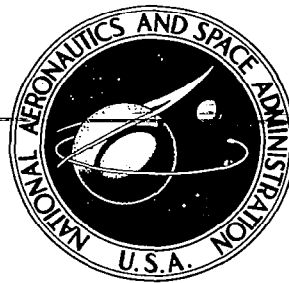


**NASA CONTRACTOR
REPORT**



NASA CR-2

0061690



TECH LIBRARY KAFB, NM

NASA CR-2840

**LOAN COPY: RETURN TO
AFWL TECHNICAL LIBRARY
KIRTLAND AFB, N. M.**

**ACOUSTIC EMISSION DURING UNLOADING
OF ELASTICALLY STRESSED MAGNESIUM ALLOY**

Samson S. Lee and James H. Williams, Jr.

Prepared by
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
Cambridge, Mass. 02139
for Lewis Research Center

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • JUNE 1977



0061690

1. Report No. NASA CR-2840		2. Government Accession No.		3. Recipient's Catalog No.	
4. Title and Subtitle ACOUSTIC EMISSION DURING UNLOADING OF ELASTICALLY STRESSED MAGNESIUM ALLOY				5. Report Date June 1977	
				6. Performing Organization Code	
7. Author(s) Samson S. Lee and James H. Williams, Jr.				8. Performing Organization Report No. None	
9. Performing Organization Name and Address Massachusetts Institute of Technology Cambridge, Massachusetts 02139				10. Work Unit No.	
				11. Contract or Grant No. NSG-3064	
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546				13. Type of Report and Period Covered Contractor Report	
				14. Sponsoring Agency Code	
15. Supplementary Notes Final report. Project Manager, Alex Vary, Materials and Structures Division, NASA Lewis Research Center, Cleveland, Ohio 44135					
16. Abstract A magnesium alloy was quasi-statically cycled elastically between zero load and tension. Both loading and unloading stress delays were found, and the unloading stress delay was further studied. An analytical expression was written for the unloading stress delay which is an elastic constitutive parameter. The potential use of these results for the acoustic emission monitoring of elastic stress states is discussed.					
17. Key Words (Suggested by Author(s)) Acoustic emission Nondestructive testing Quality control and reliability				18. Distribution Statement Unclassified - unlimited STAR Category 38	
19. Security Classif. (of this report) Unclassified		20. Security Classif. (of this page) Unclassified		21. No. of Pages 18	
				22. Price* A02	

SUMMARY

A magnesium alloy has been quasi-statically cycled elastically between zero load and tension. Both loading and unloading stress delays are found, and the unloading stress delay is further studied. An analytical expression is written for the unloading stress delay which is an elastic constitutive parameter. The potential use of these results for the acoustic emission monitoring of elastic stress states is discussed.

INTRODUCTION

Acoustic emission (AE) is the generation, propagation and detection of transient elastic strain waves in materials as they undergo deformation or fracture. During the past few years, AE has emerged as a testing method for materials research and as a monitoring technique for structural integrity assessment [1]. In 1973 we suggested that for some materials the AE behavior is characteristic of the elastic stress state of the material, and that by perturbing that stress state, the resulting AE could provide information about the stress state [2]. This paper represents one of the important requirements of that concept as we present data and analytical expressions of AE/elastic stress constitutive relations which could be used toward the goal of the AE monitoring of structures which are elastically loaded.

AE may be generated during both loading and unloading. AE during loading has received by far the greater research attention. Associated with loading AE is the so-called "Kaiser effect" which is the irreversibility of AE from a body that has been stressed in tension, such that any subsequent loading results in AE only if the previous maximum stress is exceeded [3]. The much less studied unloading AE was mentioned briefly by Schofield [4], and further investigated by Kerawalla [5], Mitchell [6], Agarwal [7], and Sankar [8]. Recently,

both loading and unloading AE from a magnesium alloy were studied by Williams and Emerson [9] during a program that was concerned exclusively with macroscopically elastic behavior. In that paper the existence of AE/elastic stress constitutive relations was confirmed. (Also, it was noted that magnesium does not observe the Kaiser effect). This paper represents an extension of that research and it provides an important step toward the elastic stress monitoring described in [2].

