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FATIGUE STRENGTH OF AIRPLANE AND ENGINE MATERIALS

By Kurt Matthaes

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INTRODUCTION

Fatigue fractures occasionally occur in airplane flight, both in the engines and in the airplanes themselves. Such fractures cannot always be avoided by the designer, since, with the many factors affecting the fatigue strength, it is very difficult to dimension the various structural parts correctly, even when the magnitude of the stresses can be determined. Recent researches, however, have brought the problem of the correct dimensioning of the stressed parts considerably nearer solution. Since the available data are only fragmentary and are considerably scattered in the literature on the subject, I have undertaken to give a brief summary of the laws governing the fatigue stresses and of the most important strength coefficients necessary for the correct dimensioning of the structural members.

I. KINDS OF FATIGUE STRESSES AND THEIR DESIGNATION IN FATIGUE TESTS

By fatigue stresses is generally meant any kind of stress regularly alternating between a higher and a lower limit. Such a stress may be regarded as being produced by a constant initial tension and a superposed alternating stress. The changing ratio of the initial tension to the alternating stress yields various load cases which determine the behavior of the material. By simple alternating stress is meant the stress which alternates between equally great positive and negative values, the initial tension

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*"Die Dauerfestigkeit der Werkstoffe des Flugzeug- und Flugmotorenbaues." Z.F.M., Nov. 4, 1933, pp. 593-598; and Nov. 28, 1933, pp. 620-626.

being zero in this case. Hence no permanent deformation of the stressed part can occur even at high stresses, because any plastic yielding of the material under the stress is eliminated by the succeeding stress in the opposite direction. By original stress is understood a stress fluctuating between zero and some maximum value. This can also be understood as an alternating stress superposed on an equally great static stress. It often happens that a small alternating stress is superposed on a relatively great basic stress. Under this kind of stressing greater deformations sometimes occur, and the fractures do not always have the characteristic appearance of fatigue fractures.

In determining the fatigue strength, one is, of course, almost always restricted to the most important cases of stressing. In most cases only the simple reversal strength is determined, but often also the original strength. The determination of the fatigue strength under still greater initial tension can usually be dispensed with, since such high total stresses, mostly with respect to the static strength characteristics (especially the yield point), are inadmissible in practice.

Fatigue tests are normally made and evaluated as follows. Several tests are made at different stresses, and the number of load reversals up to the failure of the test specimen is determined each time. Then, by plotting the stress against the logarithm of the number of load reversals, one obtains curves of the form shown in figure 1. It is seen that the different materials behave very differently. The bending-fatigue curves for steel are almost straight and slope rather steeply downward at the beginning. At a certain stress, the curve bends sharply to the horizontal position and continues parallel to the axis. Less stressed specimens do not break, even at a practically infinite number of stress reversals. There is therefore an actual fatigue-strength limit. The number of reversals at which this is reached, lies between one and ten million for all steels. The corresponding curves for wood are similar, but the fatigue limit is reached at a much smaller number of reversals (20,000 to 2,000,000). Light-metal alloys, on the contrary, show no such bend in the curves, even at more than 100 million reversals. Even in this region the fatigue strength continues to decrease, though but very little, as shown by the flatter course of the curve. In many other materials, e.g., nickel and its alloys, the bending-fatigue curve shows a still different behavior. It follows a uniform rectilinear decrease in the reversal strength throughout its whole length up to several hundred million load reversals.

II. TYPICAL FRACTURES

From the existence of a pronounced fatigue limit, as in steel, for example, conclusions can often be drawn, in connection with fractures occurring in practice, regarding the nature of the stresses developed, especially regarding their frequency, but also regarding their magnitude. Further conclusions follow from the form of the fracture, which is characteristic of fatigue fractures. The most important characteristics of fatigue fractures are the lack of deformation and the relative evenness of the fracture. Moreover, zone lines often show on the surface of the fracture. These are due to interruptions in the stressing or in operation. The alternate stressing produces a certain hardening of the material, which continues during pauses in operation and especially during periods of diminished stress. If great alternating stresses are then renewed, the fracture passes around the hardened zone. This produces the peculiar relief formation generally seen in fatigue fractures occurring in operation, but never in fatigue tests where the test specimen is subjected to alternating stresses without interruption until the fracture is produced. Figures 2 to 5 show a few typical fractures. Figure 2 shows fractures of ball studs. On the left are shown two fatigue fractures, the upper one having a particularly smooth surface with numerous fine zone lines. The lower one, which started from both sides of the stud, has a coarser surface and but few zones. Opposite the two fatigue fractures are shown two static fractures, the upper one being a shear fracture, in which the surface appears fibrous, and the lower one a tensile fracture in which the surface has a crystalline or granular appearance.* (In the fracture shown, the surface is fibrous

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*The shear fracture corresponds to the upper limit, the tensile fracture to the lower limit, of the notch-bar strength. Quite frequently transitional forms between the two typical fractures occur, in which there are alternating zones of shear and tensile fracture. On account of the zone lines such fractures are often erroneously mistaken for fatigue fractures. For the most part, however, the typical fractures can be easily distinguished by the differences in the surface structure (reference 1).

at the beginning of the break.) Figure 3 shows the fatigue fracture of a light-metal tube, starting at a hole. Even in wood there is a similar difference between fatigue and static fractures, as shown in figure 4. Figure 5 shows a torsional-fatigue fracture of a crankshaft. Torsional fractures often assume a spiral or oblique form, and almost always do when there is a notch effect. We also find longitudinal and transverse fractures. Normal tensile fractures are almost always transverse.

