



Calhoun: The NPS Institutional Archive

DSpace Repository

Theses and Dissertations

1. Thesis and Dissertation Collection, all items

1954-05-24

An investigation of the early stages of fretting

Tighe, William F.

Massachusetts Institute of Technology

https://hdl.handle.net/10945/14320

Downloaded from NPS Archive: Calhoun



Calhoun is the Naval Postgraduate School's public access digital repository for research materials and institutional publications created by the NPS community. Calhoun is named for Professor of Mathematics Guy K. Calhoun, NPS's first appointed -- and published -- scholarly author.

> Dudley Knox Library / Naval Postgraduate School 411 Dyer Road / 1 University Circle Monterey, California USA 93943

http://www.nps.edu/library

AN INVESTIGATION OF THE EARLY STAGES OF FRETTING

William F. Tighe, Jr.









.



AN INVESTIGATION OF THE EARLY STAGES OF FRETTING

by

William F. Tighe, Jr., Lieutenant, U.S. Coast Guard B.S., U.S. Coast Guard Academy (1946)

8854	THE PA	RTIAL FULPILLMENT
on spine:		SMENTS FOR THE
	TIGHE	NAVAL ENGINEER
	1954	t the
	THESIS T475	'ITUTE OF TECHNOLOGY
Letter on front	cover:	1, 1954
AN INVESTIG, TICN	CT THE FARLY	

STAGES OF FRETTING

WILLIAM F. TIGHE, JR.



ABATRACT

Title: AN INV TH TION OF THE WARLY OTLOBS OF PETTING Author: William F. Tighe, Jr., Lieutenant, U.M., Gunst Guard

Submitted to the Separtment of Haval Architecture and Marine Engineering on May 22, 1954 in partial fulfillmant of the requirements for the degree of Neval Engineer.

The primary purpose of this investigation was to determine the shape of the initial portion of the curve of fretting weight less versus the number of cyclis run. Fervious work in the field has shown this curve to be concave downward over the initial portion. It has been proposed that the curve is actually concave upward over this pertion, due to the fact that the abrasive action is presumably more violent than the shearing action. The conditions under which the tests were conducted, were chosen such that it was autibus ted that the specimen weight less would be relatively lunge over a sheart interval of time. The tests of mild steel specimens from the quarter which the duration of test from 1 to 10,000 cycles.

The results of this investigation showed that the curve in question actually had a point of inflection in the portion under investigation. At the origin, the curve was concave downward followed by a turn to concave upward. This result not only substantiated the initial proposal but also added some additional information which was not anticipated.

It is recommended that these tests be repeated in dry air as well as other atmospheres to establish definite quantitative results. It is also recommended that the frequency of alternation be lowered to as small a value as possible in order to increase the specimum weight loss in a given interval of time.

The second purpose of the investigation was to establish a relationship between specimen weight loss and some physical measurement of fretting damage. To this end, the area of damage as well as its depth was measured and plotted against specimen weight loss.

The result of this series of investigations showed that any attempt to use the area of damage as a substitute for weight loss is impractical. It appears to be quite possible to use the depth of damage as a measure of fratting damage. The relationship obtained between specimen weight loss and the depth of frotting damage can be considered qualitative only due to a lack of fficient data. The depth of damage, however, definitely incr asso as the weight loss increases. It is recommended that additional tests be made to firmly establish the quantitative relationship between specimen weight loss and the depth of frotting damage.

> Thesis upervisor: I-Ming Feng, Ph.D. Title: seistant Professor of Mechanic 1 Incincering

> > 28850

Tables all measures of the same section of the sect

The princey program of hids freeeblantics two his interacter the starys of the halfs, previous of the output of (mithing unfills, lass versus his notice of symbol was, freetant work in thick has these this correct to be a second that the provide to initial portions. It is not bout proposed that the provide to initially brance operations, it is not bout to be the there has be within the total the the start of the second that the provide the test of the provide the second that the provide the test of the provide the second the base the test of the provide the second the second the test of the provide the test of the provide the second the test of the provide the test of the provide the second the test of the test of the provide the second test of the test of the test of the test of the provide test of the test of

This recruits of tints inequilation the science hinds his percent sales and the property of the first of the property of the property of the second line of the second of the second the property of the sales who the times be recruited to the property the second line fills are described by a binner be associate of the second line fills are also the fills the time of the second line and the second line to the the second line times are and an also the second line to the second the fills the second line to the second line and the second line to the second line to

"M is remnanted had hims basis he revealed in ity site is roll as alone discretings to redebilish sufficient and the reaction is is also recommind that his interact of discretized to here to ar reall a value by predicts is easier to be recent to be another reducts here is a given at mention is faire to be recent to be

The second requires of the Enverting-ther with the straight of the straight of the straight of the second s

The recently of this worker of hereotherited out that any shined is the true the uran of these is at a minimutule for working how at hereastime. It answers to be quite possible to no the deph of hereast ratio a summer of freetiles decays. The relationarity statement between recting endots here and the depht of detailing decays are between recting endots here and the depht of detailing decays are between recting and the rest of the second of the state of the first depth of hereast provide the second of the state of the first depth of hereast (the recence define the to a both of the first depth of hereast provide the second of the state of the first depth of hereast (the recence define the to be a both of the tables the second of the rest of the recence of the state of the state of the first depth of hereast (the recence of the table) hereast and the hereast rest is the rest of the table to a state the state of the table the tables are the rest of the table to a state the state of the tables the and the rest of the table to a state the state of the tables have not the state of the table to be the table.

Design and a second second realized in the second s

8 at les

1.4

an t-sphy

TERMINET TOURING, SPILL 11, BOLL HE SETS PR

Personal Automa time, ettlern 6 Tilei & II-distortion of the easily might of Inceling, Funicescon infer measurements Tressense of Technology, (IN) Officescont offic Thesis and the measurements furthing of simples.

Cambridge, Massachusetts May 22, 1954

pellon 10.1

ryperthes.

Secretary of the Faculty Massachusetts Institute of Technology Cambridge, Massachusetts

Dear Sir:

In accordance with the requirements for the Degree

of Naval Engineer, I submit herewith a thesis entitled,

"An Investigation of the Early Stages of Fretting."

Respectfully,

William F. Tighe, Jr. Lieutenant U. S. Coast Guard Journal and States

Second of the Londby Marsobarts Instruct of Resembley And they, Barador to

DOUT ALL'S

Do accordings with the requirements for the legree of the Second Se

et is a set

111-11-10-400V

Dansame Tomman Laral 17, 103) IN 3129 MM

Particulation of ACKNWLEDGEMENTS

The author wishes to express his sincere thanks and appreciation to Professor I-Ming Feng for his advice and encouragement during this

investigation. Appreciation is also extended to Mr. J. Purdy for his help in setting up the testing equipment.

The other winter to express out channes tinter of parent to a lo reference Le marti for the stin and answer a mt during the hola the will it is is and and the safe and and t for his halp in multing on the . tran inpa a to

The second

TABLE OF CONTENTS

		Page
I	INTRODUCTION	1
II	PROCEDURE	10
III	RESULTS	12
IV	DISCUSSION OF RESULTS	20
V	CONCLUSIONS	26
II	RECONSIGNEDATIONS	27
VII	APPENDIX	28
	A. SUPPLEMENTARY INTRODUCTION	29
	B. DETAILS OF PROCEDURE	34
	C. SUPPLEMENTARY DISCUSSION	38
	D. LITERATURE CITATIONS	41

CONTRACTOR OF STREET

		lan purtually
-	Normalization (Ĩ
17	THORSE P	0.0
III	17,7950	22
T	BAINES - 00 10 10	20
7		d.s
T	the second secon	fre-
177	The second	22
	NOT TOUGHT IT IN THE OWNER AND	29
	W. LITTING OF PRODUCTS	34
	o. novements algebra	30
	N. LIVENTAL DIVISION	IA

I INTRODUCTION

Fretting is a type of damage that occurs at the interface of two loaded surfaces that are in contact and subject to relative slip. Fretting often appears on surfaces intended to have no relative motion but which are associated with vibrating machinery. It may occur, for example, on the mating surfaces of a bearing race and of a shaft tightly fitted together. It has been shown that some slippage, no matter how small, is necessary to cause fretting. In the absence of slip there is no fretting (3, 8).

Fretting damage is a continual source of uncertainty in the operation of all machinery subject to vibration, as it quickly destroys close tolerences and increases the susceptibility to fatigue (h). Examples of fretting damage are often found in variable-pitch propellers, connecting rods, knuckle pins, ball and roller bearings, clamped and bolted flanges, pins in gear trains, suspension springs, electrical contacts, and splined surfaces. This type of damage is particularly serious in the airplane and automotive industries where close fits are employed on equipment subject to vibration. In order to eliminate or mitigate the damage caused by fretting, a better understanding of the subject is essential. The purpose of the present investigation is to add to the understanding of the subject of fretting and the means of investigating fretting damage.

-1-

NOTTING MOTOR

Tretting is a type of denum black search at the interface of two bould methods that are in orthoft and mighed to painting with. Frathing often appriate on methods intermond to have no relative article bot motois are anonialed with vibrating antifacty. It approares, in manufar, on the willing prefaces of a hearton man and of a walt similar (idded tegether. It has been enorm that sear stignare, to method be walter in the bar been show that is an attract in manufar, is the second of the second forth and of a walt similar is a walter in the bar been that the sear stignare, to method tegether. It has been and the sear stignare, to method there is an first in (.).

Inviting data a to a southmal searce of second-hilling to the equivalence of all anddrawy subject to vitravites, as it quintly to be derive a stress tilescane we have an analyticality to ratigue (b). Humalos of freddate datas an offer front in vertical-outer beseders, shaped and bolted flores, based optim, ball as subtrain-outer is freddate and bolted flores, plan in year water, massaches applying, classified seatures, and official minor that type of theory is particular and and the type of theory is particular and bolted flores, plan in year water, added to theory is particularly inclose an orbital mater added to the vibration. In order to stimizable as addined an equipment the particular, is before the advective of the analytical of the datas added to the vibration. In order to stimizable or addined to another the particular, is before to stimizable or addined to another added to the respect of streation and the tor angle of the analytic strating of the addinet of streation and the anomal of the addinet for the type of the respect of streation and the anomal of the addinet strating of the addinet of streation and the anomal of the addinet freddates for the addinet of streation and the anomal of the addinet to be the addinet.

The majority of the work done to date in the field of frotting has dealt with the mechanism of fretting and some of its qualitative aspects. Feng (2, 9, 10) has analyzed the basic factors of metal transfer and wear. The mechanism of wear, as proposed by Feng, is caused by a pair of actually contacting high spots. When these contacting high spots support a normal load that is large enough to cause plastic deformation of the metal, the deformation will cause a roughening of the interface. This roughening of the interface produces a mechanical interlocking which strengthens the interface in resisting a tangential force. Thus the application of a tangential force will cause the peak of one of the pair of high spots to shear off instead of separating the contacting high spots at the original interface. This sheared peak may either become a loose wear particle or remain attached, depending upon the factors operating to cause it to adhere to the adjacent high spot. Feng and Rightmire (1) have applied this theory to explain the mechanism of fretting, and have shown mechanical wear to be the primary cause of fretting damage.

The wear particles formed by the shearing off of the peaks of the contacting high spots form hard oxides which cause abrasive wear. A number of investigations (1, 3, 8, 10) have been made in different atmospheres to determine the effect of oxides on fretting damage. These investigations have shown that oxidation, while having a very marked effect, is only a secondary cause of fretting.

-2-

The rejustic of the work does to date in the delta inter a has deale with the mobardism of far bills and none of the qualitabile aspector. Form (2, 7, 10) has analyzed the heats factory of motal Strangther and money. The mechanism of wear, an proposed by Fang, is course by a pair of otally active line big aparts. then these durant and and have a second a second land has he have not the "In come glueble is forestion of the million with the deformation with call to make a rouge of the interime . The rouge of the interest dates which the second free the second second an identified any periodine a bargenital freeze. Thus the application In the new of the second the particular the part of one of the part of pricipations all sectores in instruct The same of slope control its then spoke at the statistical inchastions. This should pasts may autonomia plana a series as mistras are seen a removed anitio tomostic add of crutche of 31 wasan at activery armited add exercit high soot. Fars and Mighteira (1) have sonlind bais toancy bo Indiantion much must have analytical to minimum only minimum. · man to be the milant of the of the state of the

The order to the formed of the starsing off of the pade of the controller ld-s space form last action which outer down to be man. A maken of investigations (1, 3, 0, 10) have been told in different elementaries to anterpice the effect of mildes on fronthing towns. These investigations have down that will be will be total a very avoid effect, in will a cosseley and of fronthing. In addition to the investigations of the effect of atmospheres, investigations have been made of some of the other factors affecting fretting damage. Tests conducted by Feng and Uhlig (8) have shown that a decrease in fretting damage is caused by an increase in relative humidity, temperature and frequency of alternation; and an increase in fretting damage is caused by an increase in the number of cycles run, relative slip and normal load. Parts of these tests have also been corroborated by previous investigators (1,3). In addition, fretting damage appears to be greater, other things being equal, the better the original fit of the mating surfaces (6).