EQUIPMENT AND MATERIAL*

The loading apparatus consisted of a hydraulic tensile loading device which produced a prescribed loading pattern and which was controlled by an electronic feedback system. The AE monitoring equipment was produced by Acoustic Emission Technology Corp. A PZT sensor (AC175) having a resonant frequency of 175 kHz was used. The AE signal was band-pass filtered between 125 and 250 kHz. The total system gain was 100 db and a fixed threshold voltage of 0.6 V after amplification was maintained. The minimum detectable stress pulse for this system has been calculated to be about $1.9 \times 10^{-9} \text{ MN/m}^2$.

The specimen was made of AZ31B-F wrought magnesium alloy in a circular cylindrical form having a gage length of $7.62 \times 10^{-2} \text{ m}$ and a gage section diameter of $7.62 \times 10^{-3} \text{ m}$. The specimen was isolated from the loading grips with nylon pads and the sensor which was located at one end face of the specimen was held in contact by a force of 22N which was exerted by a coil spring. A viscous acoustic couplant (AET SC-6) was used at the sensor-specimen interface. The specimen which was heat treated at 260°C for $1.2 \times 10^3 \text{ sec}$ and air cooled, had a 0.2% offset tensile yield strength of 184 MN/m^2 .

* Reference [9] contains more details of the equipment and material. Thorough descriptions of the testing apparatus, including system parameters and calibration details, and the test material are given in [10].

EXPERIMENTAL RESULTS

The loading pattern consisted of loading the specimen at a rate of $186 \text{ MN/m}^2/\text{sec}$ ($\dot{\sigma}_L$), holding it at the prescribed upper stress level for 20 sec, and then unloading it completely at a rate of $476 \text{ MN/m}^2/\text{sec}$ ($\dot{\sigma}_U$). This loading-unloading cycle was repeated to a total of 10 cycles with a 30 sec interval at zero stress between each cycle.

A generic cumulative AE count result obtained during a loading-unloading cycle is shown in Fig. 1. Both loading AE and unloading AE are denoted. Note that for both loading and unloading a certain amount of change of stress is required before AE is observed. These stress increments are defined as loading stress delay (σ_{DL}) and unloading stress delay (σ_{DU}) [5,9]. Because metals are generally thought to behave elastically during unloading, it is this aspect of AE which we find particularly intriguing and which we shall examine here.

Fig. 2 is a typical plot of the cumulative unloading AE and the unloading stress delay for each of the 10 loading cycles. It can be observed that the cumulative unloading AE varies considerably while the unloading stress delay is relatively constant. Thus, the stress delay appears to be a cycle-independent parameter, so it is chosen for emphasis in this presentation*.

* Note that this statement does not imply that the cumulative unloading AE can not (or should not) be considered as a material constitutive parameter. Also, as shown in [9], the cumulative unloading AE approaches a constant value at a greater number (~30) of cycles.

Fig. 3 gives the unloading stress delay results for a range of elastic loading-unloading sequences. The specimen was loaded to the stress corresponding to point a_1 for 10 cycles and the average unloading stress delay was recorded. The upper stress level was increased corresponding to point a_2 and the average unloading stress delay corresponding to a_2 was observed. The upper stress level was increased again, and subsequently the data represented by the solid circles were generated and the straight line A was fitted. The specimen was then left completely unloaded for 24 hr. Then, the specimen was loaded to point b_1 and the average unloading stress delay for 10 cycles was recorded. The upper stress level was decreased to b_2 and the average unloading stress delay for 10 cycles was recorded. The upper stress level was decreased again, and subsequently the data represented by the crosses were generated and the straight line B was fitted. The specimen was then left completely unloaded for 24 hr. Then, the specimen was loaded to point c_1 and the average unloading stress delay was recorded. The upper stress level was decreased to c_2 , and the data represented by the triangles were generated and the straight line C was fitted. The specimen was left completely unloaded for 24 hr. The specimen was then loaded to point d_1 and the corresponding data were obtained as in the cases of lines B and C.

