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AN INVESTIGATION OF THE COAXING EFFECT IN FATIGUE OF METALS

By G. M. Sinclair[1]

Synopsis

The fatigue resistance of some metals may be improved by understressing followed by a process of gradually increasing the amplitude of the alternating stress in small increments, a procedure ordinarily called "coaxing." In the present paper a study is made of the effect of various coaxing procedures on the fatigue resistance of ingot iron, SAE 1045 and 2340 steels, 75S-T6 aluminum alloy and annealed 70-30 brass. The results of this study seem to indicate that the coaxing effect in fatigue is governed by a time-dependent localized strengthening through strain-aging and not by the ability of the metal to be strengthened by cold work.

It has been known for a number of years that the fatigue limit of many common engineering metals is not a fixed quantity but may be considerably affected by the previous cyclic stress history. One of the more interesting discoveries in this respect was the fact that the fatigue limit of some metals could be increased by more than 25 per cent by suitable understressing.[2] A still greater increase in the fatigue limit of the same metals was obtained when the understressing was followed by a "coaxing" process; that is, the fatigue limit was said to be "coaxed" to higher values by a procedure of gradually increasing the applied load in small increments and allowing a relatively large number of cycles of stress to occur after each new increase in load. Very great increases in finite fatigue life have also been obtained, Kommers (**1**)[3], for example, reported an increase in life of 23,000 per cent for ingot iron which was subjected to understressing plus coaxing.

The process of failure by fatigue seems to be initiated by crystal slip (**2**) in the metal. Those factors which tend to prevent or to inhibit slip might therefore be expected to increase fatigue strength. In the past the increase in fatigue strength which sometimes resulted from understressing plus coaxing has been attributed to a beneficial "cold-working" of the metal at the initially small stress amplitudes. There is some evidence that this supposition is incorrect and that local strain-aging of the metal rather than cold-working is probably responsible for the "coaxing" phenomenon. A careful survey of the literature on understressing disclosed that the metals which exhibited an increase in fatigue strength too great to be attributable to chance, were invariably ferrous metals (**1, 3, 4, 5, 6**).

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[2] Repeated stressing at or below the fatigue limit of the virgin metal.

[3] The boldface numbers in parentheses refer to the list of references appended to this paper, see p. 9.

Further studies of the effect of rest periods on finite fatigue life indicate that long periods of rest at room temperature or shorter periods of rest at mildly elevated temperatures (200 to 400 F) will greatly extend the fatigue life of some annealed steels but have no beneficial effect on hardened steel or non-ferrous metals (**7, 8, 9, 10**).

TABLE I.—CHEMICAL COMPOSITION AND CONDITION OF MATERIALS AS RECEIVED.

Material	Composition, per cent	Condition as received
Ingot iron.........	C 0.012, Mn 0.017, P 0.005, S 0.025, Fe remainder	⅝ in. diameter rod, hot-rolled
SAE 1045 steel....	C 0.44, Mn 0.75, P 0.014, S 0.021, Si 0.21, Fe remainder	⅞ in. diameter rod, hot-rolled
SAE 2340 steel....	C 0.40, Mn 0.74, P 0.019, S 0.020, Si 0.28, Ni 3.48, Fe remainder	⅞ in. diameter rod, hot-rolled
75S-T6 aluminum..	Zn 5.6, Mg 2.5, Cu 1.6, Cr 0.3, Al remainder	⅞ in. diameter extruded rod, solution heat treated and artificially aged
70-30 Brass........	Zn 30.21, Pb 0.07, Fe 0.01, Cu remainder	¾ in. diameter rod, 20 per cent cold-drawn

TABLE II.—HEAT TREATMENT AND MACHINING OF SPECIMENS.

Material	Heat Treatment, deg Fahr	Machining
Ingot iron (A Specimen)................	1400—1 hr	Machined after heat treatment
Ingot iron (B Specimen)................	1400—1 hr, water quenched	Machined before heat treatment
SAE 1045 steel........	1500—1 hr, Normalized	Machined before heat treatment
SAE 2340 steel........	1500—1 hr, Oil quenched tempered 900 —1 hr	Machined before heat treatment
75S-T6 aluminum......	As received	Machined as received
70-30 brass............	Annealed 900 F—4 hr	Machined before heat treatment

These facts suggested that the mechanism by which the fatigue strength of some metals may be coaxed to greater values is related to strengthening of the localized areas which yield under the initial cycles of stress, by a strain-aging process which occurs during subsequent cycles of stressing. Accordingly, one might expect that only those metals having a matrix susceptible to strain-aging will exhibit the coaxing effect.