Several investigations have been made of fretting damage using various metals and nonmetals fretted against themselves and against each other. Godfrey (7) used platinum, glass, quarts, ruby, mica, and chroms-alloy steel. He found that the tendency for fretting depended upon the surface hardness of the motal tested. He also found that the introduction of a lubricant between the surfaces of the materials decreased the amount of fretting damage done in all cases, but that it was not eliminated. This latter fact was also borne out in the investigations of Tomlinson, Thorpe and Gough (3).

References (1) and (8) both present the results of mild steel specimens fretted against mild steel specimens in dry air. These results are presented in the form of curves of Specimen Weight Loss versus Number of Cycles Run. Both of these curves are concave downward at the origin, i.e., during the chifting period from shearing

-3-

The additions have been made of some of the strand inches all strandomer, hereighting dimensions have been made of some of the strand inches aligniting derividing dimenses to the statement of day as a bit (3) done shows that a decrement to the theory of angle is commit by an increase in relative handling, tangen there and frequency of illiver align on thereare in Probling damen and frequency of illiver align and align the best statement of the second of an increase in these to spatial state and compared by second land. For the last matches of spatial state best compared for an increase in the tanks to define allow best compared by contained, where a base to matche the allow best compared by contained, where a base to matche the state allow best compared by a state of the state is addition, the base compared by the base of the state of (1,3).

Inspectal formation have been able of freddom datage value random within and commital fracted spate t theorethyne and against also ether. Modifrey (7) and photons, from, quarks, roop, alon, and arrest-alley sheet. We found that the books of the fraction depended none the eventee territors to the territor. The size depended none the eventee territors of the minicipant territor. The size depended none the eventee territors of the minicipant territor. The size depended none the eventee territors to the interval territor. The size depended none the interval of a laboritors for more territors depended none the interval territors for minicipants and depended none the interval territors of the interval dependent the interval territors of a laboritors for the size all enses, but the territor territors of the interval all enses, but the territor territors of Territors, finder and dauge (3).

Antiparame (1) and (3) both protocor the room in or wild both spectrum fraction when wild shall even even by dry atr. The rounds are meanwhat in the form of norves of Sociare metrics Loss retries Mater of Spelar Bur. Both of these corrected sociare domany is the outples Lee., derive the stifter priod from statetae

action to abrasive wear. Feng and Rightmire (1) have proposed that this curve is actually concave upward during the shifting period. This proposal is based on the fact that the rate of wear probably increases during the shifting period as the abrasive action is presumably more violent than the shearing action. This proposal seems to be supported by the points plotted in Figures 5 and 6 of the investigation by Wright (11). One of the purposes of the present investigation is to substantiate this proposal by decreasing the number of cycles run and increasing the amount of fretting that occurs by decreasing the frequency of alternation. This will tend to expand the initial portion of the curve. The test apparatus shown in Figures I, II, and III and described in Appendix A was used for the investigation.

Using weight loss as a measure of fretting damage is not always the best means, even though it can be measured quantitatively and relatively accurately. An excellant example is the case in which two clean surfaces are fretted against each other in a vacuum. Because of the adhesion between clean metallic surfaces in a vacuum, the peak sheared from one high spot sticks to the opponent high spot and becomes a piece of transferred metal. Thus very little loose wear material can be produced, metal merely being transferred back and forth from one specimen to another. If the specimens are made of the same material, the weight loss of each is practically nil.

-4-

Action to instative were. Nore not thebidies (1) new proposed that, bein more in actually contains operatively in a mining point, this proposed is read on the first the solution of over pointing between their is a solution which is a the downton of the proposed access to be reported by the volute glavies in Nicerse 5 and 6 of second to be reported by the volute glavies in Nicerse 5 and 6 of second to be reported by the volute glavies in Nicerse 5 and 6 of second to be reported by the volute glavies in Nicerse 5 and 6 of second to be reported by the volute glavies in Nicerse 5 and 6 of second to be reported by the volute glavies in Nicerse 5 and 6 of second to be reported by the volute glavies in Nicerse 5 and 6 of the investigation of the frequency of the mount of frequency of the second field ported of the second of the mount of frequency is obtained to infitial ported of the second of the test frequency is obtained to infitial ported of the second of the test frequency is obtained to infitial ported of the second. The first frequency is obtained to infitial ported of the second of the test frequency is obtained to infitial ported of the second of the test frequency is obtained to infitial ported of the second of the test frequency of the test first frequency.

The probability has an a measure of frathing houses have along the host were though if an is measured qualificatively and reflectively associately. An emotion much is the mean is also we also also method as frather and the solution is to a mean. Second of the allocation between them refuile and the result. Second of the allocation between them refuile and the quantities in a mean, the pair the allocation between the and the operand high apple as because a date of franchered metal. The regulation has metal before an applied and pair of the antiput high and before the an applied of a solution. If the another has all the regulated of parameters and the another allocation and before the metalog of the antiput has a mean of the regulation of the allocation and and the another allocation and before the another allocation and an allocation and a solution and before the resonance of the another allocation and a solution of the resonance of the another allocation and a solution of the another allocation and before the resonance of the another allocation and a solution of the resonance of the another allocation and a solution of the another allocations are made and before the resonance of the another allocation and another allocation and a solution of the resonance of the another allocation and another and a solution of the another allocation and allocation and another allocation and another allocation and a solution and allocation and allocation and another allocation and another allocation and allocation and allocation allocation and allocation and another allocation and another allocation and allocation allocation and allocation and allocation allocation and another allocation and allocation allocation and allocation allocat

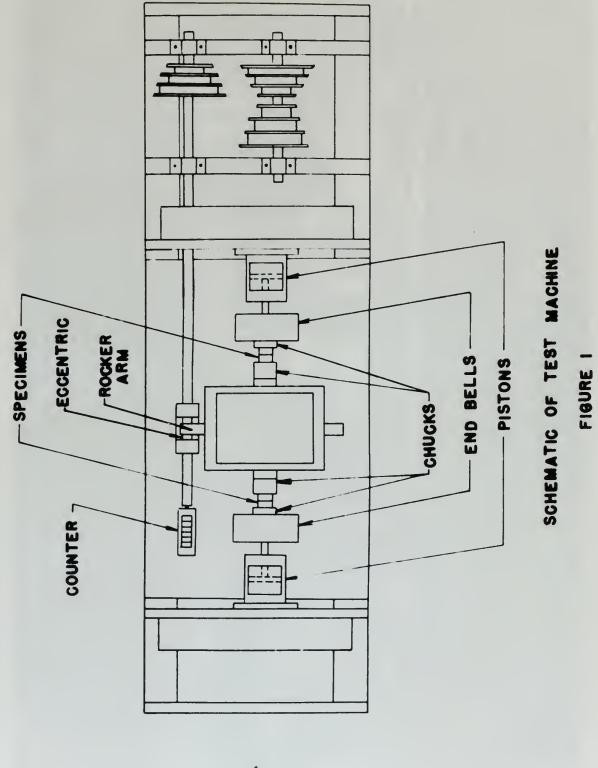
Nevertheless, both specimens are subject to serious damage caused [1] by metal transfer. A second purpose of this investigation is to try and establish a technique for measuring the damage in such cases by correlating weight loss and some physical measure of fretting damage. An attempt will be made to find some relationship between specimen weight loss and either the depth or the area of damage or both.

Feng, I. Ming, and Rightmire, B.G., "The Mechanism of Fretting", Lubrication Engineering, Vol. 9, No. 3, 1953, p. 135.

branchalant, tota entire an collection who could be not an a formation of the second entire o

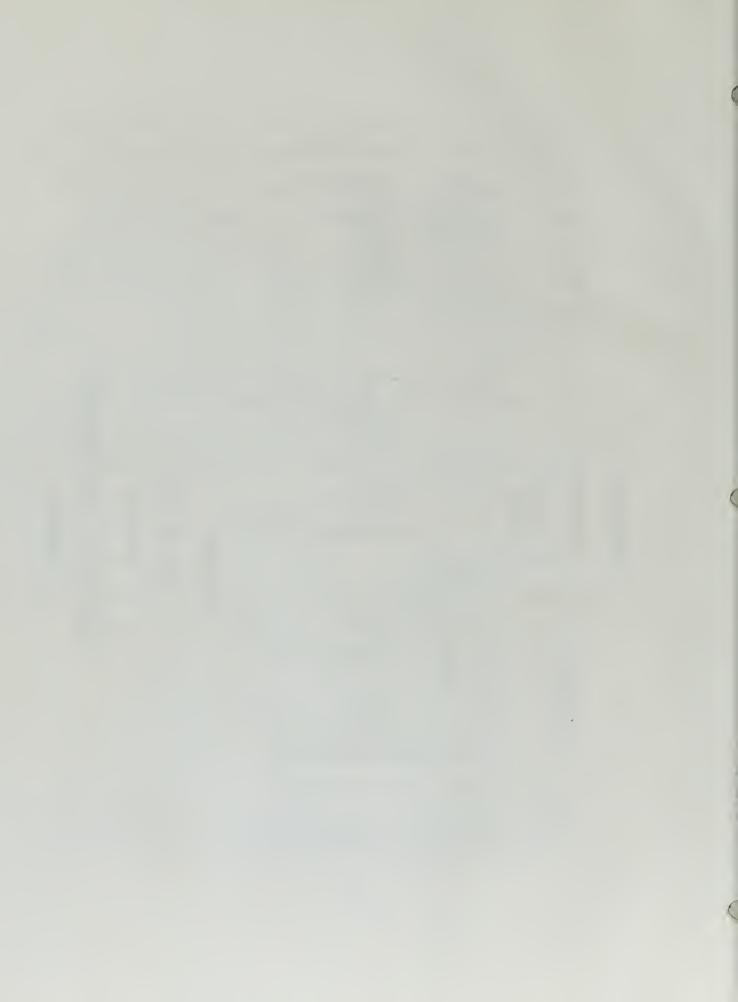
A statuter in a second second

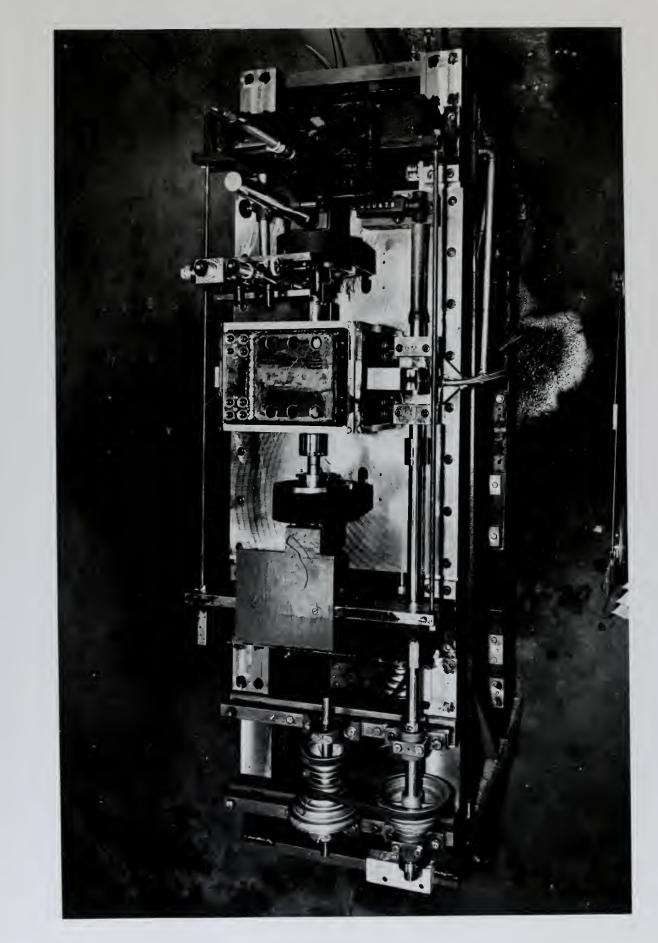
part in succession in the state of the part of the succession in the