Further conclusions regarding the nature of the stress can be drawn from the area of the remaining fracture surface. If, for example, the remaining fracture surface is very small, it follows that the normal operating stress was relatively small in comparison with the alternating stresses. The beginning of a fracture usually occurs long before its completion. Even this, however, depends on the magnitude of the basic stress and the frequency of the overstresses. This explains why incipient breaks can be discovered and fractures avoided by careful systematic inspection of endangered parts. Even the formerly frequent crankshaft fractures required, for their development from the first detectable beginning, an average of about 50 hours of operation, so that it was found possible to avoid half of the fractures in operation by inspection during the overhauling. If, however, the basic stress is high, the fracture develops rapidly. In a landing wheel of magnesium alloy, a fracture began at the hub after 1,700 landings. After 170 more landings the fracture extended more than half-way around the hub.

III. EFFECTS OF ELASTIC HYSTERESIS

Before the magnitude of the fatigue strength of the materials can be considered, a few general principles must be discussed. Figure 6 shows the effect of the frequency of the stresses on the fatigue strength (reference 2). This effect is relatively small when the frequency does not differ by very great amounts. The effect of the frequency is considerably greater, however, at higher temperatures and with combined static and dynamic stresses. This may be due to the fact that the plastic deformation is then no longer very small in comparison with the purely elastic deformation.

Even in alternating stresses, the deformations are not perfectly elastic. The plastic deformations, even when small, cause energy to be absorbed by the material and transformed into heat for every stress or load reversal. Below the endurance limit, it is relatively small, at least at the room temperature. The damping is considerably greater at higher temperatures. It also depends on the initial stress and diminishes gradually at high numbers of stress reversals (reference 3). In free vibrations the occurrence of the fatigue fracture is considerably retarded by the damping effect of the material. Of itself, however, this damping effect seldom suffices to prevent fatigue fractures, since the most highly stressed regions are generally very limited and the volume of the material for absorbing the energy is therefore very small.

Apparently in connection with the plastic deformation, a certain hardening of the material gradually occurs in fatigue stressing. Hence the strength is gradually increased by a large number of stresses which do not exceed the endurance limit. The increase in the fatigue strength is from 0 to 30 percent, according to the material and the magnitude of the initial fatigue stresses. It is therefore advantageous, even as regards the fatigue strength, to run in new engines under gradually increasing loads. It will be hardly possible, however, to make practical use of this phenomenon, since the initial fatigue stresses can be only 3 to 8 percent below the fatigue strength.

IV. EFFECT OF INITIAL TENSION

Relatively few data are available regarding the effect of the initial tension on the fatigue strength. Figure 7 shows the behavior of a chrome-nickel steel with a strength of 81 kg/mm² (115,210 lb./sq.in.) (reference 4). The line at the right represents the initial tension, while the other lines represent the sum of the static and dynamic stresses. It is seen that the additional alternating stress gradually decreases as the static stress increases. On the contrary, the reversal strength is not diminished by the initial tension due to pressure, as it is by that due to traction, but is even augmented within certain limits.

Table I (at end of report) gives the results of the tests made by the DVL (German Experimental Institute for Aeronautics). For the aluminum alloy tested, the reversal strength is 13 kg/mm² (18,490 lb./sq.in.), the original tensile strength 23 kg/mm² (32,714 lb./sq.in.), and the original compressive strength 30 kg/mm² (42,670 lb./sq.in.). The alternating stress of 13 kg/mm² borne without initial tension is reduced by the initial tensile tension to 11.5 kg/mm² (16,357 lb./sq.in.), and raised by the initial compressive tension to 15 kg/mm² (21,335 lb./sq.in.). For elektron AZM with a reversal strength of 15 kg/mm² (21,335 lb./sq.in.), the original tensile strength is 19 kg/mm² (27,025 lb./sq.in.), and the original compressive strength is 30 kg/mm². Here the alternating stress is greatly reduced by the initial tensile tension, namely, from 15 to 9.5 kg/mm² (13,512 lb./sq.in.), but is hardly affected at all by the initial compressive tension. Steel has corresponding values. The original bending strength, i.e., the original tensile strength, is about 1.7 times the reversal strength. The relations are also very similar for alternating torsional stresses with initial tension.

When the fatigue strength and original strength are known, the strength with combined static and dynamic stresses can be quite accurately estimated. Even if the original strength of a given material is not known, the following method can be employed for estimating the strength with combined stresses. One begins with the assumption that, with initial tension, the additional alternating stress is directly proportional to the share of the static strength in excess of the initial tension. For the alternating stress W supported with the static stress S, we then have $W = (\sigma_B - S)\frac{\sigma_W}{\sigma_B}$. If, e.g., the static strength of a given material is $\sigma_B = 50$ kg/mm² (71,118 lb./sq.in.) and the reversal strength is $\sigma_W = \pm 20$ kg/mm² (28,447 lb./sq.in.), that is, $\sigma_W/\sigma_B = 0.4$, then, with the static stress $S = 15$ kg/mm², the additional alternating stress W is $(50 - 15)\ 0.4 = \pm 14$ kg/mm² (19,913 lb./sq.in.). The material can therefore withstand a stress which fluctuates between 1 and 29 kg/mm² (1,422 and 41,248 lb./sq.in.). This method of estimation is generally on the safe side.

