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EFFECT OF THREADED AND SERRATED HOLES ON THE LIMITED TIME AND FATIGUE STRENGTH OF FLAT LIGHT-ALLOY STRIPS

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EFFECT OF THREADED AND SERRATED HOLES ON THE LIMITED TIME AND FATIGUE STRENGTH OF FLAT LIGHT-ALLOY STRIPS*

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The investigation was made for the purpose of ascertaining the notch sensitivity of flat strips of light alloy with cylindrical holes under initial tension stress, with special attention to the change in notch-effect factors with the number of load cycles. Then the studies were extended to similar flat strips with pin-loaded holes (tension lugs).

SUMMARY

The present report deals with fatigue tests under initial tension load on flat test specimens of 3116.5 duralumin and AZM 3510.1 electron with plain unloaded and pin-loaded holes (tension lugs) of different forms. From the findings, which are presented in the form of Wöhler curves, the ratio $\sigma_{orig}:\sigma_{n_{orig}}$ (notch sensitivity factors β_k) and $\sigma_B:\sigma_{n_{orig}}$ are computed for 10^4, 10^5, 10^6, and 10^7 number of cycles.

It was found that the notch effect of the serrated holes in both metals is greater than that of the threaded holes and that it, in turn, is greater than that of the cylindrical holes for both the unloaded holes and the pin-loaded holes. On the loaded holes the notch effect for all three forms assumes much greater values than on the unloaded ones; hence the limited time and fatigue strength of the tension lugs is considerably lower. While the fatigue strength ratio of plain and drilled specimens (notch effect factor) increases very little on the unloaded holes, it rises considerably with the number of cycles on

*"Über den Einfluss von Bohrungen mit Gewinden und Kerbverzahnungen auf die Zeit- und Dauerfestigkeit von Leichtmetall-Flachstäben." Luftfahrtforschung, vol. 18, no. 2-3, March 29, 1941, pp. 102-06.

the loaded ones. The ratio $\sigma_B:\sigma_{n_{orig}}$ increases much more with the number of load cycles, especially on the tension lugs. The exceedingly unfavorable behavior of the serrated tension lugs of the AZM electron was unusual.

In the remarks on the types of failure the peculiar location of the break on the serrated tension lugs is pointed out.

INTRODUCTION

A number of reports published within recent years deal with the fatigue strength of flat strips with "plain" cylindrical holes - that is, holes not intended for bolts or rivets, hence no pressure on walls of hole - which afford data on the notch effect factors β_k.

$$\beta_k = \frac{\text{fatigue strength by ideal design shape}}{\text{fatigue strength of notched test bar}}$$

of the drilled specimens. As to the form factors α_k themselves

$$\alpha_k = \frac{\text{maximum stress under ideal elastic behavior}}{\text{theoretical stress at notch from } \frac{P}{F}}$$

a large amount of data from photoelastic or other model measurements and strain records are available, so that the prediction of the fatigue strength of structural parts at points with holes offers no difficulty to the designer. Data are also available concerning the fatigue strength of pin-loaded tension lugs according to which the notch-effect factors on the loaded holes are considerably higher than on the unloaded ones. Thus, Thum and Bruder (reference 1), for instance, ascertained for St. 70.11 a rise in β_k from 1.23 on the plain hole to 2.8 - 3.42 on the pin-loaded hole, depending upon its design. All these data refer exclusively to cylindrical holes, but not to threaded holes or holes with other than circular section.

And in the majority of cases only the fatigue strength rather than the whole Wöhler curve is given, so that the notch sensitivity can be computed for the fatigue-strength factors, but not the corresponding proportional factors for the limited time strength. On the other hand, in aircraft design to the extent that the air frame is involved, it is the higher stresses corresponding to smaller number of load cycles the "limited-time strength," rather than the fatigue strength, which is of primary importance. Moreover, because of the occasional need for angular or serrated holes in repeatedly stressed parts, it is important to know whether and how much the limited-time and fatigue strength in such cases is superior or inferior to that of parts with cylindrical holes.