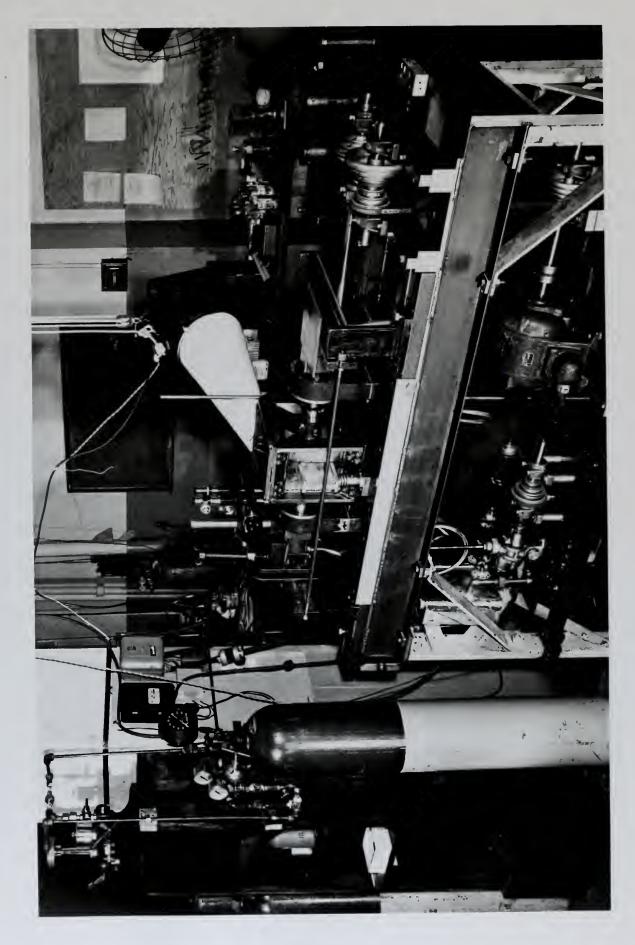
2

-6-





);



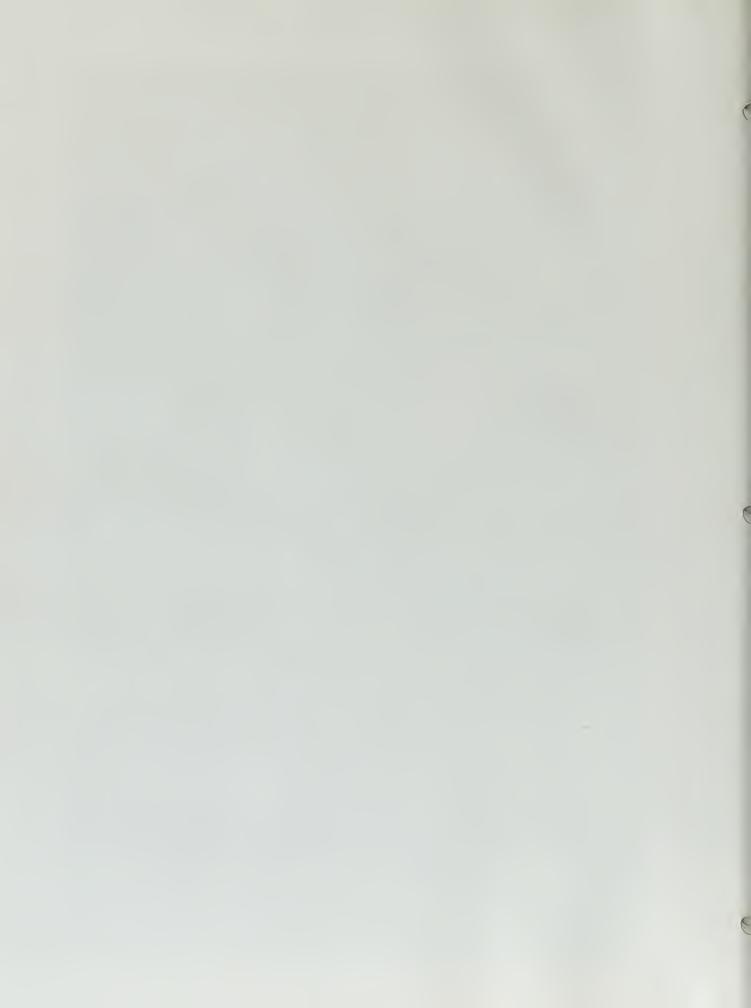


FIGURE IV Standard test specimen





II PROCEDURE

The specimens to be tested were prepared as outlined in Appendix B, mounted in the test machine and the tests made. All of the tests were made under a standard set of test conditions in an atmosphere of dry air at room temperature. The standard normal loading was 5300 psi. The relative slip was maintained at 0.0036 inch, and the frequency of alternation was kept constant at 79 cycles per minute.

owner all Designation of Strength of

Several tests were first made to determine an appropriate number of cycles at which the fretting damage was such that it was fairly easy to identify individual pits. Two runs were then made, one for five cycles duration and one for ten cycles duration. A number of individual pits were selected from each specimen and a measurement made of each pit area and its depth. This procedure was followed in order to find a relationship between pit area and depth indicating pit growth. It was anticipated that this might lead to a relationship that could be corrolated with specimen weight loss.

Several tests were then made varying the duration of test from 10 to 300 cycles. The specimens were pickled once and weighed upon the completion of each test. The recorded specimen weight loss was an average of the weight losses for the four specimens tested. A representative specimen from each of six tests was selected, and

-10-

Teal Day II

The products to be beaked more proported at conditions in the matter 7, common in the two which matchine and the foote mater. All of the futto more made under a standard set of tent conditions to an etemphone of the size of more temperature. The standard marged looding was filled pet. The relative fille was animological at 0.0036 facts, and the frequency of alternatives was here constant at 7 ordine or alteria.

Some al thats were first ands to deversine an appropriate makes of oreine at much the fraction dates and and that it much, one for the startify individual pite. The runt were then adde, one for the evolve duration and one for impleying duration. A randor of individual pite sure subsched from eyeles duration measurement sale of such alt area and the depth. This promises was followed in order to find a relationship between pit and depth individually the control of a subsched the started have followed in order to find a relationship between pit and depth individually that could be correlated with appoint with load to a relationship that could be correlated with appoint with load to a relationship that could be correlated with appoint with load to a relationship that could be correlated with appoint with load to a relationship that could be correlated with appoint with load to a relationship that could be correlated with appoint with load to a relationship that could be correlated with appoint with the laws.

Summed that were then and varying the structure of test from 10 to 300 croles. The spectarms way stabiled once and wighed open the completion of each test. The recorded monitors which lose we as even at the might loses for the for spectares borbed. A represent this modema from each of eix forth res minched, and

and Ino

a measurement was made of the total area of fretting damage and the greatest depth of damage. The purpose of this series of tests was to find the shape of the curve of specimen weight loss versus the number of cycles run. In addition to this, the tests were an attempt to find a relationship between total area and depth of damage and to corrolate this with specimen weight loss.

A series of tests was made varying the duration of test from 1 to 10,000 cycles. The specimens were cleaned and weighed after test, then pickled and reweighed. This was followed by a second pickling and reweighing. One or two specimens from each test were selected and a measurement made of the deepest depth of fretting damage. The purpose of this series of tests was three fold. First it was an attempt to determine the fretting weight loss curve. Secondly it was felt that this procedure would lead to a relationship between specimen weight loss and depth of damage. Thirdly it was an attempt to determine what effect a first and second pickling procedure would have upon specimen weight loss.

THE R. LEWIS CO., NAME AND ADDRESS OF

-11-

L measurements you make of the botal even of forebilling decage and the president double of Aurope. The purpose of this exclass of backs was to them on show of the encourt operime whight loos reaves the encourt of spales you. To shiftling to both, the tasks rears so allowed to first a relationship between both area and both of one and he servides this with another which area and

A no 10,000 mulas are aboregal as burntle of the total of the total of a state of the total of the state o

And is a second to be a second to be

III RESULTS

The results of the investigation are presented in Tables I, II, and III, and in figures V, VI, VII, and VIII. Significant points to be noted are as follows:

- Initially the area of an individual pit increases faster than the depth. The depth then begins to increase faster than the area, followed by the area again increasing faster than the depth.
- Initially the rate of specimen weight loss is high and soon reaches a steady state. Shortly after this steady state is reached, the rate of weight loss again increases markedly and settles at a new steady state value.
- 3. The specimen weight loss due to both first and second pickling is not a constant, but is a function of the amount of damage caused by fretting.
- 4. The total area of fretting damage is essentially a constant over the range from 30 to 300 cycles.
- 5. The specimen weight loss increases with an increase in the depth of fretting damage.

-12-

an III

The smeaths of the lemestinging an properties in Vables 1, 11, and 111, and in Figures V, VI, VI, and VIII. Northeast prints to be noted are as follows:

- Tethtally the area of an individual oil factor area factor than the depth. The first then beginn to increase furter than the area, followed by the area would function factor time the depth.
 - - The manufactor multiple Longe Son to holds ithree and mercoal placking to put a constantly, both its a Fungition of the extract of manual cannel by Drebains.
- A. For total organ of freeholds frames in constants a constant aver the rance from 20 to 200 dealer.
- 5. The spirature weight have from the with an incorrect in the depris of Spiriting Depris.

TABLE I

INDIVIDUAL PIT MEASUREMENT DATA

Normal Load - 5300 psi Slip - 0.0036 in.

Medium - dry air

Pit	Duration of Test(cycles)	Frequency of Test (cpm)	Pit Area (x-6in ²)	Pit Depth (x 10 ⁻⁴ in)
1	5	79	18.05	0.762
2	5	79	49.20	1.476
3	5	79	38.40	1.738
4	5	79	45.20	2.500
5	5	79	62.60	3.167
6	5	79	134.80	4.048
7	5	79	113.10	6.310
8	10	57	70.10	1.953
9	10	57	70.85	1.953
10	10	57	39.60	2.310
11	10	57	38.20	2.500
12	10	57	41.60	2.500
13	10	57	79.20	2.500
14	10	57	38.20	2.928
15	10	57	75.00	3.309
16	10	57	176.20	3.500
17	10	57	114.50	3.809
18	10	57	159.7	3.977

-13-

+ ------

The Part Plan The Substrate

The the moule of the second se

100 100 - 1000 mat

21 2 20

(m) 51-		The two stars of (mp) 2 m	Section of Sectorelas)	#1.1
2,762	Vall	anne a anne a cons a cons a P	1000 mm	
Nº La.	62. 81	ر۳	il.	2
.73	38.0	55	3	3
2.500	65.20	27	2	1
3.267	ek.sh	67	N.	5
Bdo. S	121.112	8 7	1 1	5
6.310	233.30	77	Ś	7
2,2'3	70.30	15	30	1
či -	20.07	12	6Ľ	9
0.0.2.	33.60	12	10	0
2,500	38.20	57	97	11
2,500	62.23	T	- 20	12
012.5	02.27	57	20	13
NO.	RG.BE	57	2.0	12
3.09	75.00	57	20	25
002. E	175,20	57	10	35
3.00	111.50	ĩ	10	72
3.777	T		3.0	85

TABLE II

TABULATED RESULTS

Load - 5300 pei Slip - 0.0036 Frequency - 79 cpm

Medium - Dry air Polish - No. 00 Emery/Paper

Depth of Damage after 2nd pickling (x 10 ⁻³ in.)	1	1	1	1	1		1	2.17	1	T	
Area of Damuge after lst pickling (in ²)	1		t	0.0356	0.0413	0,0350	0.0425	1	בבווס.0	0.0436	
Depth of Damage after lst pickling (x ⁻³ in.)	1.60	1		3.064	2.508	2.104	2.828	, 1	2.710	4.393	
Weight loss after 2nd pickling (mg) 2 specimen Average	1.0	1	1.0	t	ı	1		1.20	ł	t	
Weight loss after lst pickling (mg) hSpecimen Average	0.825	1.088	0.800	0.610	0.300	1.150	1.250	1.000	1.000	1.725	
Number of cycles run	10	20	20	30	140	20	22	125	150	300	