In fitting straight lines to the data in Fig. 3, the method of least squares was used. The resulting expressions for the unloading stress delay are given in Table 1.

TABLE 1

EXPRESSIONS FOR THE UNLOADING STRESS DELAY GENERATED BY THE METHOD OF LEAST SQUARES (Units: MN/m ²)	
A-Data:	$\sigma_{DU} = 0.0321\sigma + 29.67$
B-Data:	$\sigma_{DU} = 0.1897\sigma + 6.90$
C-Data:	$\sigma_{DU} = 0.1894\sigma + 11.80$
D-Data:	$\sigma_{DU} = 0.2035\sigma + 17.02$

DISCUSSION

It is observed that in Fig. 3, points b_1 , c_1 and d_1 correspond very closely to points along line A. Also, lines B, C and D have nearly the same slope. The lines A, B, C and D were all determined in exactly the same manner with a single exception, namely the value of maximum stress in the "recent"* history prior to unloading which is defined as σ_{\max} . The values of σ_{\max} for curves B, C and D correspond to points b_1 , c_1 and d_1 , respectively. On the other hand, because of the increasing loading sequence, every point along line A represents a value of σ_{\max} .

In accordance with the observations in the previous paragraph, it is assumed that the unloading stress delay σ_{DU} is a function of the recent maximum stress which is defined as σ_{\max} . The lines A, B, C and D in Fig. 3 are reproduced schematically as solid lines in Fig. 4. Defining slopes S_1 and S_2 as indicated where lines B, C and D have the same slope S_1 , the solid lines A, B, C and D can be expressed as

$$\sigma_{DU} = S_1 \sigma + \sigma_{DU}^o - (S_1 - S_2) \sigma_{\max} \quad (1)$$

* For the purposes intended here, "recent" is defined as time periods which are much less than 10^5 sec. This definition of "recent" is a material parameter for the magnesium alloy used in these experiments.

where σ_{DU}° is the unloading stress delay intercept of line A and where σ is the upper stress level for any current unloading cycle. Note that for line A where σ_{\max} is equal to σ , equation (1) simplifies to

$$\sigma_{DU} = \sigma_{DU}^{\circ} + S_2 \sigma \quad (2)$$

The quantities S_1 , S_2 and σ_{DU}° are material parameters which also depend upon loading variables such as unloading rate and holding times at both σ and zero stress. Furthermore, these parameters as well as others discussed here may depend upon the AE monitoring system itself. Thus, as already indicated in [9] and [11] there is an important need for the development of standards for AE monitoring systems, testing procedures, and technical reporting.

Equation (1) can be represented graphically by introducing a hypothetical line E of slope S_1 which intersects the ordinate at σ_{DU}° as shown in Fig. 4*. In order to obtain the unloading stress delay at a stress level σ_1 , vertical lines through σ_1 and σ_2 are drawn where σ_2 is σ_{\max} which for convenience is assumed to be known. The value of σ_{DU} corresponding to e_1 represents the first two terms on the right-hand side of equation (1) and the value of σ_{DU} corresponding to e_2 represents the third term in equation (1). So, by subtracting e_2 from e_1 , the unloading stress delay may be obtained.

* Line E is hypothetical because it represents σ_{DU} for σ_{\max} equal to zero which, of course, is not meaningful in the context described here.

Assuming that the material in a given structure has been characterized with respect to the parameters S_1 , S_2 and σ_{DU}^o , equations (1) and (2) represent relations which will likely be useful for determining residual or statically loaded stresses where a proposed trigger/AE monitoring system would perturb the stress state and observe the resulting AE characteristics [2]. In the simplest case, the trigger may be used to produce an unloading of tensile stress and the corresponding unloading stress delay σ_{DU} could be measured. If σ_{max} were known, the tensile stress prior to unloading could be determined directly from equation (1). On the other hand, equation (1) may be used to find σ_{max} if σ is known. A test such as this could prove useful in cases where an accidental overload is suspected.

