
N_{f2}= Total life at low load
N_{f1}= Total life at high load
N_2 = Number of cycles for S2 in two step loading
N_1 = Number of cycles for S1 in two step loading

In phase II & III the constant amplitude loading conditions are no more as in phase I and there is an effort to make a distinction between initiation phase and propagation phase of total fatigue life because once fatigue crack has been initiated successfully; it is very difficult to stop the growth of crack. As low load is applied for more than half of total fatigue life, Crack in specimen was in propagation when load was changed from low to high. The number of cycles to the end of initiation phase can be determined by analysis of experimentation in which the fraction of the lifetime remaining at the termination of initial low level stress cycles compared with the cycle fraction that remains at high level. The cumulative damage data obtained under mechanical and combined (mechanical + thermal) loadings is illustrated in table 3 and table 4 respectively.

Table.3 (Cumulative damage data for mechanical loading)

Ex. #	S1 [N]	S2 [N]	N1 [rpm]	N2 [rpm]	Nf1 [rpm]	Nf2 [rpm]	Ni2 [rpm]
1	160	220	109468	210596	107103	343593	213469
2	170	220	110856	165239	107103	290225	169470
3	180	220	84635	137194	107103	221784	114738
4	190	220	92657	115842	107103	205241	101904
5	200	220	75948	141895	107103	233727	104224
6	210	220	78916	82645	107103	150392	58447
7	220	250	28596	48562	37932	107103	29449

Table.4 (Cumulative damage data for combined (mechanical + thermal) loading)

Exp. #	S1 [N]	S2 [N]	N1 [rpm]	N2 [rpm]	Nf1 [rpm]	Nf2 [rpm]	Ni2 [rpm]
1	160	220	185632	495862	319938	556348	452100
2	170	220	265321	362856	319938	482965	338131
3	180	220	195321	395321	319938	485962	337491
4	200	220	215462	342652	319938	446592	292252
5	210	220	162532	285321	319938	363087	210008
6	220	250	185632	214632	250741	319938	177697

The crack is generated from the very first cycle at notch position of the specimen. The strain distribution in cracked specimens are described in terms of slip bands, more applied stress more bands are created and resultantly failure of specimen takes place at some drastic band. Once the crack generated then all other defects are considered to be stopped because all strain is functioning at the crack tip plastic zone. In the case of low stress the numbers of slip bands are reduced due to which the crack length at the termination of the initiation phase is also minimized with respect to higher stress. Such a variable crack behavior in two different regimes, initiation and propagation, is need to measure quantitatively for a safe design of a metallic structure under a cyclic load. As to avoid from strain hardening, initially low stress is applied and the number of cycle up to altering the stress level is 90% of the total cycles required for the failure of specimens as shown in fig. 4 where the vertical axis shows the situation of the crack while horizontal shows the number of cycles. The crack length produced in these 90% cycles of low stress level is equalized by only a few cycles of high stress cycle due to slip bands concentrations [18]. If the applying sequence of stresses level is altered then the whole initiation phase terminates in the same high level along with the starting of the next phase, shooting the aim of cumulative damage accumulation.

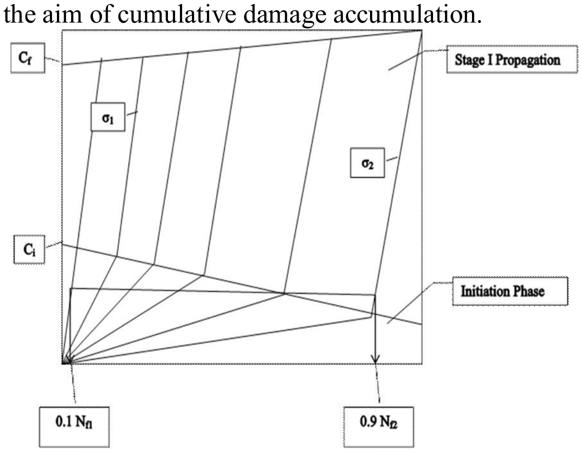

Figure 4. Schematic of initiation & stage I propagation phase

As it shown in fig 4 the life of initiation phase is negligible so the number of cycles required to end up the initiation phase is obtained from experimental results in which the fraction of life remaining after the stress altering point "(1-*x*) N_{f2}" is compared with cycles that remains at high stress level "yN_{f1}" .So the life of propagation at low stress level is compared with "1-*y*". If the value of 'x' is such that the initiation period at higher load is increased [18] then it is concluded as;