-14-

1 1	5-13	3 8	£	-1	1	1	ž	To lived Tod a share Little (· On participus	
0°472 0°471	l			32 EU. 0	1	ł		nc and states of the second se	. With a mandfamily	
CRC.1	I	5.10	2.500	. e.	1	i	04.1	To digit To digit that the (.ed Car)		II afres
i 1	05.2		1	1	0.1	1	0.1	s. I de la lad Talla (s) attrata s. Tal		
J-010	T*200	7.550	008.0	014.0	0.100	2,001	0.5%	Private (**)	10.0038 - 2300 T	
700 770	127	58	N.C.	30	-	30	CI	5" sjer 2.11 , 5 07.	TT - 0*003	

an lina

	Medium - dry air Polish - No. 00 Emery Paper Weight Loss-4 specimen avarage	Depth of Damage after 2nd pickling (x 10 ⁻³ in.)	1	the set	3.04	2.36			2.63	2.65	2.76	3.18	4.24	3.10	5.95	5.50	7.08
101	Weight Loss-4 sp	Weight loss after 2nd pickling (ng)	0*150	1.625	1.450	1.450	1.100	1.600	1.275	1.4150	1.950	1.925	1.925	2,000	2.675	3.200	001.41
TABULATED RESULTS		Weight loss after 1st pickling (mg)	0.600	1.100	1.175	1.175	0.925	0.925	1.075	0.750	1.375	1.675	1.675	1.725	1.925	2.450	3.500
	c pm	Weight loss after test (mg)	E.	0	0	0	0	0	0	0	0	0	0	0.2	0.3	0.5	I.I.
	Load - 5300 pai Slip - 0.0036 in. Frequency - 79 cpm	Number of Cycles run	r-1	80	100	100	100	200	200	200	300	500	500	1000	3000	5000	000 ⁶ 0T

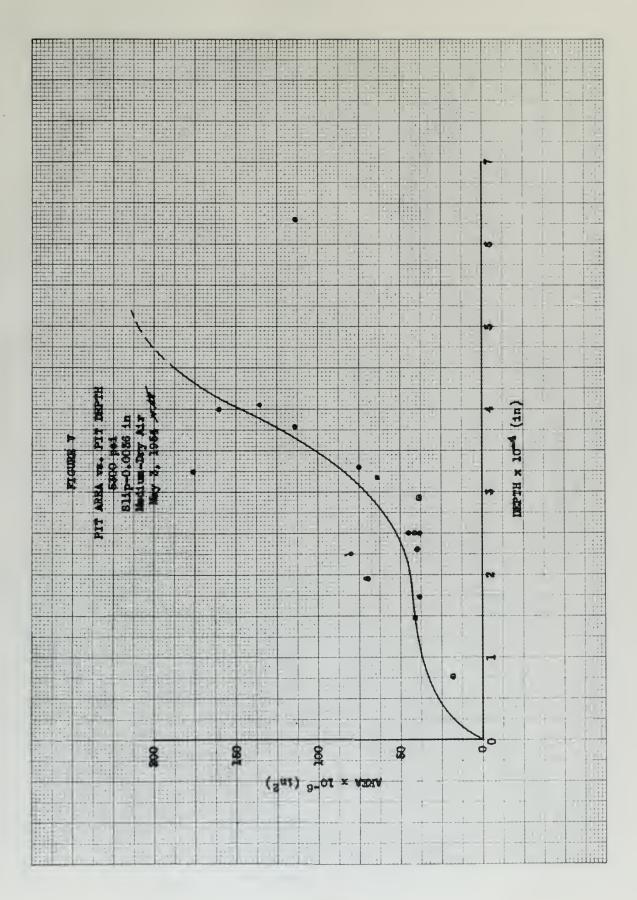
TABLE III

80.7 2.2 2.2 2.2 2.2 2.2 2.2 2.2 2.2 2.2 2	x 1 a a b d a a b	the training and the second
7.100 7.955 7.955 7.955 7.956 7.956 7.100 7.170	and dig.s. the root (=)	- frilan 1 3: Lo
5.200 1.22 1.22 1.24	2 1 2 2 2 2 2 2 2 2 (-) 2 2 2 2	
1.0000000000	() the st	
0004 al 0005 0005 0005 0005 0005 0005 0005 000	10 " 11 "	1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1

avery and the

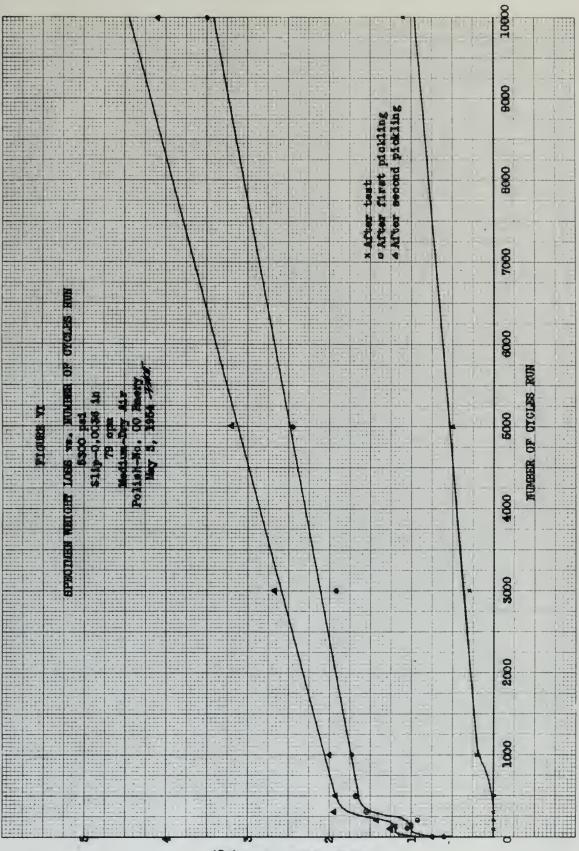
TUNE III

and the form

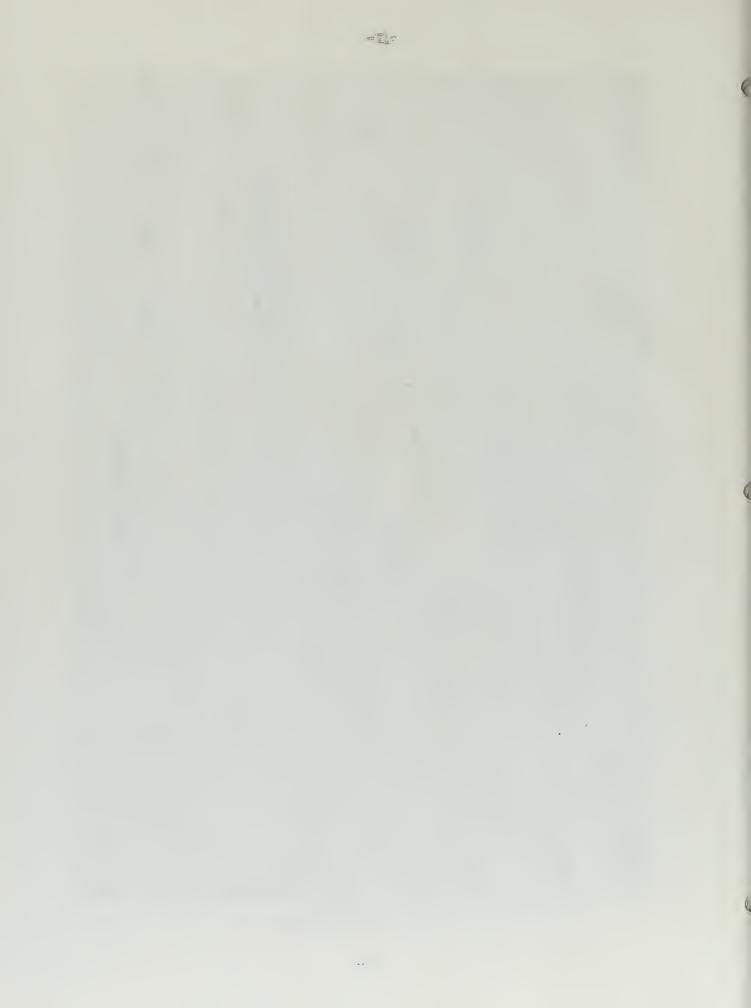


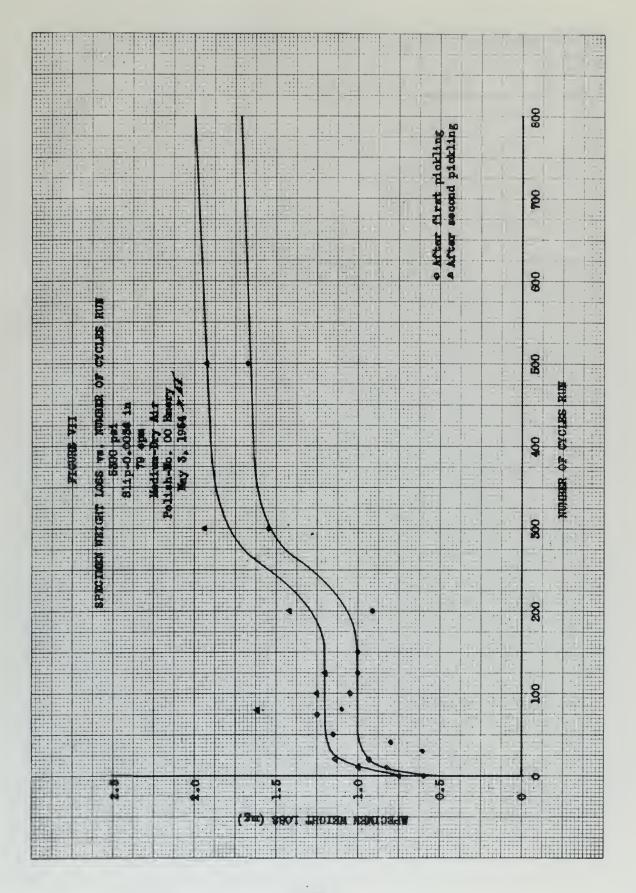
-16-



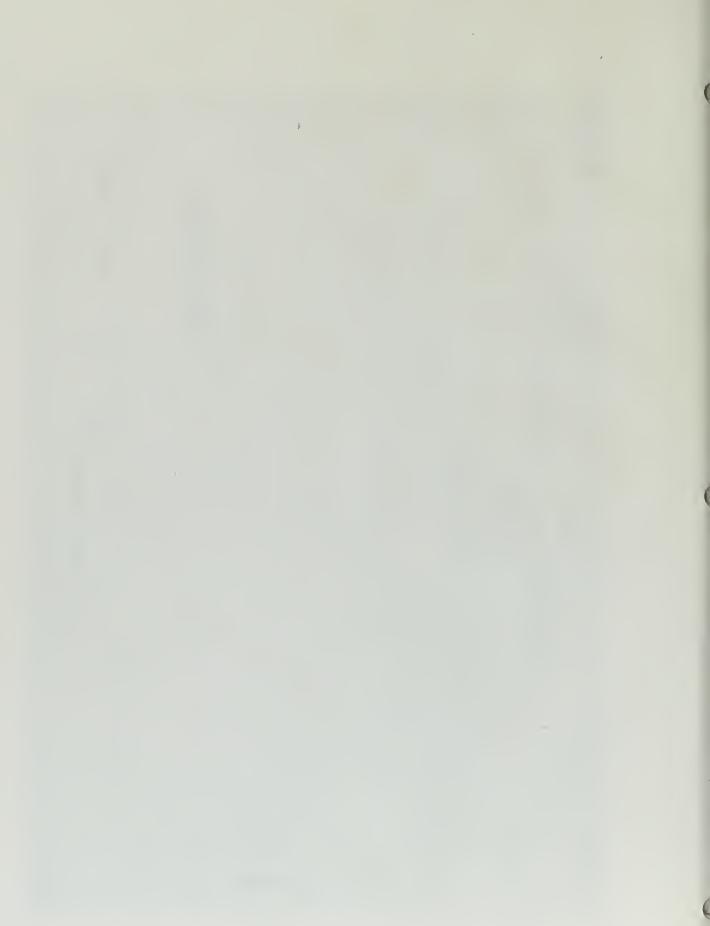


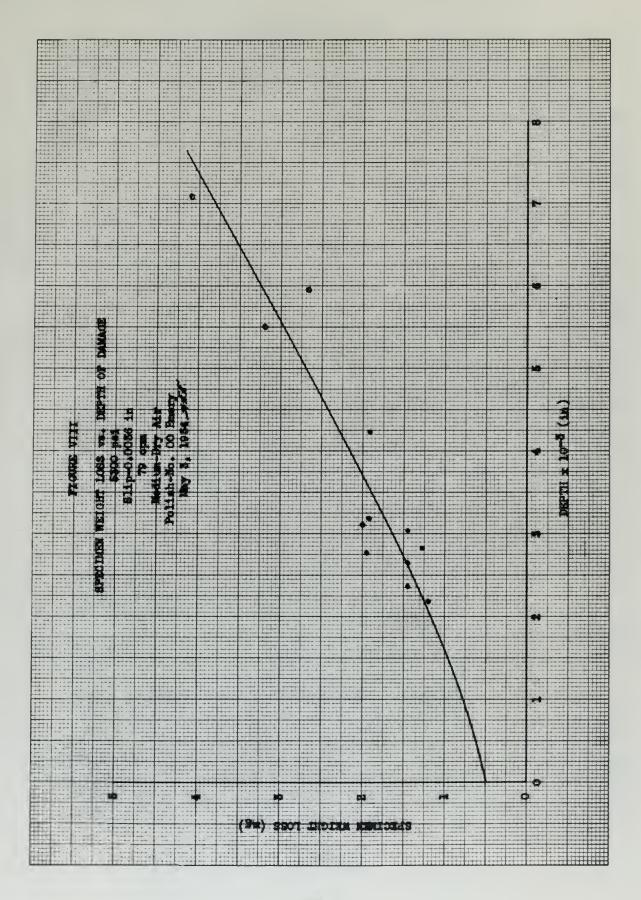
SPECIMEN WEIGHT LOSS (mg)