Allowance is made for the influence of the cross-sectional transitions by making the ratio σ_W/σ_B smaller than for a smooth rod. These relations will subsequently be considered in more detail.

V. FATIGUE STRENGTH AND STATIC STRENGTH

Also with regard to the relations between the fatigue-strength and the static-strength characteristics, a fairly conclusive judgment can now be pronounced. There is no static-strength characteristic with which the fatigue strength is absolutely proportional. In particular there is no relation between the fatigue strength and the limit of elasticity. There is, however, a general dependence of the fatigue strength on the static breaking strength, although the individual values show considerable scattering. Figures 8 to 13 show this dependence for various materials.

Figure 8 shows the values for steel (reference 5). Here the relationship was first discovered. The ratio of the fatigue strength to the static tensile strength averages about 0.5. This applies to cast steel as well as to forged and drawn steel. It does not, however, apply to cast iron, due to the notch effect of the graphite scales. The individual values show a scattering of ±20 percent about the mean value. This scattering is quite large and might throw doubt on the practical value of such a relationship. It must be remembered, however, that the fatigue strength shows a rather large scattering in any case. For example, in testing different rods of the same lot, discrepancies of ±10 percent are often found. These discrepancies cannot be avoided, since it is, of course, quite impossible to determine the fatigue strength of every individual rod before using it. If, however, this is taken into consideration, greater importance can be imputed to the static strength, since, in many cases, it may save the necessity of special endurance tests.

The bending reversal strength and the torsional reversal strength are both proportional to the static tensile strength (fig. 9) according to tests by Ludwik, Moore and Jasper, as well as by the writer. The proportionality between the torsional reversal strength and the static shearing strength is probably still more pronounced, since, for materials whose static shearing strength is very great in comparison with their normal tensile strength (castings, for example), the torsional reversal strength is also correspondingly great.

Relations very similar to those for steel also exist for the other materials. Figure 10 illustrates this for aluminum alloys.* Here the bending reversal strength averages about 35 percent of the tensile strength. The scattering is somewhat greater here, however, due probably to the greater sensitiveness of the light metals to the effects of working. The values indicated in figure 10 are for ten million stress reversals, there being here for the most part no pronounced endurance limit, as already mentioned. Figure 11 shows how the reversal strength changes at higher numbers of stress reversals (reference 6).

In figure 12 the bending fatigue strength is plotted against the static tensile strength for magnesium alloys, according to tests by Cazaud, Lehr, Ludwik, Lyon, Meissner, H. F. Moore and Jasper, Musatti, Saran, Wagner, and by the writer. The reversal strength (as based on ten million stress reversals) averages about 38 percent of the tensile strength.

A very similar relationship also exists for copper alloys. Here the ratio of the fatigue strength to the tensile strength is about 0.33, though there is very great scattering (25 to 30 percent). This is explained by the fact that here also there are alloys containing relatively large proportions of other metals (e.g., the brasses).

In figure 13 the fatigue strength is plotted against the compressive strength of wood according to O. Kraemer (reference 7). Here the compressive strength is decisive instead of the tensile strength, probably because the former is considerably less. The ratio of the reversal strength to the compressive strength is 0.59.

Apparently we are here dealing with a universal law applicable to all materials. Yet it is only roughly approximate, as shown by the wide scattering of the values. If, on the other hand, we consider the individual processes by which the static strength of the materials is increased, we find that, in the refining of steel or light metal, as also in cold working, the reversal strength cannot be in-

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*According to tests by Cazaud, Dorgerloh, Gibson, Grogan, Hatfield, Johnson and Oberg, Lehr, Ludwik, R. R. Moore, Moore and Lewis, H. F. Moore and Jasper, Musatti, Rosenhain-Archbutt-Wells, Saran, Wagner, and the writer, and according to the unpublished results of tests by the Metallgesellschaft, Frankfurt, a.M.

creased in the same proportion as the static strength. The ratio σ_W/σ_B decreases with greater refining or with cold drawing. This decrease is manifested especially in the vicinity of the maximum value attainable by the process. The effect of the chemical composition, however, is relatively small. In steel the alloy has no perceptible effect on the fatigue strength for the same tensile strength. On the contrary, the ratio σ_W/σ_B of annealed steel decreases with increase in the carbon content (reference 5). All of these effects are not very great, however, so that the fatigue strength always remains within the range of scattering shown in figures 8 to 12.

The indicated values are based on the alternating bending stresses. In tensile-compressive stresses the reversal strength is generally somewhat smaller. Perhaps this is because secondary bending stresses occur in tensile-compressive tests, due to slightly eccentric mounting. Values between 70 and 100 percent of the bending reversal strength are found.