$$xN_{f2} = N_{i2} + zN_{p2}\,, \tag{2}$$

$$x = \frac{N_2}{N_{f2}}\,, \tag{3}$$

$$y = \frac{N_1}{N_{f2}}\,, \tag{4}$$

$$yN_{f1} = yN_{p1}, \text{as } N_{i1} = 0\,, \tag{5}$$

$$z = 1 - y\,, \tag{6}$$

It is observed that the crack speed has been increased in higher load conditions and the crack length at the termination of initiation phase and stage I propagation is much smaller than the final crack length.

Hence,

$$xN_{f2} = N_{i2} + (1 - y)(N_{f2} - N_{i2}), \quad (7)$$

Or

$$N_{i2} = \frac{N_{f2}(x+y-1)}{y}, \quad (8)$$

And the initiation phase life of the total life of all crack phases up to fracture [18]

$$\%\ \text{of total life} = \frac{N_{i2}}{N_{f2}} \times 100, \quad (9)$$

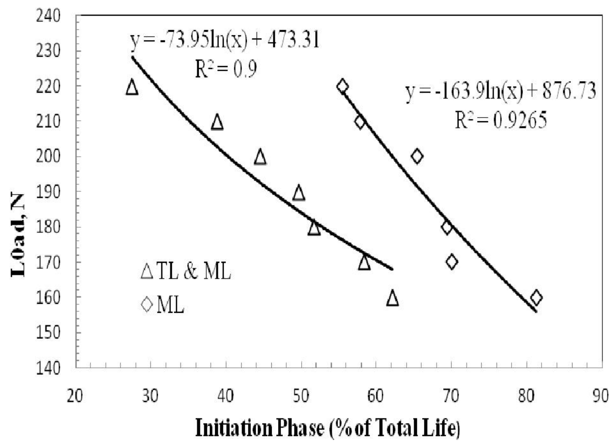

Figure 5 (Crack initiation life in varying amplitude loading)

The crack initiation and stage I propagation life is reduces during the CTC & ML with respect to ML as illustrated in Figure 5. In this paper to view how the combined loading is more catastrophic, the least square line fitting theory is used because it is problematic to apply other schemes to visualize the shifting behavior of trend lines under combined loading.

$$y = \alpha x + b, \quad (10)$$

for min. least square errors,

$$\pi = \sum_{i=1}^{n} (y_i - (a + bx_i))^2 = \min, \quad (11)$$

For coefficient α & b the least square value should be zero

$$\frac{d\pi}{d\alpha} = 2\sum_{i=1}^{n} (y_i - (a + bx_i)) = 0 \quad (12)$$

By expanding the Eq.12

$$\alpha = \frac{(\sum y)(\sum x^2) - (\sum x)(\sum xy)}{n\sum x^2 - (\sum x)^2} \quad (13)$$

Where the "α" is calculated for both the competitive curves in the same graph and their valves difference is obtained. The expression obtained in Eq.13 is calculated for both loading conditions then it is easily accessible to catch the percentage shifting of curve of CTC & ML with respect to the competitive one.

Conclusion

- It is concluded that for aluminum casting alloy AA320 the fatigue life is adversely affected by TL.
- A double exponential equation is created for damage accumulation during each phase named as initiation and stage I propagation.
- For these specific tests the initiation phase N_i life under mechanical loading is given by $\boldsymbol{10^3 N_i = 1.424 N_f^{1.424}}$ and under combined loading is $\boldsymbol{10^3 N_i = 1.413 N_f^{1.413}}$
- During the single step loading if the temperature of the specimen is enhanced from room temperature to 70 ˚C the total fatigue life of the specimen is reduced up to 17% with minimum errors.
- In the presence of TL along with multistep ML the crack initiation phase (initiation+ stage I) life shrinks 21% of total life of specimen.

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