Object and Scope

In order to test this hypothesis, five common engineering metals were selected and subjected to coaxing type fatigue tests. The first three—ingot iron, SAE 1045, and SAE 2340 steels—had a matrix of ferrite which was susceptible to strain-aging. The other materials were an annealed 70-30 brass which was capable of being strengthened by cold working but not by strain-aging, and 75S-T6 aluminum alloy which had a smaller capacity for being strengthened by cold work and none for further aging. The chemical analysis and original form of these metals is given in Table I.

Rotating-beam fatigue specimens were machined to the dimensions shown in Fig. 1 and polished mechanically using successively finer grades of emery paper. The final polish was given with a 00 grade of emery and was done in such a manner as to leave the scratches parallel to the axis of the specimen. Details of the heat treatments and mechanical processing of the specimens are presented in Table II.

Method of Testing

The tests were conducted in R. R. Moore type rotating bending fatigue machines at a speed of approximately 1200 rpm. Nominal stresses at the minimum section of the specimen were computed by means of the ordinary flexure formula:

$$S = Mc/I,$$

where:

S = the stress at the outer fiber,

M = the bending moment applied, and

I/c = the section modulus at the critical section.

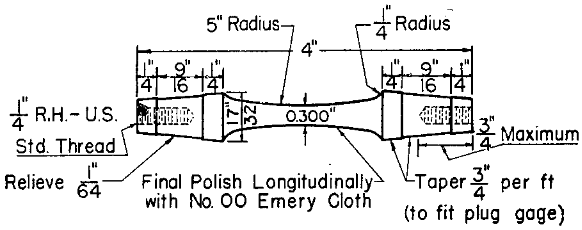


FIG. 1. Details of Fatigue Specimen.

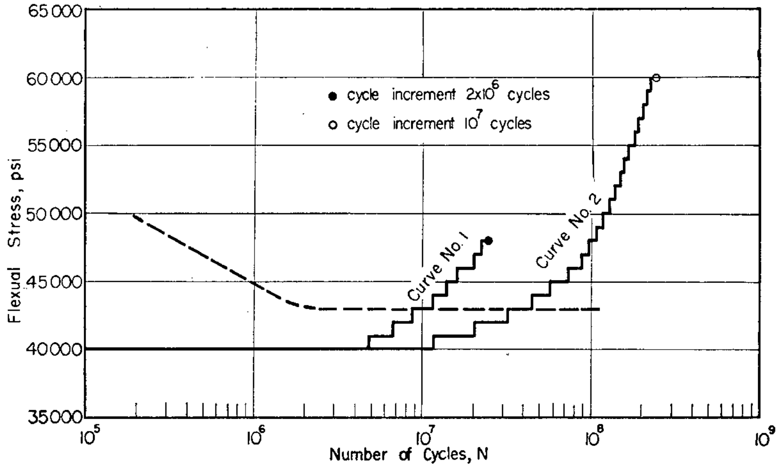


FIG. 2. Influence of Cycle Increment on Coaxing Failure Stress of SAE 1045 Steel.

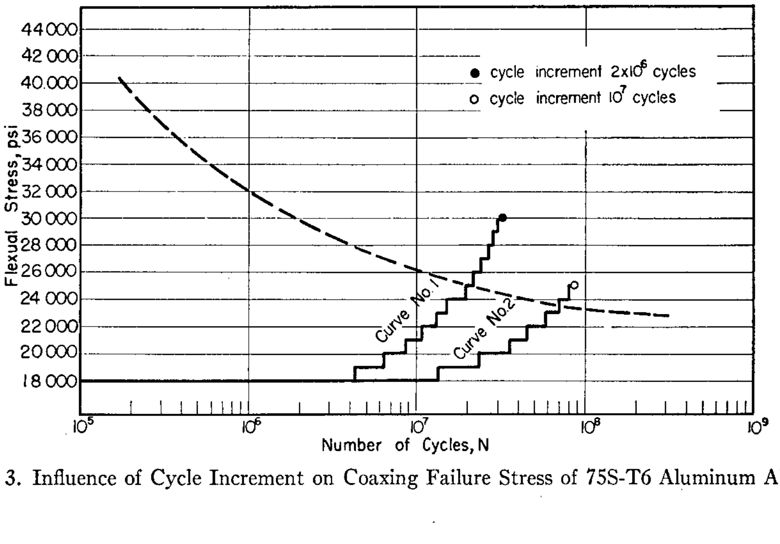


FIG. 3. Influence of Cycle Increment on Coaxing Failure Stress of 75S-T6 Aluminum Alloy.