Except for castings, the torsional reversal strength is 50 to 70 percent, or a mean of about 60 percent of the bending reversal strength. In all alloy castings the torsional reversal strength is 70 to 90 percent of the bending reversal strength. In all cases the ratio of the torsional reversal strength to the static shearing strength is approximately the same as the ratio of the bending reversal strength to the static tensile strength.

VI. PARTIALLY FINISHED PRODUCTS

The fatigue strengths given are for flawless specimens machined and polished on all sides, i.e., according to the requirements for standard fatigue tests. Thus many influences are purposely eliminated, which may be of decisive importance for the fatigue strength of structural members, especially the surface roughness and the effects of working. As a result of these influences, the fatigue strength of partially finished products is considerably lower. Therefore we will first consider the magnitude of the individual influences and their effect on the fatigue strength of partially finished products. The strengths are given in table II.

1. Effect of Direction of Grain

The microscopic inclusions of slag, which are present in every metal, do not affect the fatigue strength when the direction of stress coincides with that of the grain. When, however, the stress is perpendicular to the grain, there is usually a marked reduction in the fatigue strength, due both to the inclusions and to the unfavorable direction of the grain. This reduction depends largely on the structure and is therefore more pronounced in thick forgings, due to the generally less thorough forging and to the coarseness of the structure as compared with that of thin forgings, where it is often vanishingly small. In large forgings from duralumin, elektron (propellers) and steel (crankshafts), the reduction in strength is 10 to 30 percent and even more in special cases, according to observations of fractures and tests by Jünger and A. J. Lyon (reference 8). Large slag inclusions and holes, which, of course, would greatly reduce the fatigue strength and lead to fractures, rarely occur in the carefully selected materials employed in airplane and engine construction.

2. Effect of Grooves Due to Working

Most structural parts do not have smooth polished surfaces, but always have grooves and scratches which considerably reduce their fatigue strength. Even when greater demands are made with regard to the finishing, the surfaces almost always show slight dents, scratches, etc., which may affect the fatigue strength. It must always be borne in mind, especially as regards large pieces, that a single slight defect of any kind may considerably reduce the fatigue strength of a whole structural part. This partially explains the often-observed smaller fatigue strength of large structural parts as compared with that of small test specimens.

Of the mechanical methods of finishing, the best (next to polishing), in its effect on the fatigue strength, is grinding, providing it is done so that the direction of the grinding grooves coincides with the direction of stressing. If, on the contrary, the grinding grooves are at right angles to the direction of stressing, there is a noticeable reduction in the fatigue strength. For steel this is 10 to

15 percent, according to the hardness, and sometimes even more. About the same reduction in the fatigue strength can be assumed for parts carefully filed. On the other hand the fatigue strength of parts simply turned or planed is considerably smaller. Jünger's tests of steels, having a tensile strength of 50 to 90 kg/mm² (71,117 to 128,011 lb./sq.in.) and a fatigue strength of 25 to 45 kg/mm² (35,560 to 64,000 lb./sq.in.) for longitudinally ground specimens, yielded, with transversely planed specimens, a fatigue strength of 25 to 30 kg/mm² (35,560 to 42,670 lb./sq.in.) (reference 9). In contrast with the fatigue strength of the longitudinally ground specimens, that of the transversely planed specimens increased but very little with the tensile strength, since the strength was greatly reduced by the machining grooves. From this fact it follows that good surface finishing is desirable for the harder steels, in order to utilize fully their greater strength even in parts subjected to alternating stresses. On the contrary the strength of soft steels is only slightly increased by grinding or polishing and is therefore generally uneconomical. The great discrepancies between various steels are also partially due to the fact that their workableness differs greatly and that therefore their surface condition after treatment differs correspondingly. The reduction in the fatigue strength of longitudinally planed specimens is only about half as great as that of transversely planed specimens.

For duralumin the effect of surface injuries is less. The fatigue strength of filed specimens is not over 5 percent less than that of polished specimens. On the other hand, sharp-edged scratches are more easily produced in the softer metal than in hard steel. Hence one must always allow for a 5 percent loss of strength, due to unavoidable surface injuries.

3. Partially Finished Light-Metal Products

The effect of surface injuries, drawing grooves, rolled-in splinters, etc., in the production of sheets and section metal is naturally similar to that of the grooves produced in finishing. Hence tests of sheet and section metal with unfinished surfaces often yield lower fatigue strengths. The defects due to drawing and rolling the metal (such as high internal tension and surface tears and, under some circumstances, excessive stressing in the production of the unfinished materials) are still more dangerous. These defects are especially pronounced in parts (such as H sections and rectangular tubes), the production of which is especially difficult and liable to be accompanied by excessive stresses. The liability to such injuries varies greatly with the material used. Relatively unfavorable in this respect is the behavior of the light metals, the unfinished products of which often have very low fatigue strengths. (See table II.) Thus unfinished sheet duralumin has a fatigue strength of 10 to 12 kg/mm (14,220 to 17,070 lb./sq.in.) and tubes and sections 9 to 9.5 kg/mm (12,800 to 13,510 lb./sq.in.). The fatigue strength of "hydronalium" sections is still lower, obviously due to the poorer workability of this material. Sheet elektron has a fatigue strength of about 8 kg/mm (11,380 lb./sq.in.), while tubes and sections of the same material have a fatigue strength of 5 to 7 kg/mm (7,112 to 9,956 lb./sq.in.).*