TEST SPECIMENS

With this in mind a series of tests was made on flat strips of two kinds of light alloy commonly used in aircraft design with a view to ascertaining the extent to which limited time and fatigue strength of the plain cylindrical hole is affected by other hole forms over the range of 10^4 to 10^7 cycles. Since it is anticipated that the serrated holes would cause a greater reduction in fatigue strength than angular holes, only the forms with serrated holes were studied. Experiments were also made on threaded holes and, to insure conformative data, on such with cylindrical holes and undrilled flat strips polished lengthwise with emery.

These tests on strips with plain holes were supplemented by tests with pin-loaded holes, that is, tension-luglike flat strips. These test specimens were simple double-shear pin joints, on which the middle tension lug represented the drilled flat strip to be tested.

All samples were 40 millimeters (1.57 in.) wide; the size of the holes being so chosen that in all three hole forms a reduction in width of 10 millimeters (0.393 in.) occurred in the test section. The ratio of hole diameter to strip width accordingly amounted to $d/B = 0.25$. The corresponding form factor for the plain cylindrical hole is $\alpha_k = 2.55$, according to Henning (reference 2). The serration 8 × 10 Kr 231 was secured by stamping out the teeth from the rough-drilled holes on a hydraulic press. The M 10 threaded holes were cut with three screw taps. The corresponding specimen shapes for the samples with unloaded holes are shown in figures 2 to 4, those with loaded holes, in figures 5 and 6.

The surfaces of the drilled samples were left in the as-rolled condition, the electron samples were, however, pickled on the surface. The sides were polished with no. 0 emery paper, and their corners and those of the cylindrical holes were slightly broken. The seating between the bore and the pins on the tension lugs corresponded approximately to the drive fit according to DIN standard 777. The undrilled flat samples (fig. 1) were rubbed lengthwise with 0-3/0-5/0 emery paper until the rolling and pickling marks just disappeared.

MATERIAL AND TEST PROCEDURE

The experiments were made with two light alloys (each), duralumin according to aircraft standard 3116.5 and AZM electron according to standard 3510.1. The material, available in sheets of 6 millimeter (0.2362 in.) thickness, had the characteristics shown in table 1. The shear pins needed for the tension lug tests were of CrMo steel of 90 kg/mm² (128.010 lb per sq in.) strength (standard 1452.5).

The testing machine was a 3-ton centrifugal pulsator (Schenck "pulsator") operating at a frequency of 25 cycles per second. The tests were made under initial tension stress; the mean stress produced by a prestressing spring was therefore equal to the stress deflection ($\sigma_m = \pm\sigma_a$). For reasons of time the load limit was set at 10^7.

Table 1

		Duralumin 3116.5	Electron 3510.1	
Analysis	al	rest	6.98	percent
	cu	3.81	-	percent
	mg	.73	rest	percent
	mn	.60	0.4	percent
	fe	.37	-	percent
	si	.54	-	percent
	zn	-	1.05	percent
Strength	σ_B	42.6	31.5	kg/mm²
	$\sigma_{0.2}$	29.4	21.5	kg/mm²
	δ_5	19.9	14.4	percent
	σ_{orig}	15.0	14.0	kg/mm²

RESULTS OF TESTS

a) Duralumin Samples

The experimental curves for the plain holes are shown in figure 7, those for the loaded holes in figure 8. Of the drilled strips in figure 7, those with cylindircal holes show the highest Wöhler curve, those of the serrated holes the lowest. The drop in fatigue strength of the samples with serrated holes amounts to about 20 percent. In spite of the steadily increasing divergence of the two curves in the range of a low number of load reversals, the percentage reduction remains about the same. On the threaded holes the reduction is only 11 percent and becomes still less in the limited time-strength range.