The experimental procedure consisted first of determining an S-N curve for each material in the usual manner (11) and then of finding the stress at fracture which was obtained for various conditions of coaxing. The effect of coaxing on each metal was determined for the following conditions: (1) increasing the coaxing stress using uniform increments of 500, 1000, 2000, and 3000 psi, respectively (2) increasing the number of cycles applied at each new stress from approximately two million to ten million. All tests were conducted at room temperature.

RESULTS OF TESTS AND DISCUSSION

Figure 2 presents two typical examples of the effect of coaxing procedures on the fatigue behavior of SAE 1045 steel. This material exhibited a relatively strong coaxing effect. The ordinary S-N diagram which was obtained by testing specimens to failure at a single stress level is represented by the broken line. The load and cycle changes which were made during the coaxing procedure are indicated by the solid lines. The results of two variations in coaxing procedure were shown in this diagram to help illustrate three terms which will be used throughout the remainder of this report. The number of cycles which were applied at one stress level before the stress was raised to a higher value during the coaxing process will be referred to as the cycle increment. The uniform step-like increase in stress which was applied during coaxing will be referred to as the stress increment. The stress at which failure occurred after a number of these coaxing steps were applied was called the coaxing failure-stress or for brevity, simply the failure stress.

In Fig. 2 the stress increment which was used in obtaining the two coaxing curves amounted to 1000 psi. Curve No. 1 resulted when a cycle increment having a value of approximately two million was used while curve No. 2 was obtained when the cycle increment was

TABLE III.—SUMMARY OF TEST DATA GROUP I.

Material		Ingot Iron B, unaged		SAE 1045 Steel		SAE 2340 Steel		Ingot Iron A (Aged)		75S-T6 Aluminum Alloy		70-30 Brass	
STATIC TENSION PROPERTIES													
Ultimate strength, psi		47 400		97 300		155 300				78 000		53 200	
Yield strength, 0.2 per cent offset		28 500		59 800		147 500				69 600		21 000	
Elongation, per cent in 2 in.		31.0		27.8		19.2				14.7		54.0	
Reduction of area, per cent		69.4		47.5		60.2				32.3		75.7	
FATIGUE PROPERTIES													
Fatigue strength at 10^8 cycles		24 000		44 000		85 000		37 000		23 000		17 000	
Initial coaxing stress		20 000		40 000		70 000		30 000		18 000		12 000	
EFFECT OF COAXING PROCEDURE ON FAILURE STRESS[a]													
Cycle Increment		2×10^6	10^7	2×10^6	10^7	2×10^6	10^7	2×10^6	10^7	2×10^6	10^7	2×10^8	10^7
Stress increment, psi	500	32 500		53 500				41 000		27 000		21 000	
	1000	34 500[b]	40 000	48 000	60 000	98 000	97 000	41 000	40 000	30 000	25 000	23 000	19 410
	2000	28 000	38 000	46 000	54 000	95 000	97 000	42 000	40 000	30 000	26 000	22 000	20 000
	3000	26 000	35 000	46 000	49 000	93 000	96 000	42 000	42 000	33 000	27 000	24 000	21 000

[a] Values listed in the table are those of the coaxing failure stress.

[b] Initial coaxing stress 19,500 psi.

increased to approximately ten million. It should be noted here that the machines used in performing the coaxing tests required approximately one day to apply a cycle increment of two million and five days to apply a cycle increment of ten million. It may be observed in Fig. 2 that increasing the cycle increment has resulted in a higher coaxing failure-stress. This was observed to be generally true of the materials which had a matrix capable of being strengthened by strain-aging. That is, increasing the number of cycles applied at each stress level during the coaxing process resulted in an increase in the failure-stress.