Finally, because the parameters S_1 , S_2 , σ_{DU}^o and thus σ_{DU} itself may depend upon the AE monitoring system, they are not material constitutive parameters in the strict sense. Until any contributions of both the loading apparatus and monitoring system are removed from the reported values, they should more appropriately be defined as "pseudo-constitutive" parameters. Thus, the proper AE characterization of materials for the purposes discussed here as well as many others must await the development of more versatile AE equipment and standards for AE testing and reporting.

CONCLUSIONS

A magnesium alloy has been loaded elastically in tension and then unloaded. It was found that a fixed amount of stress increment is required before AE activity is detected. This stress increment for increasing stress is called the loading stress delay and for decreasing stress, the unloading stress delay. As observed in [9], it is noted here also that magnesium does not observe the "Kaiser effect".

It has been shown that the unloading stress delay is an elastic constitutive parameter that is cycle-independent. The unloading stress delay depends on the upper stress level, any higher stress level undergone in the recent history of the material, and the loading pattern. It has been discovered that for a fixed loading pattern, a relatively simple analytical expression can be fitted to the unloading stress delay data.

A discussion of the applicability of these results including the analytical expression for the purpose of stress level evaluations has been given. Thus, with a trigger that can generate a stress increment slightly greater than the stress delay and with adequate AE monitoring equipment, residual stress, static operating stress levels, and recent stress overloads can be determined.

A magnesium alloy has been used for these experiments because (1) compared with other metals magnesium generates a large amount

of AE activity and (2) magnesium is predicted to become one of the major structural materials of the future [12]. Because unloading AE has been observed from other metals also [4-8,10], the results reported here appear to be conceptually applicable to a range of materials.

REFERENCES

1. R.G. Liptai, D.O. Harris and C.A. Tatro, "An Introduction to Acoustic Emission", Acoustic Emission, ASTM STP 505, American Society for Testing and Materials, 1972, pp. 3-10.
2. J.H. Williams, Jr., and S.S. Lee, "Monitoring of Elastic Stresses by Acoustic Emission", International Journal of Nondestructive Testing, 1977.
3. J. Kaiser, "Untersuchungen uber das Auftreten von Gerauschen beim Zugversuch", Dr.-Ing. Thesis, Technische Hochschule, Munich, 1950.
4. B.H. Schofield, "Acoustic Emission Under Applied Stress", Technical Documentary Report No. ASD-TDR-63-509, Part II, Wright Patterson Air Force Base, May 1964.
5. J.N. Kerawalla, "An Investigation of the Acoustic Emission from Commercial Ferrous Materials Subjected to Cyclic Tensile Loading", Ph.D. Thesis, University of Michigan, 1965.
6. L.D. Mitchell, "An Investigation of the Correlation of the Acoustic Emission Phenomenon with the Scatter in Fatigue Data", Ph.D. Thesis, University of Michigan, 1965.
7. A.B.L. Agarwal, "An Investigation of the Behavior of the Acoustic Emission from Metals and a Proposed Mechanism for its Generation", Ph.D. Thesis, University of Michigan, 1968.
8. N.G. Sankar, "Unload Emission Behavior of Materials and its Relation to the Bauschinger Effect", Ph.D. Thesis, University of Michigan, 1969.
9. J.H. Williams, Jr., and G.P. Emerson, "Constitutive Acoustic-Emission Elastic-Stress Behavior of Magnesium Alloy", NASA CR-2839, 1977.
10. G.P. Emerson and J.H. Williams, Jr., "Acoustic Emission from Elastically Stressed Metals", Composite Materials and Nondestructive Evaluation Laboratory, Department of Mechanical Engineering, Massachusetts Institute of Technology, August 1976.
11. J.H. Williams, Jr. and S.S. Lee, "Acoustic Emission Monitoring of Fiber Composite Materials and Structures", Composite Materials and Nondestructive Evaluation Laboratory, Department of Mechanical Engineering, Massachusetts Institute of Technology, January 1977.
12. "Trends in Usage of Magnesium", National Materials Advisory Board (NAS-NAE), NTIS No PB-254 189.