The Wöhler curves for the specimens with loaded holes are considerably below those with plain holes (fig. 8, table 2). The endurance strength has dropped to less than half, In the range of small number of load reversals the reductions become progressively less in percent. The distinct differences in the aspect of the Wöhler curves for the free holes become greatly obscured on the loaded holes, where the sequence does not change. The curves themselves are then so close to each other that the scatter values of one frequently fall in the region of the other two. Even so, the reduction due to the serrations still amounts to 20 percent at 10^7 load cycles.

b) Electron Test Specimens

The respective Wöhler curves are shown in figures 9 and 10. The flat strips with the plain holes show theoretically the same tendency as the corresponding duralumin strips, except that the curves are, on the whole, lower. The reduction in limited time and fatigue strength of the specimens with cylindrical holes due to the serrations is about 18 percent for electron, with the threads 12 percent and less.

On the electron tension lugs the Wöhler curves for cylindrical holes and threaded holes almost coincide above the 10^5 load cycles, but diverge below this figure. The curve for the serrated tension lugs is, on the whole, substantially below that of the other two. The divergence is particularly apparent at higher load cycles. The reduction at 10^7 relative to the cylindrical hole amounts to more than 50 percent. At lower load cycles it becomes less.

INTERPRETATION

Tables 2 and 3 contain, besides the limited time and fatigue strength for various load repetitions, the ratios of original tension stress of samples without holes to the original stress of samples with holes ($\sigma_{orig}:\sigma_{n_{orig}}$). This ratio is identical with the notch-effect factor β_k in the case of endurance strength. In the following the term "notch effect factor" is being retained also for small numbers of load cycles, although, according to the VDI specification, this concept is only defined as the ratio of the two endurance strengths. The ratio of tensile strength to original tension stress of the drilled test pieces $\sigma_B:\sigma_{n_{orig}}$ was also secured and added in the table so as to afford some concept of the utilization of the static tensile strength of the material. In figure 11 the notch effect factors for all test-piece forms are shown plotted against 10^4, 10^5, 10^6, and 10^7 number of cycles. According to this representation the pieces with loaded holes generally show a substantial rise in β_k with the number of load cycles in contrast to those with plain holes. The serrated holes cause a greater increase in notch effect than the threaded holes, as particularly shown by the tension lugs made of AZM electron. An unusual fact is that this adverse behavior of the notch serration is by far less noticeable on the plain holes made of electron.

From the ratio $\sigma_B:\sigma_{n_{orig}}$ plotted in figure 12, it is seen that in the lengthwise emery polished state the two types of material do not differ abnormally respecting the utilization of static tearing strength. On the specimens with plain holes, on the other hand, the utilization of the static tensile strength of duralumin is distinctly a little better than that of electron. Of the tension lugs with cylindrical holes and threaded holes, those made of electron are in part superior at higher number of cycles, but in the limited time-strength range there is no distinct difference between the two metals. Here also the adverse behavior of the serrated tension lugs made of electron is apparent.

TYPES OF FAILURE

On the specimens with unloaded holes the fatigue failure on all three forms occurred in the cross section of the smallest hole (figs. 13 and 15). The same applies to the tension lugs with cylindrical and threaded holes. But in the serrated tension lugs the break no longer occurred in the minimum section, that is, in the direction of the hole diameter at right angles to the longitudinal axis, but shifted parallel toward the lug restraint (figs. 14, 16, and 17a), the latter being taken from a different study. Occasionally the break in the tension section was accompanied by several bending breaks in the serrations ahead of the principal section of failure. Frequently several cracks emanating from different serrations were observed in the tension section (fig. 17a). Whether the tension breaks or the bending breaks of the serrations come first,could not be ascertained. The likely cause of the shift of the tension failure is that the serrations located between the minimum section (A-A) (fig. 17a) and the break section (B-B) primarily participate in the transfer of stress to the pin, while those closer to the restraint absorb the greater part of the force. The serrations closer to the lug must receive continuously decreasing load portions, so that, viewed in force directions, a load distribution in the serrations similar to that existing in the threads of a screw under tension takes place. As a result of this load distribution the fatigue failure occurs in the section of the most highly stressed serration rather than in the minimum section. The stress in serrations itself may become so high as to induce bending failure.