The results obtained by applying these same coaxing procedures to specimens of 75S-T6 aluminum alloy are illustrated in Fig. 3. It may be seen that the reaction of this material to the coaxing procedure was quite different from that of the 1045 steel. Increasing the cycle increment for the aluminum specimens resulted in a reduction of the failure stress. This behavior was observed to be characteristic of the second group of materials which were examined; namely, those materials in which little or no strengthening due to strain-aging could be expected.

In the present paper an increase in the coaxing failure stress caused by increasing the cycle increment or by decreasing the stress increment has been interpreted as indicating that the fatigue resistance of the material may be improved by coaxing procedures.

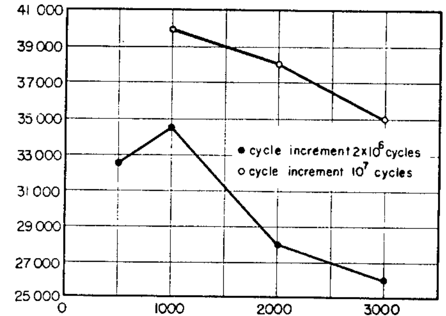
In Table III the results of the entire coaxing study have been tabulated. The first section of Table III lists the static tensile properties that were obtained from standard test specimens of each material. The second section of the table records data obtained from the ordinary fatigue tests and from the various coaxing procedures. The endurance limits or fatigue strengths obtained from the ordinary *S-N* diagrams of each material are listed as well as the stresses at which the coaxing experiments were begun. The various coaxing procedures utilized cycle increments of two million and ten million cycles and also four different values of stress increment as indicated. Values of the coaxing failure-stress that were obtained for different combinations of these stress and cycle increments are listed in the corresponding places in the table.

The coaxing failure stress for the combination of a 500 psi stress increment with a cycle increment of ten million was not determined since this would have required an extremely long time in testing. However basic differences in the response of the materials to coaxing were clearly shown by the testing procedures which required less time. For convenient reference, the materials listed in Table III have been separated into two groups. The first three metals listed are those which had their failure stress increased by the coaxing processes while the last three were apparently unaffected by coaxing.

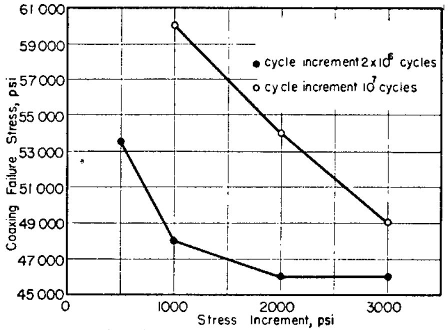
In order to simplify interpretation of the results given in Table III, the effect of the different stress and cycle increments on the failure stress for each material is shown graphically in Figs. 4(*a*, *b*, *c*, *d*, *e*, *f*). The ordinate in these figures represents the coaxing failure-stress of the metal and the abscissa indicates the stress increment used. Each point in the diagram represents the results obtained from a single test specimen. The specimens subjected to a cycle increment of two million are represented by the solid black dots while those which received a cycle increment of ten million are represented by the open circles.

Results obtained from tests of the metals susceptible to coaxing are presented in Figs. 4(*a*, *b*, and *c*). It may be seen that there were certain trends in the data which were characteristic of these three metals. For a given cycle increment, decreasing the stress increment has resulted in an increase in the coaxing failure stress. Increasing the cycle increment for a given value of stress increment has also resulted in an increase in the coaxing failure-stress.

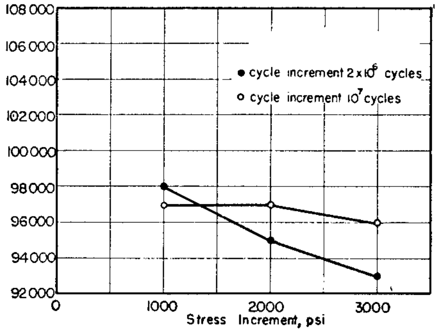
In Figs. 4(*d, e* and *f*), results are shown for materials which did not appear to have their fatigue resistance improved by the coaxing procedure. Here it is seen that changing the values of cycle and stress increments produced fundamentally different effects on the failure stress than was shown in the previous three figures. For these metals, increasing the cycle increment or decreasing the stress increment reduced the failure-stress. This indicated that the fatigue resistance of these materials was not improved by the coaxing procedures