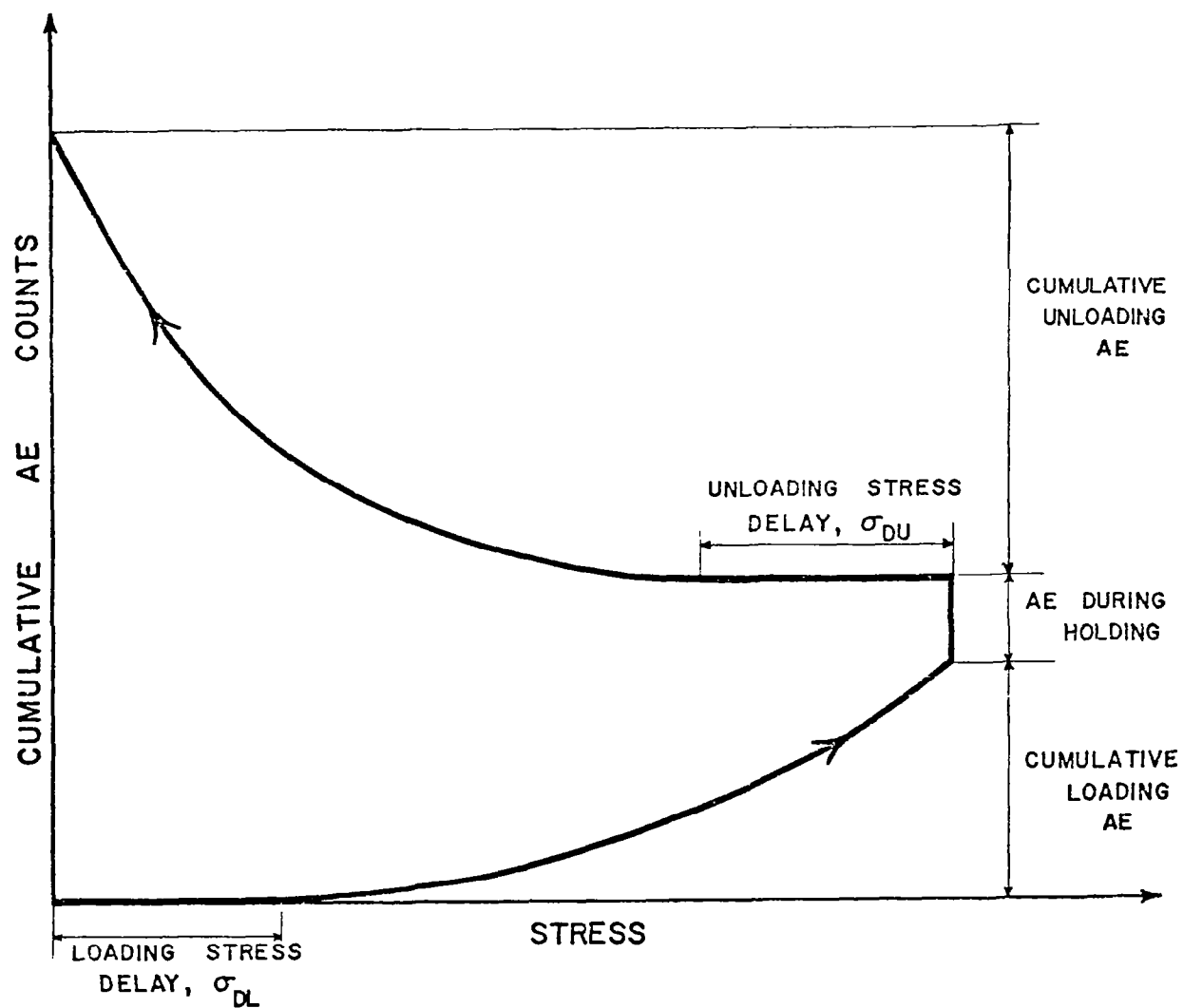


Fig. 1 Generic cumulative AE counts for a loading-unloading cycle.