In this connection the unusual form of failure obtained in another study on serrated tension lugs under fatigue compression stress (fig. 17b), which substantiates the foregoing explanation, is pointed out. The photograph discloses ten bending failures in serrations primarily engaged in transmitting the force to the pins. It was possible to observe how the individual failures in the serrations originated successively, starting at the highest stressed serration. No break in the strip section was noticeable when the test was stopped.

Translation by J. Vanier,
National Advisory Committee
for Aeronautics.

REFERENCES

1. Thum and Bruder: Gestaltung und Dauerhaltbarkeit von geschlossenen Stabkopfen. Deutsche Kraftfahrtforschung, Heft 20.

2. Lehr, S.: Spannungsverteilung in Konstruktionselementen.

TABLE 2.- DURALUMIN 3116.5

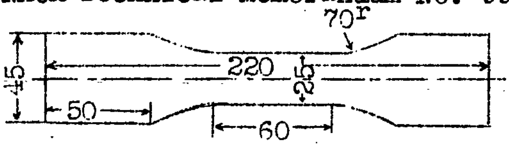
Load cycles	A			Plain holes B			C			D		
	σ_{orig}	$\frac{\sigma_{orig}}{\sigma_{n_{orig}}}$	$\frac{\sigma_B}{\sigma_{orig}}$	$\sigma_{n_{orig}}$	$\frac{\sigma_{orig}}{\sigma_{n_{orig}}}$	$\frac{\sigma_B}{\sigma_{n_{orig}}}$	$\sigma_{n_{orig}}$	$\frac{\sigma_{orig}}{\sigma_{n_{orig}}}$	$\frac{\sigma_B}{\sigma_{n_{orig}}}$	$\sigma_{n_{orig}}$	$\frac{\sigma_{orig}}{\sigma_{n_{orig}}}$	$\frac{\sigma_B}{\sigma_{n_{orig}}}$
10^7	15	1	2.84	8.8	1.7	4.84	7.8	1.92	5.46	7	2.14	6.2
10^6	18	1	2.37	9.8	1.84	4.35	8.8	2.04	4.84	8	2.25	5.33
10^5	24.9	1	1.7	14.7	1.69	2.8	14	1.78	3.04	12	2.07	3.55
10^4	33	1	1.29	23.5	1.4	1.81	23	1.43	1.85	19	1.73	2.24

Load cycles	Loaded holes (tension lugs) E			F			G		
10^7	3.8	3.95	11.2	3.6	4.18	11.8	3	5	14.2
10^6	4.8	3.75	8.88	4.5	4.0	9.5	3.8	4.75	11.2
10^5	8.8	2.83	4.84	7.9	3.14	5.4	7.5	3.32	5.7
10^4	17	1.94	2.51	16.5	2.0	2.6	16	2.06	2.67

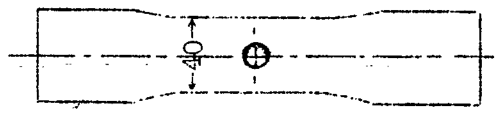
TABLE 3.- ELECTRON 3510.1

Load cycles	A			Plain holes B			Plain holes C			Plain holes D		
	σ_{orig}	$\frac{\sigma_{orig}}{\sigma_{n_{orig}}}$	$\frac{\sigma_B}{\sigma_{orig}}$	$\sigma_{n_{orig}}$	$\frac{\sigma_{orig}}{\sigma_{n_{orig}}}$	$\frac{\sigma_B}{\sigma_{n_{orig}}}$	$\sigma_{n_{orig}}$	$\frac{\sigma_{orig}}{\sigma_{n_{orig}}}$	$\frac{\sigma_B}{\sigma_{n_{orig}}}$	$\sigma_{n_{orig}}$	$\frac{\sigma_{orig}}{\sigma_{n_{orig}}}$	$\frac{\sigma_B}{\sigma_{n_{orig}}}$
10^7	14	1	2.25	5.9	2.37	5.35	5.2	2.69	6.06	4.8	2.91	6.58
10^6	14.9	1	2.11	6.8	2.19	4.64	5.5	2.7	5.74	5.1	2.92	6.18
10^5	17.1	1	1.84	8.9	1.92	3.54	7.7	2.22	4.09	6.8	2.52	4.64
10^4	23.1	1	1.36	14.7	1.57	2.14	14.5	1.59	2.17	11.9	1.94	2.65