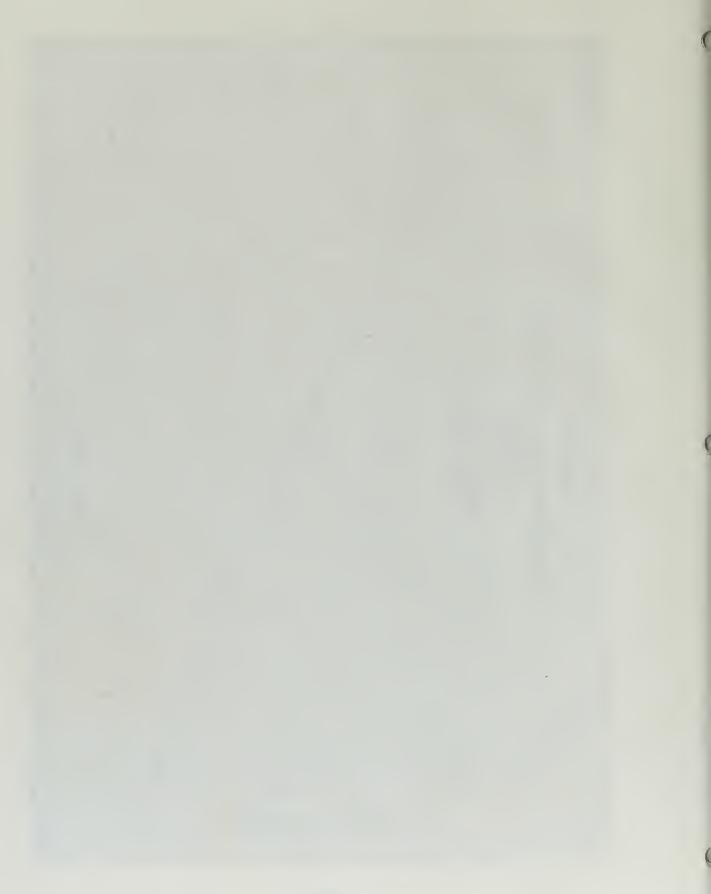




-18-







IV DISCUSSION OF RUSULTS

During the investigation of pit growth, it was found that individual pits could be easily identified in the neighborhood of ten cycles. In attempting to measure the area of the individual pits, however, it was found that a random surface polish with No. 1 emery paper was not satisfactory. When a pit was photographed under the microscope, the scratches left in the surface by this polish were so large and random that the boundary of the pit could not be determined with any degree of accuracy. When the surface was given a unidirectional polish with No.200 or No. 0000 emery paper, the scratches left in the surface were considerably smaller. Since these scratches were unidirectional, the boundary of any pit running slightly off the direction of polish could be accurately determined.

It was found that any attempt to use individual pit areas or depths as a substitute for weight loss was impractical. This is due mainly to the fact that in order to distinguish a pit as a single pit, the pit must be so small that the area and depth of all pits so selected fall in the same range of values.

That the above is true may be seen from an analysis of Figure V. When two clean surfaces begin to fret, the sheared off high spots begin to form an area of damage with essentially no depth. Thus we see that in Figure V the area increases faster than the depth. The depth then begins to increase faster than the area. It is suspected that this is due to the abrasive action of the loose wear particles,

-20-

During a investigation of is great, it is found that initial pits could be easily item if a to in the neighborhood of the scale. In the spite because the a of be individual pit, some, it as found to the random surf or pitch with ho. I emery nor a not found to the random surf or pitch with ho. I und r the mine control as left in the scale by this polither are observed as left in the scale by this is not be the random that he could on the it could not be a standard to be are of the in and by this is a standard to be and the scale of the it could is a standard to be and the scale of the it could the scale of the

If we rand hat any stress to we individual pit areas or depths as a mutilitate for within lass we har shoul. This is due saled to the last blat in order to distinguish a dit as a sirele mit, the is mut be no small that the aver and depth of all site so coloring this in the some range of values.

The ball of the may be seen for an allois of the V. When the interior of the first, the second of high spate be in to for an est of denomination entropy in depth. Thus we not that in Fore V the are increase for the transformed. It is apported depth that beins to increase for the transformed. It is apported that this is set to the fraction with a to be a particle ;

-20-

limited by the samll amplitude of the relative motion of the specimens. The pit will eventually reach a size such that it will join with the adjacent pit forming a new pit of increased area but with a depth essentially the same as that of the old pit. Thus the area of what is still a single pit, begins to increase faster than the depth. This process continues, the pits increasing in size, until very shortly a single band of damage is formed on the specimen. It is for this reason that "individual" pit areas and depths begin to fall in the same range of values. It is further felt that the process just described will cause the curve of Figure V to continue to increase in a stepwise fashion until such time as the area of damage becomes such that it will remain essentially constant, and the depth of damage will continue to increase. This theory appears to be borne out by the data on the total area of damage given in Table II. The areas over the range from 30 to 300 cycles appear to be essentially constant which would indicate that this particular range is over a flat step in the curve.

In Figure VI, the curve of specimen weight loss after test and before pickling serves no real purpose. Above about 500 cycles the values are inaccurate due to the fact that a certain amount of the debris remains on the specimen and some falls off. In either case, the amount is unknown and thus the value recorded is not a true measure of specimen weight loss. This portion of the curve can serve only to indicate that specimen weight loss increases with the

-21-

limit by in mall willie of he welative wiln of the and the spin of the state of the second seco jou in the locat it for ing new it of incread ar a hot -it . den ' seen tin the set of the black of the old mit. "hus the ar a di si d the doth. The conte c stings, the pite increase n drey, her at strength of the state of the strength of the until viry h tly ' -1 and of deage 1 - - - t s pecimen. the state of the property of the other has again the state during It i for 'h' - - on the "individual" - the ora - doubh be in to fill in the set runs of vilder. It is with r felt that the county That's Bull and in These others which in the latter a county constant india cause the cause V to continue and a sublime to be the second rate which there are not the second rate of the second rat o increase in a provide fashion and i each the se the mea of the last the property of a party from the party of the second party and and the second of the second first of a second shall constant, and and the second of the state the depth of divers will continue to increase. The theory appears The second secon to a correct of the total and the total and the total Table II. The mouse over the rear from 30 to 300 symlas angear to the star wanted the fact that the start of the start of Taluaiting in tal talin' bloom dar to inco - I-treas of and the state of the second and them in add them by the allow allow muthe is not a fight stop in the curre.

Me and 1, as and of oction alor loss about est and ble out 1, are and normal number. Now anot 500 croles the value in the interval of the fact that a contain anount of the debrie reached on the sole of the loss of the set the walk of the and these the who react to be the case, manual is also and these the who react to be the curve can mere and the react of the fact of the curve can mere and the state of the sole of the curve can

-27.00

number of cycles run. Below about 500 cycles, the recorded weight loss was zero, but it is felt that this is not actually the case. It is felt that if the weight loss could be measured fine enough, the initial portion of this curve would have a shape similar to that of the curves after pickling.

It may readily be seen from an examination of the curves of weight loss after first and second pickling, that the weight loss due to pickling is not a constant. It is thought that this is caused by two factors. First, the plastically deformed material is attacked more readily than the material that has not been plastically deformed. Secondly, the first pickling does not remove either all the plastically deformed material or all the debris. This is substantiated by the findings of Feng and Uhlig (8). Their investigations showed that the loss of weight for clean, untested specimens was about 0.3 milligrams per specimen. An investigation should be made to determine a means of finding the true weight loss of the specimens.

The curves of Figure VII are enlargements of the initial portions of the curves of Figure VI. An analysis of their shape not only substantiates the initial proposal of this investigation, but also the basic mechanism of fretting. The early portion of these curves resembles ordinary wear curves. The shearing off of the contacting high spots produces loose wear particles which do not exidize immediately. These loose wear particles remain relatively soft and

-22-

motion of grains run. Sales about 500 spales, he recorded malpha loss and area, bat is as Sale into the second by analysis Its is falt line, if the redgin loss could be measured firm annexity the tableic curvice of bhis more would have a shape while to black of the average affect could ge.

It are really in our from the and from a maximum that of the second of second tone ofter from second pholitary, that the second tone that in a second to the follows. These, the electricity tetranet antential is second to the follows. These, the electricity tetranet antential to actuated error reality than the estartick tool ton and been showed in the follows. A second pholically tetranet antential photocond error reality than the estartick tool ton and been showed in the following detranet meetal, tool ton and been showe all the photocolic detranet meetal we detries the atomic of the following detranet meetal we that the detries the second in the photocolic detranet meetal we that the detries the second in the photocolic detranet meetal we the the detries the second in the photocolic detranet meetal we the the detries the second in the second too the term and which the detries there have the there at and too the main of ratio the too and the second meetal has a been of the meetal for the second the second too of the metal to the too of the second of the second of the second too the second of the second of the second form of the metal to the too the second of the too of the second of the second of the second of the second of the too of the second of the second of the second of the second of the too of the second of the too of the second of

The nerves of Lynew VII are enhancement of the teitled particum of the moreous of Romes VI. An antipits of their shape not only missionalising the initial proposal of this branchedden, but also the body maintains of fractily, "To early performed the same repeal is welfacty may there. The model of the sertenting idea welfacty may there. The model of the sertenting idea probase have there are performed on the order of the testing idea, well probase have performed and the order of the testing idea, well probase have performed and the order of the testing idea, well probase have performed and the order of the testing idea, where here and perform and a start of the order of the testing idea of the order of the set performed and the order of the testing idea of the probase and perform and a start of the order of the testing idea of the order of the order of the order of the order of the testing idea of the finance for the order of the testing testing the order of the order of the testing idea of the testing the order of the testing testing of the order of the testing the of the order of the order of the testing testing testing to the testing testing to the testing testing to the testing testing testing testing to the testing testing to the testing testing testing testing to the testing testing testing to the testing testin the abrasive action caused by them is not too great. The original loading is rather poor, being distributed over a relatively small number of contacting high spots. A better distribution of loading takes place through the wear process itself. These two factors combine to cause a leveling off of the rate of wear, and a tendency to arrive at a steady state value.

The loose wear particles tend to be trapped in the hollows of the small-scale waviness of the surface, due to the small amplitude of relative motion. These loose wear particles now begin to oxidize, forming the hard oxide Feg02. The accumulation of oxide particles quickly fills the space among the high spots. An entire group of high spots thus unites into a single area. These united areas will. develop into large pits as the process continues. The rate of weight loss thus increases sharply during this period, as the abrasive action is very effective when the layer of oxide particles is thin. The abrasive action itself will tend to thicken the layer of oxides and thus the rate of weight loss will begin to decrease as time increases. The oxide particles eventually escape into the depressed regions associated with the largo-scale waviness of the surface. This eventually leads to a thickening of the layer of oxide particles over the entire area. As the oxide layer becomes thicker and thicker, further increase in the thickness has less effect on decreasing the abrasive action and the rate of weight loss thus tends to reach a steady state.

-23-

the dependent and a maxed by them is not too mood. The original heiding is velocy out, being istudied over a relationly wallmeder of score-line blan spots. A motion investoring of landing black broade the wave pressent therit. These two formation consider to come a locally off of the retu of many, and a bening to retive as a closer plate when.