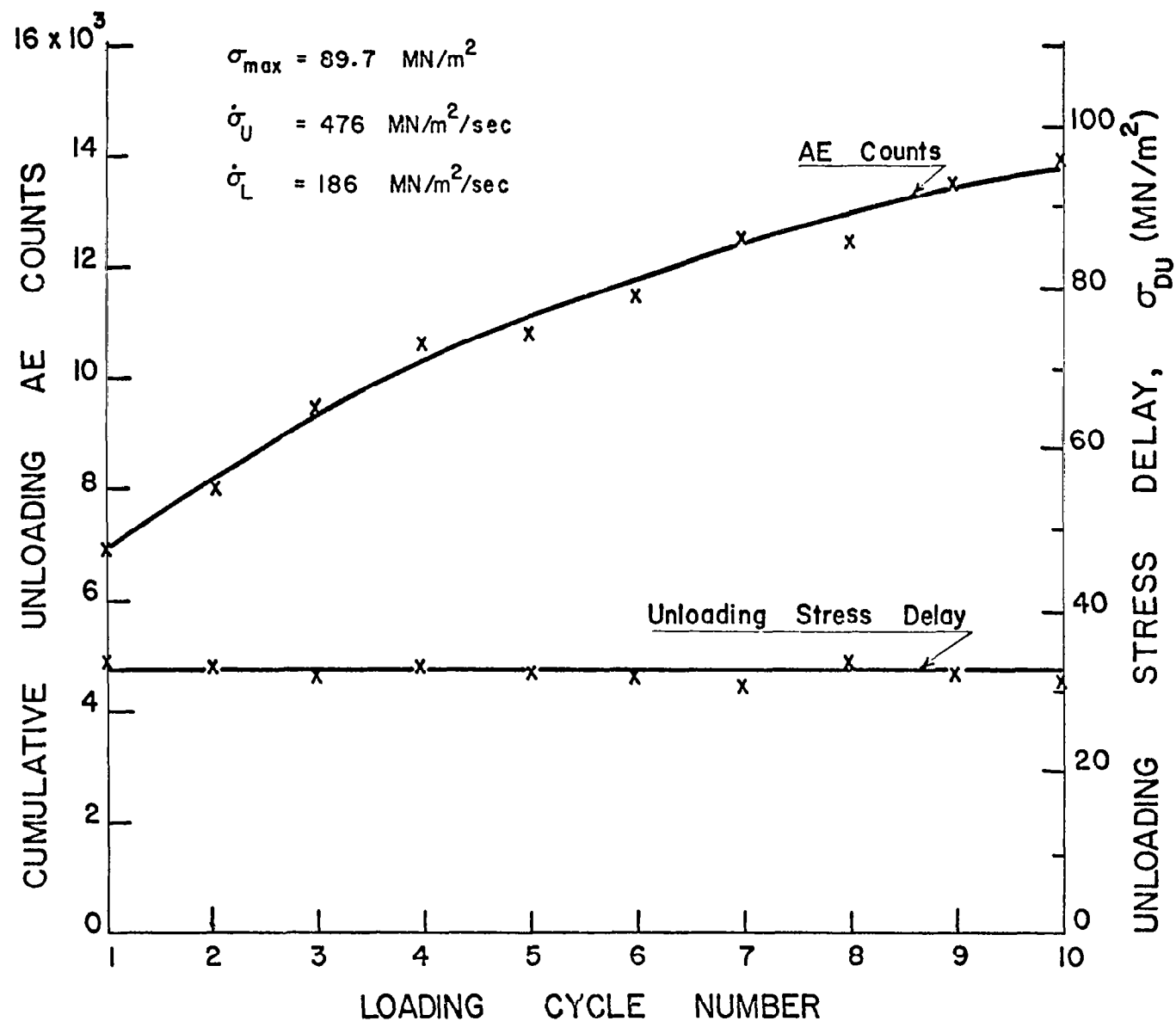


Fig. 2 Cumulative AE counts and unloading stress delay as a function of sequential loading cycles.