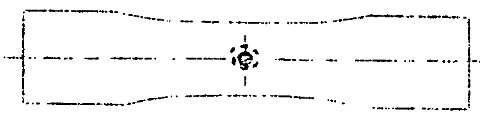
Load cycles	Loaded holes (tension lugs) E			Loaded holes (tension lugs) F			Loaded holes (tension lugs) G		
10^7	3.2	4.37	9.85	3.0	4.66	10.5	1.5	9.3	21
10^6	3.7	4.02	8.52	3.5	4.25	9.0	2.2	6.77	14.3
10^5	5.7	3	5.53	5.3	3.22	5.95	4.4	3.88	7.2
10^4	11.1	2.07	2.84	9.7	2.37	3.26	8.8	2.62	3.58



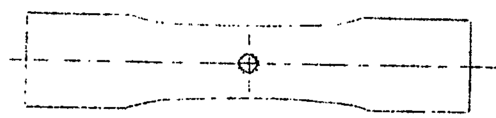
-A-
Figure 1.-Plain specimen(no hole)



-B-
Figure 2.-Specimen with 10 mm diam cylindrical hole.



-C-
Figure 3.-Specimen with M 10 threaded hole.



-D-
Figure 4.-Specimen with 8x10 Kr 231 serrated holes.

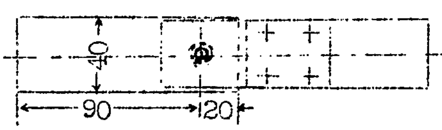


Figure 5.-Specimen with pin loaded holes (tension lugs).

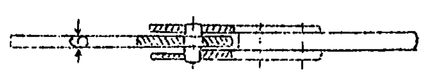


Figure 6.-Specimen with pin loaded holes (tension lugs).
E-hole and pin 10 mm diam
F-hole and pin threaded M 10
G-hole and pin serrated 8x10 Kr 231

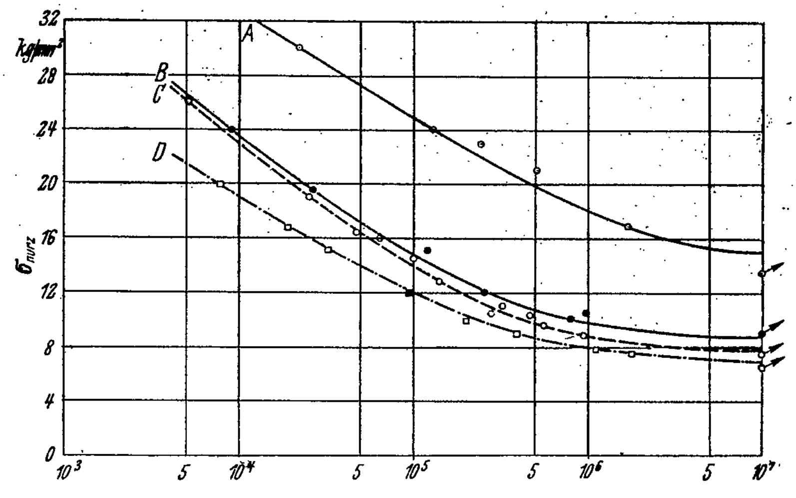


Figure 7.-Duralumin 3116.5,plain holes.
A-plain rods
B-cylindrical holes 10 mm diam,
C-threaded holes M 10
D- serrated holes 8x10 Kr 231