4. Partially Finished Steel Products

While light metals are very sensitive to the process of finishing, this is seldom the case with steel, since excessive stressing of this material can be readily avoided by heat treatment. Hence we find in steel sheets and tubes of low and medium strength only a slight diminution of the fatigue strength, which can be entirely accounted for by the surface scratches.**

In steel other phenomena also occur, which are specially noticeable in the more highly refined steels and which may reduce the fatigue strength considerably. These are the hardness stresses and, above all, the decarbonization of the surface layer by the heat treatment. In forged, hot-rolled or tempered parts, the surface layer is decarbonized by oxidation during the heat treatment. The sur-

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*That we are not here dealing with any form or surface effect is shown by the fact that, e.g., test specimens from rectangular tubes likewise yield strikingly low fatigue strengths, which cannot be raised to normal values even by removing the surface layer and by polishing. (Under "form effect" it is to be understood that the stressing of the sections due to cross-sectional variation may be locally greater than the stress corresponding to the section modulus.

**Even structural steels show occasional surface injuries from rolling, which materially reduce the fatigue strength (reference 10).

face layer then consists of a considerably weaker substance, soft iron in the limiting case. Hence surface cracks occur at relatively low fatigue stresses and continue inward, due to the notch effect. This effect of the surface decarbonization is naturally proportional to the carbon content and to the fineness of the steel. As shown by figure 14, the fatigue strength of unfinished forgings increases but little with the tensile strength.* Rolling the surface has a similar effect. For example, various alloyed spring steels, having a strength of 120 to 140 kg/mm² (170,680 to 199,130 lb./sq.in.) under combined static and dynamic stressing, showed a bending fatigue strength of 40 ± 20 kg/mm² (56,894 ± 28,447 lb./sq.in.) for specimens with rolled surface, and 40 ± 48 kg/mm² (56,894 ± 68,273 lb./sq.in.) for specimens without rolled surface (reference 12). Even the slight surface decarbonization in hardening or refining considerably lessens the fatigue strength. (See table II.) Hence, e.g., the fatigue strength of sheet steel one millimeter (0.04 in.) thick refined to a strength of 160 to 170 kg/mm² (227,575 to 241,800 lb./sq.in.) is only 16 to 25 percent of the static tensile strength. The properties of wires are naturally similar to those of sheet metal. Thus, according to Hankins and Becker (reference 13), the bending reversal strength of refined steel wires is reduced by 25 to 40 percent and the original strength by 20 to 30 percent, if the surface layer, decarbonized in the process of hardening, is not removed or the decarbonization itself is not prevented (e.g., by heat treatment in neutral gases or cyanide baths). It is therefore necessary to remove the surface layer and to polish, when especially high fatigue strength is desired. Tests by Swan, Sutton, and Douglas (reference 14) on the fatigue strength of valve-spring wires under combined static and dynamic torsional stresses showed, e.g., an upper limit of 44 to 63 kg/mm² (62,583 to 89,608 lb./sq.in.) as delivered, the fatigue stress being 60 percent of the static stress. A maximum strength of 96 kg/mm² (136,546 lb./sq.in.) was obtained by removing the decarbonized surface layer. Ground and polished wires such as are now used for the valve springs of aircraft engines, are rather expensive. Very good results can be obtained, however, by using cold-drawn wire, since the effect of the surface decarbonization is at least partially offset by the cold hardening. In practice the extreme limit to which very good valve springs can be stressed is about 80

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*In addition to the surface decarbonization, it is also necessitated in this case by the rougher surface of the forged specimens (according to tests by Hankins and Becker). (See also reference 11.)

kg/mm² (113,788 lb./sq.in.), this being the upper limit of tension for the case when the alternating stress is 40 percent of the static stress. This is at the very fatigue limit, however, and all supplementary stresses must therefore be taken into consideration. In valve springs, however, the actual fatigue stress is often twice as great as the stress determined from the valve lift, since free vibrations of the spring windings occur.

5. Surface Hardening

While the fatigue strength of the whole piece is reduced when the surface layer has a low fatigue strength, the effect of surface injuries is reduced by hardening the surface, and under some circumstances the fatigue strength of the whole piece can be considerably increased. In nitrided steels (reference 15), for example, the fracture always begins underneath the nitrided layer and even when small sharp notches, corrosion scars, or similar surface injuries are present, provided, of course, that these surface injuries do not penetrate through the nitrided layer. Thus we always have a fatigue strength corresponding to that of the inside material in the ideal condition, i.e., free from any surface injuries. In parts subjected to bending or torsional stresses, we find, moreover, corresponding to the thickness of the nitrided layer, a slight increase in the fatigue strength of the part as compared with that of the inside material. Results similar to those of nitrogen hardening can also be obtained by casehardening and, though in a lesser degree, by cold hardening of the surface by pressure polishing, rolling, compression, etc.