The icene was particles tend to be crucked in the Mailance of the mall-actic employee of the suffrees, the to be the mall and had of relation environ. Times loom must writely an an incharge a statistics forday the hort wills Yes, or the toreslables of units particles quick fills his years the idea white in out it and the black woods black without takes a storig most. These with a create will develop intervent of the process and the process of volume. I as this house a share of sucher this period, as the chrastin soliton is very effective along him layer of under problem in term, The advector article (their will have to this be light at the light at the light and then blue with an announce of adapt first and driller in the barrenses. han nor beninged off ofer searan of Easterna and dirig align of clicchrown sight and be mandress also - ages with fills basedownes Looks by a vidamental of the lapse at spide particule over the widen second and a los of the los wolden the contract with the los of the the sounded available of the bas dealer and the sounded of at the side of watches I use there have been by should a should be back and

-23-

The foregoing analysis was roughly substantiated by optical observations. After a run of 500 cycles duration, the reddish oxide could just be seen with the maked eye and was quite visible under the microscope. In the vicinity of 200 cycles, some reddish oxides were just visible under the microscope. Examination of the specimens run for about 50 cycles showed no trace of oxides. These observations tend to check the analysis of the shape of the curve.

It is felt that the results presented in Figures VI and VII should only be treated in a qualitative way. The data presented is rather limited in amount and somewhat random in nature to be considered quantitatively. This data should be substantiated by further experiments. If the present test machine were altered to produce frequencies in the neighborhood of ten cycles per minute, it should be possible to obtain a much better quantitative result. It would also be beneficial if a finer balance were used for measuring the specimen weight loss. Additional tests should also be made in the range a little above 10,000 cycles, and the entire range repeated in different atmospheres.

Figure VIII presents a curve of specimen weight loss versus the depth of damage. The data for this curve is inadequate to determine any exact relationship between weight loss and depth of damage. The curve does indicate, however, that the depth of damage should be able to be used as a substitute for weight loss in the measurement

-24-

Testine of bonomous of the or the define related of

observations. Mitter area of 200 crains durates, or reduicing maids couply, but is area with the mated one and all quite statile under the diservance. In the visiontry of 200 crains, now which he could a set is a but visible mater the addresses, bandantion of the mateions are for the boot 50 cycles showed on teness of colder. These deservations tool to check the madyris of the single of the static.

It is not a second in results proceeded in Egreen VI and VII should only to tracked in a qualitation may. To take presented is rother liabled in around and councies reader to mism to in coordiant providationly. This ists straid to another liable by forther experiment. If the present test model to another liable produce frequents to the malphorhood of the estimate and, it would also be been algorithm of the straight and to the would also be been algorithm. The first balance was used for the would also be been and first balance was used for the male is do not all if a first balance was used for the male is do not all if a first balance was used for the male is do not all if a first balance was used for the male is do not all if a first balance was used for the second of the provide is a state of the second for the second of the provide is a state of the second for the second of the provide is a state of the second for the second of the provide is a state balance was used for the second of the provide is a state of the second for the second of the second of the second of the second for the second of the second of the second of the second for the second of the second of the second of the second for the second of the second of the second for the second of the second of the second for the second of the second of the second of the second for the second of the second of the second of the second for the second of the second of the second of the second for the second of the second of the second of the second for the second of the second of the second of the second for the second of the second of the second of the second for the second of the second of the second of the second of the second for the second of the second

Henri VIII primeria a oursen of speciator weight from warman the depth of durage. The data for this curve is incompare to deform mine any oursely relationship introduct raight loss and wete of durage. The errors due failents, homever, that the oopth of durage thereid be able to be treat as a schettbake for which lose in the anomaly incomed be

-

of fretting damage. From this data and the preceding discussion of area measurements, it is felt that any attempt to use area as a measure of fretting damage is impractical. It is recommended that investigations be conducted over a wide range of cycles and in different atmospheres; and the relationship between specimen weight loss and the depth of fretting damage be firmly established.

-25-

of Section (. . In this take and the recession consumdon of area concourter, it is faile that the organization to us mean a measure of Section demon to there will all the moreounded that is still areas of section of a section of a section in different the orificted over a vide many of areirs and in different the depth of frething demon be first, could held reside form and her depth of frething demon be first, could held the first of the depth of frething demon be first, could held reside to the depth of frething demon be first, could held the first of the depth of frething demon be first, could held held.

100 - 100 - 100 - 100 - 100 - 100 - 100 - 100 - 100 - 100 - 100 - 100 - 100 - 100 - 100 - 100 - 100 - 100 - 100

the state property in the last state and the state of the

V CONCLUSIONS

The significant conclusions drawn from this investigation are as follows:

- 1. A unidirectional surface polish with No.000 emery paper is satisfactory for measuring the area and depths of individual pits.
- 2. A unidirectional surface polish with No. 00 emery paper is satisfactory for measuring the depth of fretting damage.
- 3. The use of any area measurements of the depth of individual pits as a substitute for weight loss is impractical.
- 4. The specimen weight loss due to pickling is not a constant but is a function of the amount of fretting damage.
- 5. The curve of specimen weight loss versus the number of cyclos run is initially concave downward. The curve then becomes concave upward followed by a downward curvature loading to a steady rate of weight loss.
- 6. The depth of fretting damage may be used as a substitute for weight loss in measuring fretting damage.

-26-

V. OCNUTAKION

The might local constructors dense from this formulantian

- A making which and fine politic wine is.000 speep rates
 A making whorp for spacesting the same and onghins of innimited pine.
- a regularezitarzi corface polich while to. 00 enery poor is additionatory for manufact the dopth of fraiding diracto.
- The use of any area sessionershe of has depice of fairfilling pills is alesticate for sedric loss to improvided.
 - b. The monthed watched loss ine to phobling for both a comptone.
 - 5. The owner of meetings which i lose versus the masses of opolas was is initially consume communi. Her store then below conserve opened followed by a dominant committum leading in a shady rule of weight lose.
 - The Anghle of Freiliden design may be used as a milethrough for reduity lots in neuroscing froiting domain.

-

VI RECOMMENDATIONS

The following recommendations for future work are mude:

- 1. An investigation should be made to determine a method for finding the true weight loss of the specimens.
- Additional tests should be made in dry air plus other atmospheres, to substantiate quantitatively the shape of the curve of fretting weight loss.
- 3. Tests should be run at a frequency in the neighborhood of ; to 10 cycles per minute to quantitatively determine the very early portion of the curve of fretting weight loss.
- h. Investigations should be conducted over a wide range of cycles and in different atmospheres to determine the quantitative relationship between the depth of fratting damage and specimen weight loss.

-27-

THE FORMATION AND

The full day remains the finites with a same

- 1. An Lon-disetton dealt to adde to deta mine a set of for
- Additional teste darable to and in any air (los offers threadeness) to addresserizate quantitatively the drops of the serve of fastiling weight low.

 - i. Investigation should to contacted over a side many of synlos and in oll/scene characters to determine the openidicitys relationship between the explicit of fretting coners and specimum related.

VII APPENDIX

within my limit transfer with another primary suffer Erit and

MARTIN A ILY

Annual in the same in the last of the same in the same

second in case where here a reason is the second se

APPENDIX A

SUPPLEMENTARY INTRODUCTION

J 10 11 DITUUSION SAME SAME ~ 5m

SUPPLEMENTARY INTRODUCTION

DESCRIPTION OF APPARATUS

The fretting test machine used for this investigation is shown in Figures I, II, and III. The machine was designed by H. H. Uhlig, W. D. Tierney, and A. McClellan and is described in detail in Reference (8).

The machine was designed to produce fretting damage by oscillatory motion of two pairs of test specimens held in place by two moving and two stationary chucks. The chucks allow the tangs of the specimens to fit into a clearance slot. Opposing pairs of set screws in the clearance slot of each chuck, acting against thin shims, clamp the tang perpendicular to the axis of the specimen. The shoulder of each specimen is seated against sheet mylon cemented to the chuck to avoid fretting at this area. The two moving chucks are shrunk on square milled sections at opposite ends of a square shaft. This shrink fit provides a positive joint and minimizes fretting in this area of the machine. The square rocker-arm shaft. which carries the moving chuck, is pinned and bolted to eight leaf springs. These leaf springs form two co-axial crosses, which are bolted and pinned at their extremities to a square cage. The laf springs thus provide a bearing which will allow small torsional oscillations but which is extremely stiff with respect to any lateral motion.

-30-

NULTRADUCTIC TRATISTICS.

THE AT A TO SOLTS A DECK

De Brettin test modime and for this Lowerhigelie is shown in Figures 1, 12, and 111. The months was deciged by R. H. Willy, N. D. Showey, and A. McChellan and in described in detail in formerine (0).

The problem was destined to produce freehold of peollinger method at the poles of test spectrum haid in place by two anythe and two stationary country. The enacts allow the the private and the contract of the of the private of the sound of ont serves in the elevence alot of such shade, eching analyst thin shine, Lucy the Lucy or a willoud as to the adde of the availant. the shorting of all metanes is and a submet of mylum commented source the entrie of the source and the addition blocks of there add of are threak on square allies near in opposite must of a square toahunda na hibi ethi hog a abbreve (51 seiste abfr. . Staa frotting in this same of the wolling. The squere rocker-and have, The study of endlose has there at sleans at all success and serbres. Norm last switter form two co-artal crosses, which my bolted and allowed a common a born to a route one ballo optimize the provide a learning shade will allow some in a second or dillation has manned a variant suit will reason to any interval , noldae

-

An I-beam of aluminium is shrunk on the rocker arm shaft at its midpoint, and is the member through which the motion is applied to the shaft. One end of the rocker arm goes to a cam drive and the other end to a coil spring used to keep the rocker arm in contact with the cam. A variable eccentric in which rotation of the sheeve relative to the shaft changes the eccentricity is used to vary the amount of relative motion between the specimen pairs. The drive shaft is connected to a three-phase, one horsepower motor, operating at 1300 rpm, by a system of V-belt pulleys which allows tests to be conducted at a number of different frequencies.

The normal load between the fixed and moving specimens is applied by pneumatic pistons actuated by high pressure nitrogen. The pistons have hardened spherical ends which bear on hardened plates pinned to the back of end-bell diaphrams in order to transmit the load through the fixed chuck and fixed specimen to the test surface.

To conduct tests in other than laboratory air, two split rectangular cells are provided. Each cell is clamped over a mated pair of specimens and the desired environment is then introduced to the cell. A glass window bolted and cemented to the top of the cell allows observation of the specimens during test.

The standard test specimen (shown in Figure IV) is cut from SAE 1080 cold-finished steel. The specimen is one inch in diameter and one inch long. One end of the specimen is counterbored 7/8 inch

-31-

In T-base of clarifiers is derive on the collector are such at its addpoint, and is the parties through which is action to another to her staft. One and of the rooter are man to a construct and the other set to a solid spring used to boy the resider are in nontead with the sum. A relacie secondrife in which relation of the silonin all the to the abuse construct the action relation of the start with the sum. A relacie secondrife in which relation of the start with the sum. A relacie secondrife in which relations of the start with the sum. A relacie secondrife in which relation of the start with the sum of the abuse construct the action relation of the start with the sum of the abuse construct the action of the start with the sum of the abuse construct the action of the detive shaft is commetted to a furne-phase, so homework with a constitute to be sumpleted on a matter of different integration.

The averal load between the fixed all porter sportance is applied by semantic distant an arbitrary of the moments difference in pictors then hardward sports I sole which bur on burdand pictors ployed to the task of mi-ball discloses in a def to be the load through the fixed simple and fixed modium to the best curface.

To concrete terms in other then laboriery at , the well's rectance of a second of the destried and sell is there is noted pile of evidence and the destried environment is then is noted to the sell. A runa statew bolted and commune to are here at the coll siller observation of the speciment destrict here.