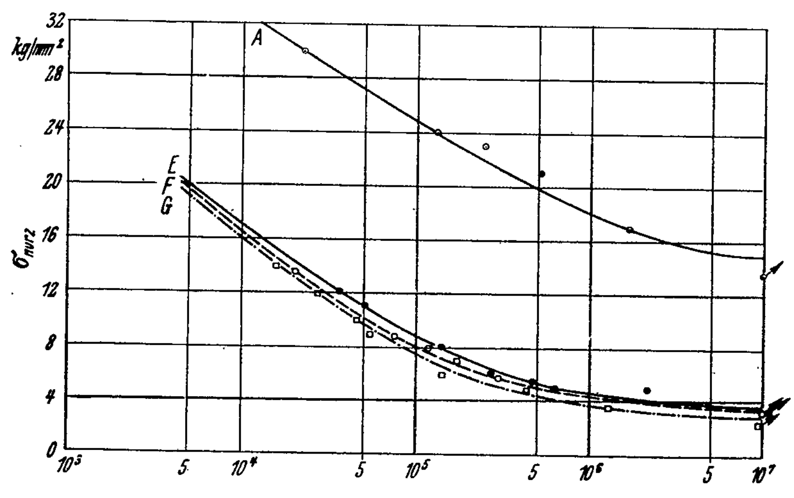


Figure 8.-Duralumin 3116.5,loaded holes.
A-plain rods
E-cylindrical holes 10 mm diam.
F-threaded holes M 10
G-serrated holes 8x10 Kr 231

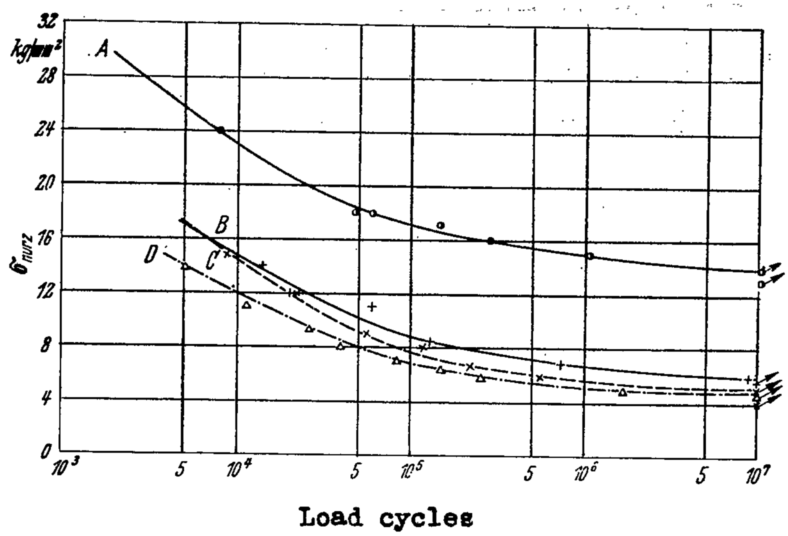


Figure 9.-Elektron 3510.1,plain holes.
A-plain rods
B-cylindrical holes 10 mm diam.
C-threaded holes M 10
D-serrated holes 8x10 Kr 231