6. Effect of Corrosion

Corrosion produces a greater or smaller notch effect through the formation of scars which considerably diminish the fatigue strength. Tests were made in the DVL with steel sheets of 1 mm (0.04 in.) thickness, which had been exposed to salt-water spray for a month or two before the fatigue test. The fatigue tests yielded the same results, whether the process of corrosion had been continued for one month or for two months. The reversal strength of a Cr-Ni-W (chrome-nickel-tungsten) steel, refined to a strength of 160 kg/mm² (227,575 lb./sq.in.), was reduced to 25 kg/mm² (35,559 lb./sq.in.). The effect of corrosion may be almost as great in the case of corrosion-resisting steels. The 14 percent chrome steel V3M, with a strength of 170 kg/mm² (241,800 lb./sq.in.) has, uncorroded, a reversal strength of 43 kg/mm² (61,161 lb./sq.in.), but only 27 kg/mm²(38,403 lb./sq.in.) after being corroded. If the resistance to corrosion is still greater, as in the more highly alloyed steels V5M and V2A, there is generally no reduction in the fatigue strength. In original stressing the reduction in the static strength from corrosion is generally less than in the alternate stressing. The static strength of Cr-Ni-W steel, e.g., falls from 48 kg/mm² (68,273 lb./sq.in.) (refined, but not worked) to 40 kg/mm² (56,895 lb./sq.in.) (corroded), while that of the corrosion-resisting chrome steel V3M falls from 53 to 50 kg/mm² (75,385 to 71,118 lb./sq.in.). For duralumin the fatigue strength of corroded specimens is 8 kg/mm² (11,379 lb./sq.in.), as compared with 12 to 14 kg/mm² (17,068 to 19,913 lb./sq.in.) for uncorroded specimens. The decrease in the fatigue strength is considerably greater, especially for steel, when corrosion and fatigue stressing occur simultaneously. In this case the conditions are quite complicated, since the corrosion time is affected by the frequency of the stresses and by the total number of load reversals. For example, with ten million load reversals in 55 hours and simultaneous corrosion, the fatigue strength of duralumin 681B and 681ZB is 7 to 8 kg/mm² (9,956 to 11,379 lb./sq.in.); of elektron AZM, 3.5 kg/mm² (4,978 lb./sq.in.); and of all steels with a strength of 30 to 160 kg/mm² (42,670 to 227,575 lb./sq.in.), about 12 kg/mm² (17,068 lb./sq.in.).

VII. EFFECT OF INCREASED TENSION AT CROSS-SECTIONAL TRANSITIONS

The values thus far given chiefly concern the fatigue strength of smooth test specimens and of partially finished products. The fatigue strength of the structural part itself, however, is often considerably reduced by stress increments at the unavoidable cross-sectional transitions. A fatigue fracture is therefore a brittle fracture. There is no yielding and therefore no offsetting of the local stress increments. Hence such stress increments cannot be disregarded, as is permissible in static stressing. As an indication of their magnitude, it was found by Inglis that, with a notch of depth d and a fillet radius r at the apex, the tension increment under normal stressing is $2\sqrt{d/r}$. Strictly speaking, this is valid for an elliptical hole and for a notch in the form of a semiellipse on a plate of infinite width, but is applicable approximately to many notch forms. The increase in tension at a cross-sectional transition can be approximately estimated in this way for uniplanar tension conditions. In order to determine the maximum tension at the bottom of the notch, the mean tension must simply be multiplied by $1 + 2\sqrt{d/r}$. In many cases the values thus estimated are not very accurate. The tension of structural parts has often been accurately measured, however, and the results published. The making of such measurements, which are very valuable for designing structural parts, cannot, however, be here described in detail. We will only call attention to the method of measuring the elongation, as developed by the Maybach Engine Company (reference 16).

Let us consider the behavior of the material in fatigue stressing with respect to such tension increments. For the computation it would indeed be very simple if it were only necessary to measure or estimate the tension increment and then introduce the fatigue strength of the smooth test specimen. Apparently, however, the fatigue strength in most cases is not reduced to the extent which the tension increment according to the theory of elasticity would lead us to expect. This is due in part to a certain internal notch effect in the material, resulting from the directional dependence of the modulus of elasticity in the individual crystallites. (In many materials the modulus of elasticity in the crystal varies about as 1:2 according to the location with respect to the axes.) It is also due to the ever-present small inclusions of slag. The phenomenon may also be due to the fact that the fatigue strength is not the same in the 3-dimensional tension field as in the uniaxial field. Unfortunately very little is known concerning the laws here applicable.

The question now is, as to how much the reduction in the fatigue strength depends on the tension increment $\sqrt{d/r}$ according to the theory of elasticity (provided this relationship is applicable to the form of the specimen). Tests, which were made in the DVL on bending-fatigue specimens with a middle collar of constant magnitude but varying radius of fillet, showed the effect of the latter on the effective increase in tension, as plotted in figure 15. From this it is obvious that the reduction in the fatigue strength, i.e., the practically effective tension increment is not proportional to $\sqrt{1/r}$, but increases less rapidly.

In order to determine what relation exists between the effective tension increment and $\sqrt{d}$, the bending fatigue tests, which Ludwik (reference 17) had made with test bars having notches of various depths, were represented in this manner. As shown by figure 16, the relationship is here rectilinear. The actual tension increment is $0.45\sqrt{d/r}$, i.e., considerably smaller than $2\sqrt{d/r}$.