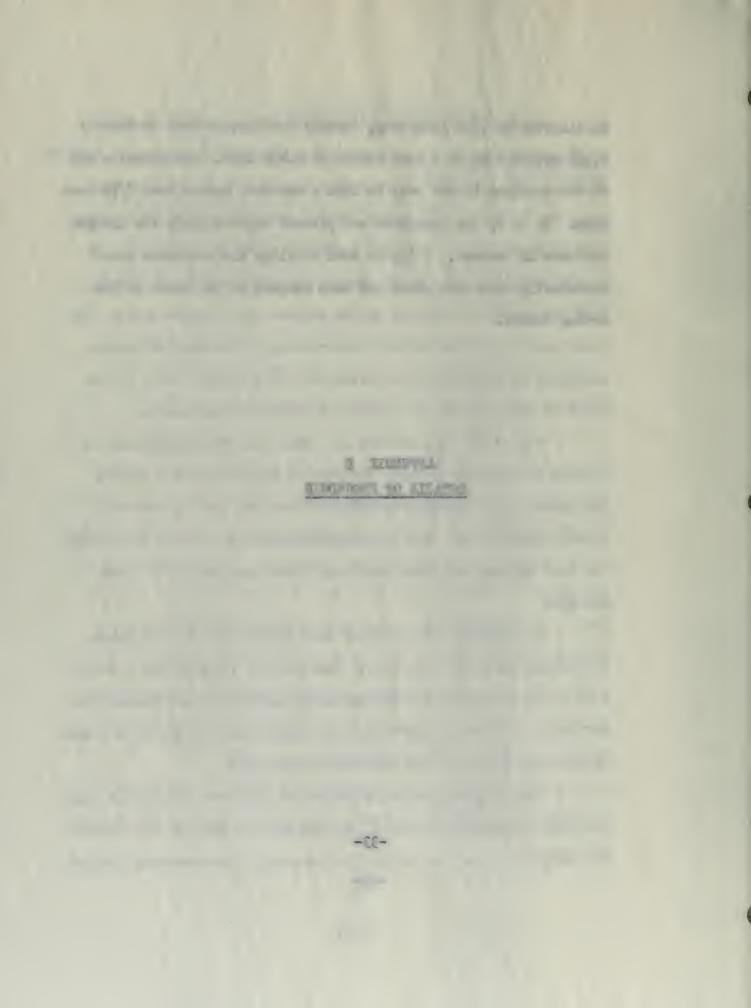
The tradied book speciame (shown in Furner IV) is out from the 1000 anti-Firstered steal, The speciment is and inch in Manusker and one insta Long. One and of the speciment is questioned 7/6 that in diameter by 1/16 inch deep, forming and annular test surface of 0.184 square inch at a mean radius of 0.438 inch. The opposite end of the specimen is cut away to form a centered square tang 5/16 inch long. In test, the specimens are pressed together with the annular surfaces in contact. A jig is used to align the specimens concentrically with each other and with respect to the shaft of the moving chunks. In diameter by LVM for a dampy for day on a will a second a market of 0.1M square limb of a war reason of 0.13% limb. The spaceties was all the specific in the mark may be form a market of our first limb lang. In tool, the marketon are proved bound or the land. marketon is consist. I the is used to all a the marketon acts are brind if the ises of the and the all a the inclusion of the are brind of the ises of the and the all a the inclusion of the are brind of the ises of the and the all a the inclusion of the are brind of the ises of the and the all as the inclusion of the are brind of the ises of the and the all as the inclusion of the are brind of the ises of the and the all as the inclusion of the

Condition, Spectral

All a day both or reactions of product the book open back, "the last control on a second office through a both of the second is a value by second of these the both of the second second of the second

APPENDIX B DTTAILS OF PROCEDULE

a had were not in the bird apples only remains hering a manner module within and they's 3 here y types a "were to think infinitein and any of set the manufactury way state have a linear transmitter and a set of a "were the set of the particular transmitter in the bird of the set of the set of the linear state of the set of the field in the bird of the set of the linear state of the set of the field in the bird of the set of the linear state of the set of the field in the bird of the set of the linear state of the set of the field in the bird of the set of the linear state of the set of the field in the bird of the set of the set of the set of the set of the field in the bird of the set of the set of the set of the set of the field in the bird of the set of the bird of the set of the bird of the set of the bird of the bird of the set of the bird of the set of the bird of the set of the s



DUTAILS OF PROCEDURE

All of the tests were run under a standard set of test conditions, varying only the number of cycles that the tests were run. The test conditions were selected after a study of reference (8), and were so chosen that a substantial amount of damage would be caused in a fairly short interval of time. The standard conditions selected were, a normal loading of 5300 psi, a relative slip of 0.0036 inch and a frequency of alternation of 79 cycles perminute. The atmosphere chosen was dry air at room temperature.

Having selected the test conditions, several tests were first made to determine an approximate number of cycles at which the fretting damage was significant yet such that it was possible to identify individual damage pits. The surface of specimens for these tests was given a random polish with No. 1 emery paper.

A test was then run for 10.5 cycles using specimens having a random surface polish with No. 1 emery paper. Prior to final polishing, the surfaces of all the specimens were given three diamond indentations spaced approximately 120 degrees apart. These diamond indentations were made using a Vickers Hardness Test machine and a diamond indentor having a major axis ratio of 35 to 1 and a minor axis ratio of 6 to 1. The loading used on the Vickers machine was 20 kilograms. Upon completion of the test, several individual pits were selected at random from one specimen and photographs taken of them using a magnification of 120X. A photograph of one of the diamond indentations was also

-34-0

a vicinity do Vitrain

Ell af fun taste were ran under a standard set of fact conditions, varying only the makes of sycles that the backs were ran. The back modificate were enlanted after a manip of reference (0), and were to choose their a maket of the second difference of point he a fairly deriving the interval of them. The skewled conditions expected many, a second loading of S200 pet, a relation offer of 0.0030 here and a frequency of situatedian of 19 cycles perfected. The stanget domain an day of situatedian of 19 cycles perfected. The stanget domain and offer of situatedian of 19 cycles perfected. The stanget ofference

Reader to determine an experimination of avoid the second treat and to determine an experimized and we of avoid an which has the thing damage now significant pet much that is was presible to thenhilly individual damage pite. The extins of speciases for these were determined and which he, i service of speciases for these were eiter a reader polich with No. 1 service parts.

A test we due one for 10.5 appine with a final poliching a maximum earther polich with the 1 every power. Atten to final poliching, the surfaces of all the module ware given trave blaced indextations for a pacet approximate to all the module apart. Then dimensi indextations aparts are also approximate to all the module aparts. The dimension indextation ware approximate and a dimension indextation ware approximate and a dimension indextation aparts are and a dimension indextation aparts are and a dimension indextation aparts are also aparts. The dimension indextation of the test and a dimension indextation aparts are also aparts and a dimension indextation aparts are also aparts and a dimension indextation of the local approximation and a dimension indextation aparts are also aparts aparts and a dimension indextation aparts are also aparts aparts and a dimension indextation aparts are also aparts aparts and a dimension approximate and a dimension approximate and a dimension aparts and a dimension aparts aparts aparts are aparts aparts and a dimension aparts a

taken using the same magnification. The specimen was carefully dressed down by hind, using No. 000 and No. 0000 emery paper, until each pit under o servation just disappeared. As each pit disappeared, a photograph was avain taken of the same diamond indentation. The area of each pit was measured from the photograph using a planimeter. The depth of each pit was determined by the difference in the successive indentation photographs using the trigonometric relationships for a right triangle.

A test was run for 5 cycles duration at a frequency of 79 cycles per minute. The surface preparation was a unidirectional polish with No. 0000 emery paper. Another test was run for 10 cycles at a frequency of 57 cycles per minute. The surface preparation for this test was a unidirectional polish with No. 000 emery paper. Four to six individual pits were selected from each of two specimens and the area and depth of each pit was determined as set forth in the preceding paragraph. These tests were run at different frequencies and with different surface finishes because it was felt that the pit growth should depend only on the length of time that the pit uas allowed to grow.

A number of runs were made varying the duration of test from 10 to 300 cycles. The surface preparation of the specimens for these tests was a unidirectional polish with No. 00 emery paper. All specimens were weighed before testing and were pickled and weighed after testing. One specimen from each of six tests was selected and a photograph taken

-35-

water order the new mynification. The am other monomolity drawing dawn in t al, wing To. 000 and To. 000 war parts, would wash ply draw stream they have it may need to a solution a photoseresh was a sin taken in the ansa dimensi interaction. The sea of and ply on measured from the ansa dimensi interaction. The of and ply of each ply was interacted from the dimension with a hoph of each ply was entered from the dimension with a dimension. The information state and with the televanementation with a second information and a state the televanementation with a second information and a state the televanementation with a second right tetting to a state and the televanementation with the state of the tetlevanementation of the televanementation of the second right tetler.

A boost was run for 5 myeles dametion al a fractancy of 79 syches we situes. The surface presention were an indifferentional solidated to the second second dense in the second second second a frequency of 57 ageles per single. The second second second second best mere a multiple of and called of a 10, 000 energy second. For the effect hellwilled ying are minded from each of two spectations and the second second second of the second of the second second second meres and decide of each pills were delargeland as set for the products are and decide of each pills were the rest for the frequencies and with survay and decide of each pills were the rest for the frequencies and with all former to be found to the second of the second to the products all formed as a set of the fourth of the back with the second state of the second of the second of the second to the second state of a second set for the back of the second of the second state of the second of the second of the second of the second state of the second of the second of the second of the second states of the second of the second of the second of the second states of the second of the second of the second of the second states of the second of the second of the second of the second of the second.

I combine of beam ware and a weyding the during of beek from 10 to 300 comits. The meriade susparation of the spectrum fre them both war a midlewithreat colder with 10.00 corp page. 111 contracts many variable to the bootton and man picture of mid-od with beam. Our excitant these costs of the both our mid-od with the our excitant these costs of the both our mid-od with the second sector of the both our mid-od with the second sector of the both our mid-od with the second sector of the both our mid-od with the second sector of the both our mid-od with the second sector of the both our mid-od with the second second of the second sector of the both our mid-od with the second second of the second sector of the both our mid-od with the second second of the second sector of the both our mid-od with the second second of the second sector of the both our mid-od with the second second of the second sector of the both our mid-od with the second second of the second sector of the both our mid-od with the second second of the second sector of the both of the second of the second second of the second sector of the both our mid-od with the second second second of the second second of the both of the second of the second second second of the second second of the both of the second of the second s of the entire frotted surface. The photographs were enlarged until the specimen was 10 times its original size. The entire area of damage was then measured using a planimeter. The deepest depth of damage was then measured, the specimen being dressed down until all damage just disappeared. The technique for measuring depths was the same as that used before except that the standard Vicer's diamond indentor was used with a h0 kilogram load. The standard indentor was used since it was felt that the depths would be too great for the previously used indentor.

A second series of tests was made varying the duration of test from 1 to 10,000 cycles. The specimen surface preparation for these tests was a aim a unidirectional polish with No. 00 emery paper. The specimens were again weighed before testing. Upon completion of the test, the specimens were rinsed in boiling benzene, dried and weighed. The specimens were then pickled and weighed a aim. All specimens were then given a second pickling and reweighed. After the second pickling, one or two specimens from each test were given a diamond indentation with the standard Vickers indentor using a load of h0 kilograms. The small ridge formed around the indentation was carefully dressed off and the deepest depth of damage to the specimen then determined as previously outlined for the preceding tests.

FOR ME DAMA AND AN ADDRESS WARRAND AND ADDRESS INC.

-36-

To attribute

of the anithe field of raises. The photoests was added that a be question for 10 theor for relation date. To taking one of dates the site of the relation of ductor, the bound depin of dates was the manned, the method being treased can meth all demonstrates there also a start the dates treased can meth all and a probable of the second on the second of the relation to the rest of the second of the formation of the second of the taken of the second of the bound of the formation of the second of the taken of the second of the bound of the formation of the taken of the second of the bound of the second of the second of the taken of the second of the bound of the formation of the second of the take method is and the bound of the bound of the second of the second the restard of the following the depthe would be too grade for the restard of the following.

A necessitization of forther and mode recovery the modules of book from 1 to 10,000 synthet. The specifies service properties requiring a synthethere to be an a min a restitue crucial poliar with 10,000 emerging or the specification was about balling brances, then normalation of the test, the specific or a mergeles of the boliging brances, there and whitted. The specific or a mergeles of the boliging brances, there and the second (bibling) are not react a polyhering to the bolig operations are to the specific of the boliging brances, the time account (bibling, and to the specific of the boliging brance of the second (bibling, and to the specific of the bolig of the second (bibling, and to the specific of the bolig of the second (bibling) are not of the ball of the ball of the second (bibling) are not off to be bolig of the bibling of the balance of the ball of the ball of the the second (bibling) are not off to be ball of the ball the balance of the bibling of the ball of the ball of the bibling to the bibling of the ball of the ball of the bibling to the bibling of the ball of the ball of the ball the ball of the bibling of the ball of the ball of the bibling to the bibling of the ball of the ball of the ball the ball of the bibling of the bibling of the ball.

PREPARATION ID CLANING OF SPICINGINS

The test specimens were given the desired surface finish by hand polishing on emery paper, using a polishing guide to maintain a flat surface. The specimens were then cleaned in acetone and weighed. The specimens were then clamped firmly in the test machine and the full test procedure applied.