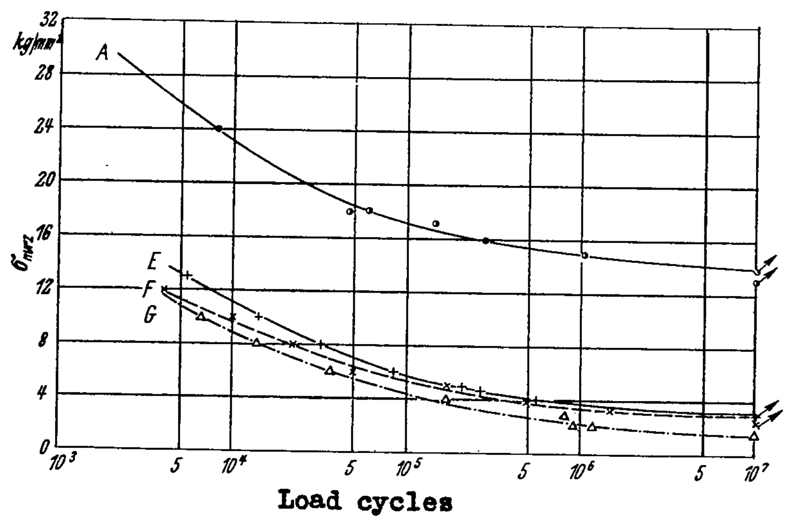


Figure 10.-Elektron 3510.1,loaded holes.
A-plain rods
E-cylindrical holes 10 mm diam.
F-threaded holes M 10
G-serrated holes 8x10 Kr 231