With very small notches, the absolute magnitude of the notch also apparently has an effect. This is particularly important in connection with the small surface injuries produced in working the material. Tests by N. Thomas (reference 18) with a 0.33C steel showed that with notches of about 0.02 mm (0.0008 in.) depth, the tension increment is only $0.16\sqrt{d/r}$ instead of $2\sqrt{d/r}$. With notches of 0.1 to 0.7 mm (0.004 to 0.028 in.) depth the notch factor was 0.46. The diminution of the notch factor in this field of very small surface notches or scratches is chiefly attributed to the internal notch effect. No answer has been found, however, to the question as to whether, in large cross-sectional transitions, the notch factor is affected by the absolute magnitude.

From all this it is obvious that the actual relation between the effective tension increment and the tension increment according to the theory of elasticity could not yet be determined. So long, however, as this matter is not settled, the danger of fatigue fractures cannot be determined directly from tension measurements. This danger must therefore be determined for the present from fatigue tests of the structural elements themselves or of whole structural parts.

It must also be remembered that the effect of the tension increment depends on the material used, so that even the results of fatigue tests cannot be transferred directly from one material to another. The sensitiveness to notches is proportional in steels, e.g., to the tensile strength, as shown in figure 17 (reference 19).

The notch effect is less in torsional alternating stresses than in bending alternating stresses or in alternating tensile-compressive stresses. The percentage reduction in strength is proportional to the ratio of the torsional reversal strength to the bending reversal strength (reference 17). For $\tau_W = 0.6\ \sigma_W$, we thus obtain

$$\frac{\tau_W - \tau_{Wk}}{\tau_W} = 0.6 \frac{\sigma_W - \sigma_{Wk}}{\sigma_W},$$

in which τ_W and σ_W represent the reversal strength without notch; τ_{Wk} and σ_{Wk}, with notch. Table III shows the effect of a small notch and of a collar on the bending and torsional reversal strengths of several materials. The notch sensitiveness is the greatest in hard steels and in magnesium alloys, but very small in light-metal castings and in wood. The notch effect in combined static and dynamic stressing is considerably smaller than in pure alternate stressing (fig. 18) (reference 12). Very few numerical data are available in this connection, however. When no corresponding values are at hand, one may start, in estimating the fatigue strength, with the assumption that the notch effect is operative only in connection with the dynamic share of the stress. If, e.g., the original strength of a steel is 60 kg/mm² (85,340 lb./sq.in.) and if a notch is present by which the reversal strength is reduced 50 percent, then, with an initial stress of 30 kg/mm² (42,670 lb./sq.in.), the alternating stress is changed by ±15 kg/mm² (±21,335 lb./sq.in.). Such an estimate, however, is rather inaccurate, the resulting values not being on the safe side.

VIII. FATIGUE STRENGTH OF STRUCTURAL PARTS

1. Effect of Holes

The influence of various notch effects on structural parts is indicated in table IV. A very common form of not notch is a simple hole. The reduction in the fatigue strength is then due not alone to the hole itself but also to the grooves in the hole and sometimes to the burr on the the edge of the hole. The results of a whole series of experiments regarding the effect of holes on the fatigue strength are available. In bending fatigue tests (reference 20), steel rods of various strengths with transverse perforations were found to have 50 to 60 percent of the reversal strength of specimens without holes. Tests of tubes and sections with holes are more important for their bearing on airplane construction. Table I contains the data for ordinary carbon-steel tubes. The ratio between the fatigue strength of the perforated tube and that of the smooth tube is 0.47 with alternating stresses and 0.50 with initial tensile stresses. Since the initial compressive strength is considerably greater, the fatigue strength of a structural part can sometimes be considerably increased by shifting the connections to the pressure side. Cr-Mo steel tubes, which had a considerably higher fatigue strength, yielded, when perforated, no higher values than the carbon-steel tube. The ratio of the reversal strength with hole to that without hole was very unfavorable, being only 0.32. A corrosion-resisting chrome steel with a strength of 170 kg/mm² (241,800 lb./sq.in.) yielded better results. A riveted tube of this material yielded, with hole, a reversal strength of 23 kg/mm² (32,714 lb./sq.in.), while the reversal strength of a smooth test strip (without hole) was about 43 kg/mm² (61,161 lb./sq.in.). For duralumin and elektron tubes the ratio of the reversal strength with hole to that without hole is about 0.44 (according to tests by Hertel at the DVL).

Under alternating torsional stresses, fractures often start at the holes. The formerly frequent crankshaft fractures often began at the oil hole. In order to ascertain the effect of the hole and to be able to estimate the strength of crankshafts, torsional fatigue tests with crankshaft models were made several years ago at the DVL.* These tests showed a torsional reversal strength of the model of 22 kg/mm² (31,290 lb./sq.in.) as compared with a strength of 37 kg/mm² (52,627 lb./sq.in.) without hole. The original strength of the model was 30 kg/mm² (42,670 lb./sq.in.). Figure 19 shows the fracture, which proceeds from the inner edge of the oil hole, as is always the case in fractures during operation. This is due to the fact that the burr is not removed on the inner end of the hole, resulting in a considerably greater stress at this point. This example also shows clearly the need of careful sur-

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*The model was a two-throw crank corresponding in dimensions (on the scale of 1:5) to a shaft which had often broken in operation. The crank-pin diameter of the model was 12 mm (0.472 in.), the length of the crank pin 12 mm, the diameter of the inside hole 4.8 mm (0.189 in.), and the diameter of the oil hole 0.8 mm (0.031 in.). The material was Cr-Ni-W steel, with a strength of 120 kg/mm² (170,680 lb./sq.in.).

face finishing, especially for such highly refined steels. Stress reversal tests of large crankshafts in operation show, moreover, that in these the fracture may occur at a considerably lower stress than in the models.* It has not yet been determined whether this involves the influence of the absolute magnitude on the danger of local increases in the tension.