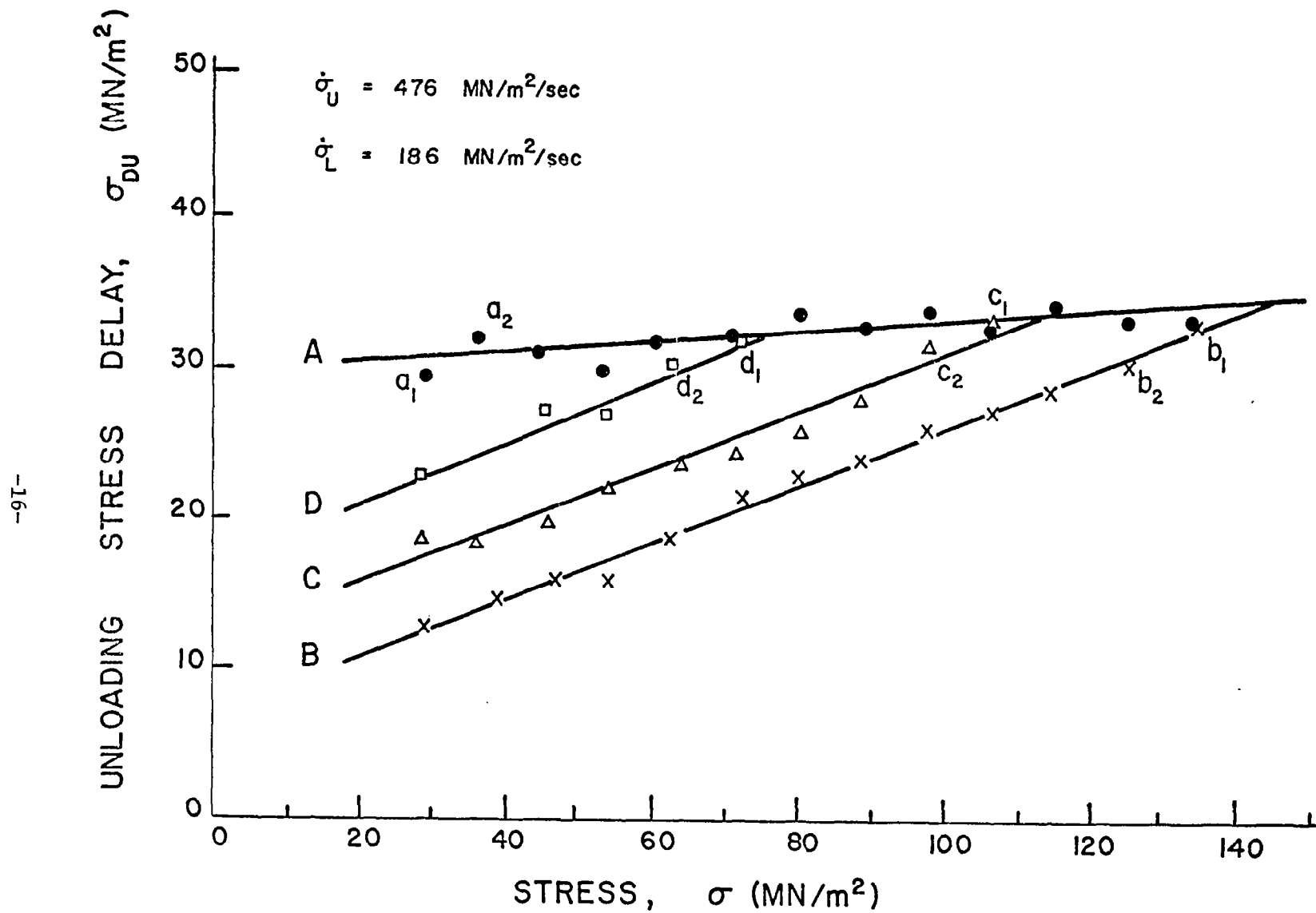


Fig. 3 Average unloading stress delay for increasing upper stress levels (Curve A) and decreasing upper stress levels (Curves B, C and D).