When the test was completed the specimens were degreased in hot benzene. Depending upon the particular test under study, the specimens were then weighed, or pickled and weighed after pickling. The pickling procedure was carried out as follows:

- The specimen was immersed for 30 seconds in a pickling solution heated to 50°C (120°F). The pickling solution is 5% by weight sulfuric acid and 0.1% by weight of quinolinethiodide, a pickling inhibitor.
- 2. The specimen, held in tongs, was taken from the pickle solution and placed under running water.
- 3. The fretted surface of the specimen was then scrubbed with a stiff bristle brush and rinsed again in running water.
- 4. The specimen was then rinsed in hot acctone followed by a rinse in boiling distilled benzene.
- 5. The dried specimen was placed in a desiccator and left for at least one hour to allow thermal equilibrium to be attained.
- 6. Each specimen was then weighed and the weight recorded.

The state of the state of the second

The the contactor ware direct the desired contace their ophard publicher on more paper, where a subjecting while to subplice a flat surface. The speciment ware then all and is welcase and soluted. The sesteme ware then alwood firstly is the tast archites all the full heat providers applied.

Nam Aba bart was completed the most was work depressed in het horares. Republing upon the perficular fort wher shely, for species after large the stated, or tighted and vehicles flur ploiling. The ploiling reconverse are carticle on a follow:

- We specially mus finner/ed for 20 succells in a pishting wain/ing bushed in St"S (100°2). The picklin -eoleking.
 - in adjuter of 41.0 how how scrutter distance of 12 at
 - and the set of the solution a deciding the the

 - The Strailed mortion of the execution and then encoded mitting a statistic break and strain in equilary meter.
 - 4. She meetime are then ethant to int sectors followed by a -tage 1s follow of tabilited bargers.
 - S. The drind epartmen was placed in a distanting and laits the for the level as wave to allow the module to be allow the set attack.
 - 6. She c'at a with a with a to the today is south.

and an Alta Man

The summary of any operation many one constraint is barried to be and the second state of the second state

APPENDIX C SUPPLEMENTARY DISCUSSION

The number weight from our measured with its marphing fitting that that the Sch attribution, "20" is this that the overrapy tory to be prevent, perturbutions to be taken if would within here, to be replaced in the pair with spectrum to be taken index, such that by a suffered street.

At its constantion times the server developed for pickting its anglighted on the provide gridge from all all publicly its range my

-38-

D THE MORE DE CONTRA

-86-

And the second s

SUPPLIEMENTARY DISCUSSION

The diameters of the specimen faces were accurate to 0.0005 inch. With careful hand polishing on a flat glass or steel plate, the error in the surface flatness of the specimens was negligible.

NT RAIS ANYTH

The pressure at the interface of the specimens is estimated to be within \pm 30 psi. Even with an accurate pressure gauge there is an error. If the faces of the two specimens do not meet exactly parallel and together with no pressure applied, a small amount of pressure is necessary to bring them into contact when the test begins.

The frequency of alternation was checked periodically and was accurate to within ± 1 cpm. The total number of cycles run, measured with a counter attached to the eccentric shaft, was estimated to be accurate to within ± 5 cycles in 10,000 cycles.

The specimen weight loss was measured with an analytical balance that read to 0.1 milligram. It is felt that the accuracy here is in question, particularly in the regions of small weight loss. It is recommended that each specimen be weighed twice, each time by a different person.

It is estimated that the error involved in pickling is negligible. This is particularly true if all pickling is done by the same person and is done in exactly the same manner each time.

-39-

i c I i i

the state is the excluse flattens of the spectrum we were readed.

The process of the interface of the conductor is anti-stat to be within ± 10 ml. from with an executede protecte place there is an error. If the faces of the two constants is not and empiric placellel and buyether with so pressure upplied, a mull mouth of pressure is postmary to bring them into concept the test being.

The frequence of Alterestion was dested periodically and was socured to sticking 1 apre. The tobal mader of colles way, manched with a counter of a side of the second via society, sur asticuted to be assumets to with a t is evolve in 19,000 yelos.

When more than not the low measurement with an analytical balance that small to 0.1 milligner. It is fall has the more way have is in qualiton, burticularly in the regimen of mull weight form. It is recommended that such are simple to weight bulles, and then by a different corner.

It is not used the error include in dation is realized. Thus is not foul view if all position is done by the and puriod at is done in caucily the any much wine, the

and them

There are errors involved in the measurement of the depth of damage. If the two specimens do not meet exactly parallel, the pressure is not the same over the entire surface of contact. Since the depth measured is the deepest found, this difference in pressure will introduce errors in the measurement. The diamond indentations may also introduce errors if they are not exactly correct. It is felt, however, that the standard Vickers indentor this error is usually negligible. There is also an error introduced in the measurement of depth due to an inaccuracy in determining when the damage just disappears. If the dressing down is done by hand, and all observations are made under a microscope, it is felt that this error may be reduced to the point where it will also be negligible. ANALYSIS OF SPICIMEN STOCK

The certified mill analysis of the SAE 1018 cold-finished steel used in the specimens is as follows:

Carbon, percent	0.15
Manganese, percent	0.75
Phosphorus, percent	0.008
Sulphur, percent	0.027

A check analysis made by the Department of Metallurgy indicated a carbon content of 0.16 percent. Mana as arranged in the anumentation of the argins

or dense. If to be parines to not it a white or list, the near to are the as over to entire sailed of contest. Since the defineseered is no depert oreal, but different in pressed will triveled a more if the number of a duroni intervices any ise in orea areas if no are not sholl, correct. It is if it, ho are, "et al."" and different intervices is nearly areline. The is is on orre in roomed in the second state is a to or orre in the order of a during just it. The or simpler of a list of a state is a second of a second in the second of a difference. If he or simpler of a list and the state is a second of a second of a second in the second of a difference. If he or simpler of a list of a state is a second of a difference of a list of a second all denovations are added and a second of the second of a list and the order of a difference. If he or simpler of a list and the state is a second of a difference of a list of a second all denovations are added and a second of the second of a list.

NIXAD IN THE PARTY

The cock int and relate of the Wo 101, cold-Christened

0.15	371102 en 1923
0.75	Same en anno
900.0	Accessing Concomposition
720.0	Non- , state

A check wilreds and by the Brownant of Wallary tableshed

ann 1 stan

- Ar Draw International Concession of the State of Concession of Providence's
- As Finite Country in the lot of t
- the standard of the second strategy (Lesson), which had,
- A. Sandhard and S. Sandhard S. Sandhard S. Sandhard S. S. Sandhard S. Sandh
- As have been a brand morning with third, shit, \$, 50, 2, Denary, 1999, 199
- APPENDIX D LITERATURE CITATIONS
- No. 1992 Manager, "Surgery process of themping by Managers's Statements
- No. Bally Bally Second of Period of Borrestin', Bit Problem, S.
- ¹⁴ Delay Deliking "An Articular of the Different of Tarran Distance on Article Distantions with distr formation Spectrums Delay of Darra Distance in Article Minister, 19 Dist Builds Sufferent of Federalization on Board Destantion and Hint", from its positions.
- LD. Surger, Lothing, "In matteria of the littlers of Variani Mathematical and denoid Typenative and Son," between Spectrum Philes of Consumation and Lines Engine LL. However, all the Sorresponding Statistical and constantiation.".
- (1) United Lifety, "in Departmentary in Protocol Containing Conversion," Int. U. Inc. 11, Intelligible pp. 105.
- The birth with the bound, the products and like both of the birth

put the part of the second sec the state of the s the party of the local state of the party of a strength and a strength of the second stren INDIVITION IN THE REAL PROPERTY OF THE REAL PROPERT e

LITERATURE CITATIONS

- 1. Fong, I-Ming, and Rightmire, B.G., "The Mechansim of Fretting", Lubrication Engineering, Vol. 9, No. 3, 1953, p. 134.
- 2. Fong, I-Ming, "Motal Transfer and Wear", Journal of Applied Physics, Vol. 23, No. 9, September, 1952, pp. 1011-1019.
- Tomlinson, G.A., Thorpe, P.L., and Gough, M.J., "An Investigation of the Fretting Corrosion of Closely Fitting Surfaces", Proceedings Institute of Mechanical Engineers (London), Vol. 141, No. 3, May, 1939, pp. 223-237.
- 4. Warlow-Davies, R.J., "Fretting Corrosion and Fatigue Strength. Brief Results of Preliminary Tests", Proceedings Institute of Mechanical Engineers (London), Vol. 146, No. 1, November, 1941, pp. 32-38.
- 5. Dies, Kurt, "Fretting Corrosion, Chemical-Mechanical Phenomenon", The Engineer's Digest (American Edition), Nol. 2, No. 1, January, 1945, p. 14.
- 6. Sakmann, B.W., and Rightnire, B.G., "An Investigation of Fretting Corrosion Under Several Conditions of Oxidation", NACA Technical Note No. 1492, June, 1948.
- 7. Godfrey, Douglas, "Investigation of Fretting by Microscopic Observation", NACA Report 1009, 1951.
- 8. Uhlig, H.H., Feng, I-Ming, Tierney, W.D., and McClellan, A., "A Fundamental Investigation of Fretting Corrosion", NACA Technical Note No. 3029, December, 1953.
- 9. Feng, I-Ming, "An Analysis of the Effect of Various Factors on Metal Transfer and Wear between Specimen Pairs of Same Metal and Same Shape. I. The Basic Scheme of Formulation of Metal Transfer and Wear", (to be published).
- Feng, I-Ming, "An Analysis of the Effect of Various Factors on Metal Transfer and Wear between Specimen Fairs of Same Metal and Same Shape. II. Effect of the Surrounding Atmosphere", (to be published).
- Wright, K.H.R., "An Investigation of Fretting Corrosion", Proceedings Institute of Mechanical Engineers (London), Vol. 1B, No. 11, 1952-53, p. 556.
- 12. Shaw, M.C., and Macks, E.F., Analysis and Lubrication of Bearings, McGraw-Hill Book Company, Inc., New York and London, 1949.

a fail of a solution of

- 1. Fordes (- Lines and Laboratory Leos, "The anti-ask of Frentzine", Laboratory Backmenting, Wall, 0, Da Fr. 1911, p. 131.
 - 2. Nage 1-Burg, Terral receiver une Weit", imprest of Angliant Floriton, Vol. 15, Sc. 9, aptember, 1982, pp. 1031-1016.
- 3. Tenlinson, 2., Thorpes, M.L., and South, L.G. M. Leverth et im of the Freethin German of Lowely 543 action, Presenting Thethere of established budgents (Lowen 1993, 18), To. 5, Ray, Life m. History.
 - 4. Wirkenwirder, L.H., To vic Corners and Friender, Frier Boah of Friender, Social, Frie Charlenter Sochurizal Augusterer (London), DJ. Len, F. L. Forenbar, 1942, 50. 1-0.
- M. Mart, "Institut Correction, Classical and all for marting,", The Gradinant's Digmat (anarteen Meltine), Mat. 2, No. 1, 200005; 1940, 5. M.
- 6. Submun, D.V., and defautra, D. An Invertigation of Freitung Bornelin Teder Several Souththes of Calentine, ONTA fooduicel Note No. 1102, Ann. 1949.
 - Godfrey, Hougher, "Dermenting time of Francisco by Manoneouto Observentor", Stok Encore 1600, 1901.
 - O. Uhlig, M.J., Mars, 1-1-16, Pharman, M.J., and Dollarine, M. S. Punderson and Connect (contact) (Corporting", Nach Tenhalani Note in. 8000, Descent, 1400.
- Party, Felduge, No Audigete within (fresh of Version Patrice of Mercal Versation and Near Determine Spectrum Patrie of Asses Mercal and Same Mayes. 1. The Merca of Version School of Mercales and Merca. (as an product of Version School of Version School of and Merca.)
- 10. Nong, L-Ching, "A scaling and the Fflord of Torsan Instance on Heal Inseries of New Torsa of Los Montes, Petre of Loss and Sens Shape. It offers of the Hormoniting Assumptions", (bo be publicated).
 - Wright, and . As forestly Mon of Freditor Content.
 Proveduce institute of elemental heliperte (builden). When it's
- 12. Marry Melling and Marry Marrie and Marrie Marry of Harrison



- and the second s
 - And a second sec
- AND THE REAL PROPERTY AND ADDRESS OF THE REAL PROPERTY ADDRESS OF THE REAL P
- And the second second in the second in the second in the second s
- And the second s
 - And a second sec
- And and the second second in the second in the second seco
- or and a second the second sec
- And a second of the second of