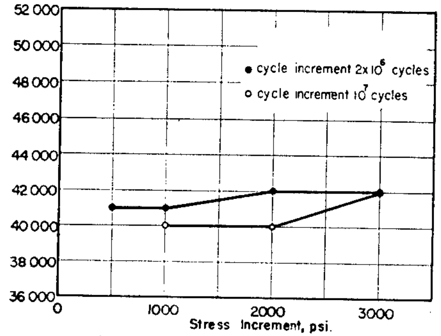
(a) Ingot Iron "B" Specimens



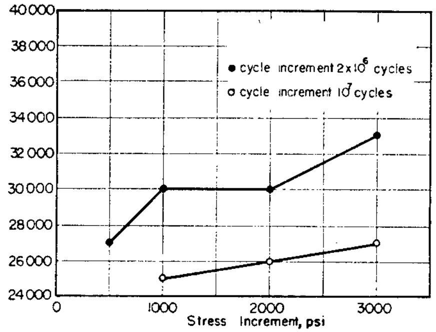
(b) SAE 1045 Steel



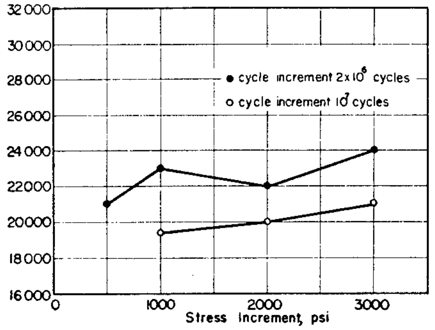
(c) SAE 2340 Steel



(d) Ingot Iron "A" Specimens



(e) 75S-T6 Aluminum Alloy



(f) 70-30 Brass

FIG. 4. Influence of Cycle Increment and Stress Increment on Coaxing Failure Stress.

used. Differences in the failure-stress obtained by changing the stress increment sometimes amounted to only a few thousand psi. In view of the known statistical variation in fatigue properties, there may then be some question as to the accuracy of these failure-stress values. It was felt, however, that the fact that data from all three of the metals in this latter group show the same general trend indicated that the results were not due to chance alone but represented a real material effect. The effects of changing the cycle increment are more clearly indicated than those of changing the stress increment. Increasing the cycle increment for the metals shown in Figs. 4(*d*, *e*, *f*), invariably resulted in a decrease in the failure-stress which was quite the opposite of the trend found in the metals of the first group (Figs. 4(*a*, *b*, *c*)).

One of the points which should be clarified at this time is that the ingot iron "A" and "B" specimens were prepared from the same heat of material. Data obtained from the "B" specimens (Fig. 4(*a*)) indicated that the fatigue resistance was definitely improved by the coaxing procedure while the resistance of the "A" specimens (Fig. 4(*d*)) was not improved. An explanation for this variation in behavior of the two groups seems to lie in the different sequence of the heat-treating and machining operations used in preparing the specimens. The "B" specimens were heat-treated subsequent to the machining and polishing operations. This sequence of preparation left the metal at the surface of the test section in an annealed condition which was capable of being strengthened by strain-aging. On the other hand, the ingot iron "A" specimens were machined and polished mechanically *after* the annealing heat-treatment. The machining process produced a layer of deformed metal on the test section which was then slightly heated by abrasive action during the process of mechanical polishing. This action and the considerable time interval which elapsed before testing resulted in a layer or "skin" of strain-aged metal on the surface of the test section. This surface had a relatively large effect on the fatigue date since the tests were conducted in rotating bending machines which subject only the outer fiber of the specimen to maximum stress. Therefore, in fatigue and coaxing tests, ingot iron "A" specimens may be considered as strained and aged *prior* to testing. Further evidence of this effect may be found in the fact that the ordinary fatigue limit of the B specimens was 24,000 psi while that of the A specimens was 37,000 psi.

INTERPRETATION OF TEST RESULTS

As mentioned previously, the mechanism by which fatigue damage is developed in a metal seems to be associated with slip. Studies of the formation of fatigue cracks by use of the optical or electron microscopes have disclosed that initiation of the crack is preceded by the formation of slip lines or by other indications of plastic deformation. Cracks form within localized zones which have suffered severe plastic deformation and on a microscopic scale have usually been observed to grow within and parallel to the slip lines in these areas. In general, it is believed that any process which will prevent or quickly inhibit the continuation of slip in the metal will also increase its fatigue strength. In attempting to account for the coaxing phenomenon, then, it is apparent that the process of understressing must somehow increase the elastic limit or resistance to slip of these localized weak spots in which fatigue damage begins. Work-hardening of the metal has been suggested as a possible explanation of the coaxing effect. This, however, is not easily accepted since the cracks are observed to form in the very regions which should be work-hardened most.