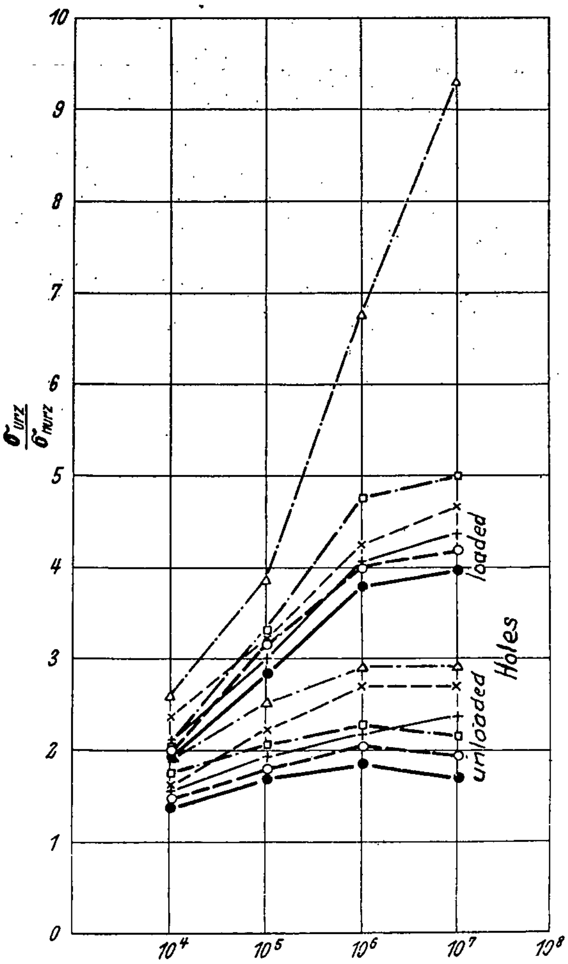


Figure 11.-

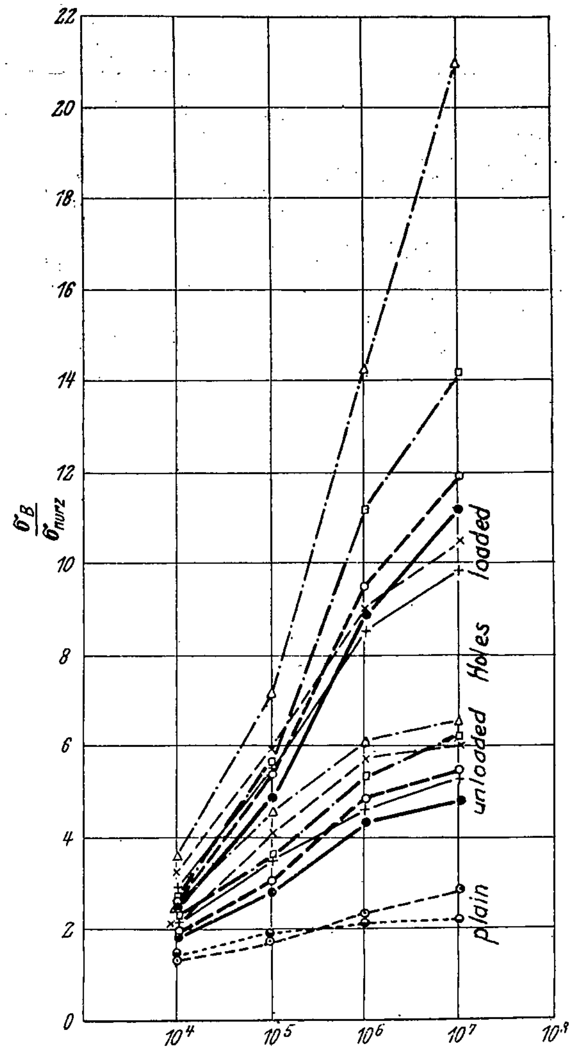


Figure 12.-

	Duralumin	Elektron
Cylindrical hole	●———●	+———+
Threaded hole	○– – –○	×– – –×
Serrated hole	□–·–·–□	△— — —△

	Duralumin	Elektron
Without holes	⊙- - - -⊙	⊕- - - -⊕
Cylindrical hole	●———●	+———+
Threaded hole	○– – –○	×– – –×
Serrated hole	□–·–·–□	△—·—·—△

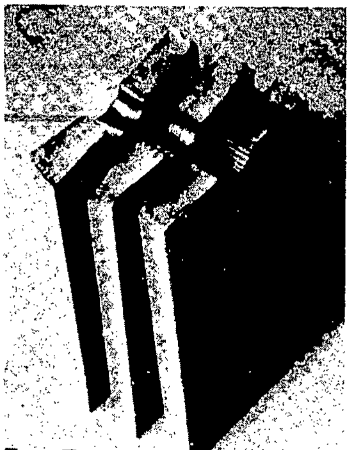


Figure 13.-Fatigue failure on specimens with unloaded holes.

Figure 15.-Fatigue failure on specimens with unloaded holes.

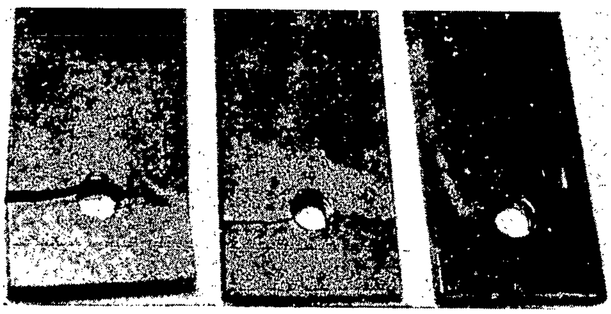
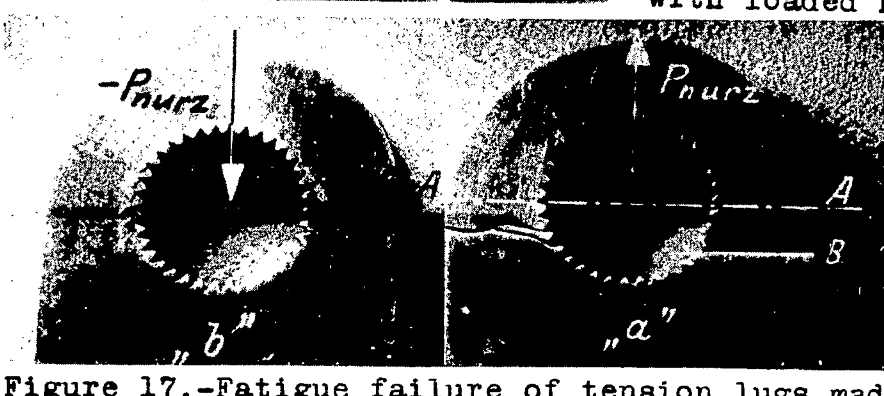


Figure 14.-Fatigue failure on specimens with loaded holes.

Figure 16.-Fatigue failure on specimens with loaded holes.



a-under original tension stress
b-under original compressive stress

Figure 17.-Fatigue failure of tension lugs made of elektron 3510.1.