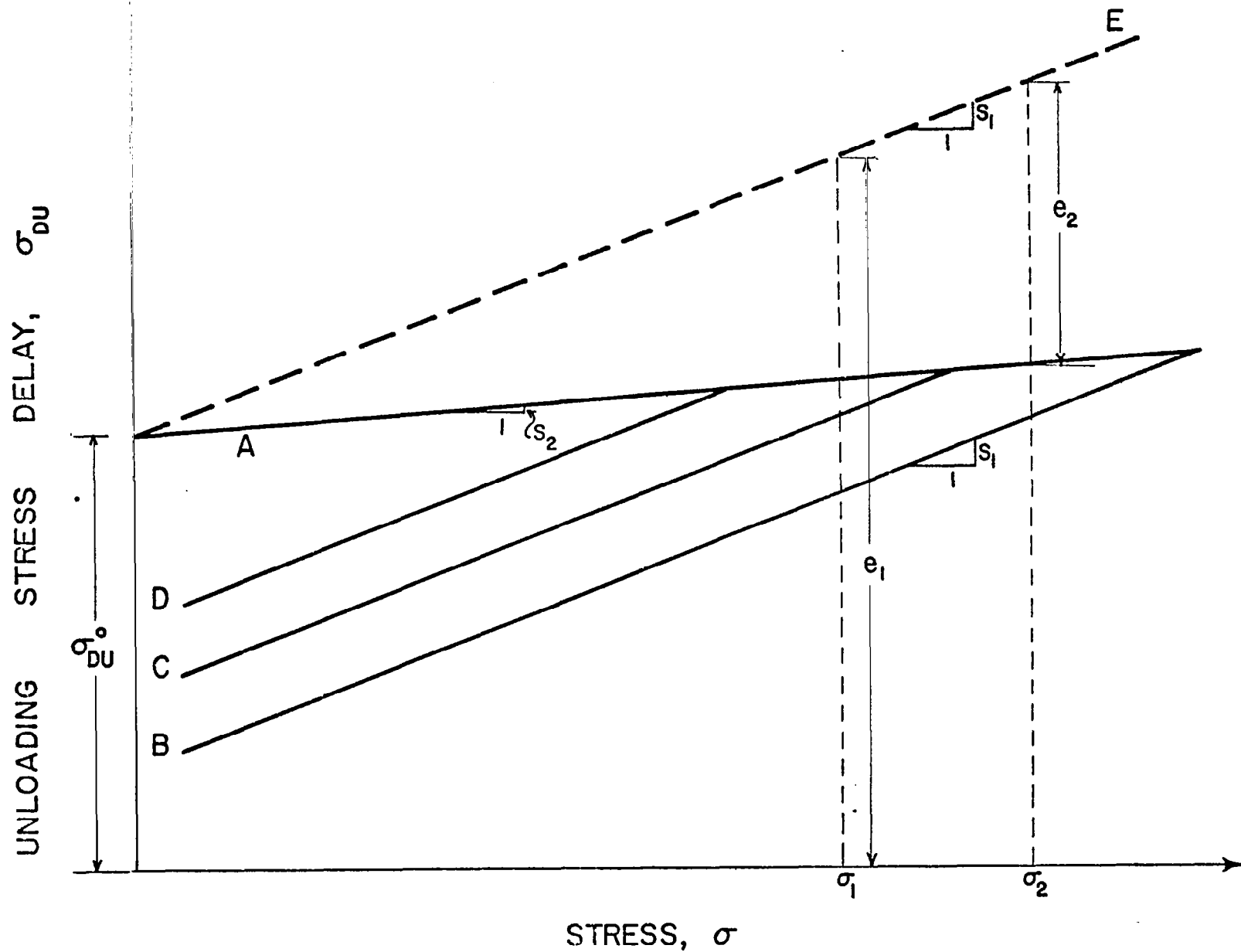


Fig. 4 Schematic illustrating parameters relating unloading stress delay and stress levels.