A more reasonable explanation of the coaxing effect appears to be the phenomenon of strain-aging which is found in many of the common ferrous metals. Strain-aging may be observed in mild steel for example, when it is first strained plastically in tension by some small amount and then allowed to rest or "age" at room temperature for several days. On retesting the metal in tension, it is found that the elastic limit of the metal has been increased to a value greater than that of the unstrained material. The increase in the elastic strength is considerably larger than that which may be accounted for by work-hardening alone; this is one of the characteristic results of the strain-aging effect. Increasing the elastic strength of the metal by strain-aging will also increase its fatigue strength as shown by the work of Körber and Hempel (12). A review of the literature has disclosed that those metals which had their fatigue life increased by rest periods or which exhibited a strong coaxing effect were ferrous metals which presumably could be strengthened by strain-aging in the local regions where fatigue damage initiates.

Results of the present study indicated that those metals which had a matrix of ferrite capable of further strain-aging had their fatigue resistance improved by a coaxing procedure. The metals which were work-hardenable but which had little or no capacity for strain-aging (or for further aging) showed no coaxing effect. The annealed 70-30 brass, for example, had an excellent capacity for being strengthened by work-hardening and yet did not have its fatigue resistance increased by coaxing.

In the present study, data obtained from the metals which had their fatigue resistance improved by coaxing indicated the following:

1. Increasing the cycle increment increased the coaxing failure-stress.
2. Decreasing the stress increment increased the coaxing failure-stress.

It is believed that these two results may be related through a common factor of *time*. Increasing the cycle increment or decreasing the value of the stress increment simply provided the material with more time during which a strain-aging process could continue and thus resulted in a greater improvement in the localized elastic strength of the metal.

According to the results obtained in the present investigation, the effect of the coaxing process on a metal susceptible to strain-aging might occur in somewhat the following manner. At the initially small cyclic stress amplitudes, slip occurs in only a few localized weak regions which happen to contain crystals favorably oriented for slip. Plastic deformation by slip slightly relieves the stress in these few areas, and the slip process does not continue since the initial stress was relatively small. The elastic strength of these deformed areas is then gradually increased by strain-aging (which occurs during subsequent cycles of stress) until these regions are finally more resistant to slip than the surrounding metal. When the load is increased slightly according to a coaxing procedure, yielding occurs in new areas which in turn are strengthened by strain-aging. This process of gradually improving fatigue resistance by strengthening the "weakest links" continues until finally a stress is reached at which slip is initiated in regions which no longer have the capacity for further strengthening by strain-aging and fatigue crack development then begins.

SUMMARY AND CONCLUSIONS

A study was made of the effect of coaxing procedures on the fatigue resistance of a number of metals which had various differences in their ability to be strengthened by strain-aging and in their capacities to work-harden. These metals were ingot iron (in both unstrained and strained and aged condition), SAE 1045 steel, SAE 2340 steel, 75S-T6 aluminum alloy and annealed 70-30 cartridge brass. The fatigue resistance of the unstrained ingot iron and the SAE 1045 and 2340 steels was considerably increased by coaxing while the fatigue resistance of strained and aged ingot iron, 75S-T6 aluminum alloy and 70-30 brass was not improved.

As a result of these studies, it was concluded that the coaxing effect in fatigue is due to a time-dependent localized strenthening of the metal by strain-aging which occurs during cyclic stressing at small stress amplitudes. From the standpoint of additional benefits in fatigue strength, the coaxing effect appears to furnish a very practical reason for gently "breaking in" new machinery providing that the components which are subjected to repeated stresses are formed of a metal which is capable of being strengthened by strain-aging.

Acknowledgment:

The research studies outlined in this report were conducted in the Department of Theoretical and Applied Mechanics, of which F. B. Seely is the Head, as a part of the work of the Engineering Experiment Station of the University of Illinois. The investigation was directed by T. J. Dolan and was sponsored by the Office of Naval Research, U. S. Navy under contract N6-ori-71, T.O. IV. The assistance of J. R. Owen, who prepared the figures, is gratefully acknowledged.

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