2. Strength Reduction in Keyed Joints

Fatigue fractures often occur in keyed joints, e.g., between the shaft and propeller hub. The points are especially dangerous where there is seizing of the parts. Hence, for example, the torsional reversal strength is reduced by a power-transmitting, keyed connection considerably more than would correspond to the notch effect of the keyway alone. Even when the key rests on a flattening of the shaft, i.e., when there is no appreciable notch effect, there is a reduction of about 35 percent in the torsional reversal strength.

3. Fatigue Strength of Screwed, Bolted and Riveted Joints

The fatigue strength of screwed and bolted joints is especially important. In this connection it is remarkable that the notch effect of a screw thread is less than that of a single notch of the same form. A rather important role is played by the fillet radius, which often deviates considerably from standard values. Tests at the DVL with commercial 14 mm (0.55 in.) screws yielded, for bright screws of screw-machine steel and of annealed carbon steel, a reversal strength of 17 to 22 kg/mm² (24,180 to 31,290 lb./sq.in.). The reversal strength of subsequently heat-treated screws was the same, since the effect of the greater strength (σ_B = 71 kg/mm² (100,987 lb./sq.in.) instead of 55 kg/mm² (78,229 lb./sq.in.)) is offset by the effect of the surface decarbonization (reference 21). Previous tests with rather poor 8 mm (0.315 in.) screws of screw-machine steel showed a reversal strength of only 11 kg/mm²

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*The difference is considerably greater than the strength reduction due to the stronger influence of the fibrous structure.

(15,646 lb./sq.in.). Moreover, tests were made regarding the effect of heat treatment on the strength of 10 mm (0.39 in.) threads on a Cr-Ni-W steel. With a refining to σ_B = 150 kg/mm² (213,350 lb./sq.in.), a reversal strength of 31 kg/mm² (44,093 lb./sq.in.) was obtained in the thread, when the thread was cut after heat treating the material. (If, however, the thread was heat-treated after finishing, the resulting reversal strength was only 15 kg/mm² (21,335 lb./sq.in.)). Still greater strength can be obtained by a special thread with a larger fillet radius and by surface hardening. For example, a reversal strength of 42 kg/mm² (59,739 lb./sq.in.) was obtained with 3/8-inch screws of nitrided steel with σ_B = 72 kg/mm² (102,409 lb./sq.in.), while the reversal strength of the same screws before nitriding was only 26 kg/mm² (36,980 lb./sq.in.) (reference 22). These methods for increasing the strength are important because it is often necessary in practice to replace broken screws or bolts by others of the greatest possible fatigue strength.

In this connection, attention must be called to the fact that the stresses to which screws are subjected are often not pure tensile stresses as commonly assumed in construction. On the contrary, bending stresses of considerable magnitude are often present, due to unequal support of the head of the screw or deformation of the supporting surface. Furthermore, in designing, insufficient allowance is often made for the fact that, in joints with several screws, they are not all equally stressed and can easily be overstressed.

While fatigue breaks occur quite often in screws subjected to tensile stresses, they very seldom occur in screwed or bolted joints stressed in shear. On the other hand, fractures often occur in the parts joined, beginning at the holes. The same is true of riveted joints. Here also a fatigue fracture of the rivets almost never occurs, but the fatigue strength of the riveted joint as a whole is considerably reduced. Tests of the fatigue strength of riveted joints yielded about 30 to 60 percent of that of the uninjured material, or 70 to 100 percent of that of the perforated piece. Figure 20 shows the conditions obtaining in this kind of joint. If the riveted joint is subjected to initial tensile stress, then the edges of the holes are subjected to the normal stresses and to the bearing pressure. The fatigue strength in this case is therefore lower than that of a single perforated piece. The conditions are quite different in the case of an initial compressive stress. The forces are then transmitted by the rivet directly to the opposite cross section, thus eliminating the stress increment on the wall of the hole due to the normal tension. In this case, therefore, a greater fatigue strength is to be expected than that of a single perforated piece. Accordingly the conditions in the alternately stressed riveted joint are such that the increase in tension at the edge of the hole is effective only during the tensile stressing and that therefore the effect of an original stress is felt. Hence, even in this case, there may sometimes be a smaller notch effect than what would correspond to the simple hole. It is also true that, in this region of low stresses, the transmission of force by friction between the strips becomes very pronounced and the rivets may be considerably relieved by the distribution of the forces throughout the whole riveted cross section. Of course the strength of the joint as a whole is still further increased by butt straps (with several rows of rivets), or by splicing.

4. Fatigue Strength of Welds

Quite different conditions exist in welded joints. Here there is less of a notch effect than at the points of transmission in the other kinds of joints thus far considered. There is, however, between the parts joined, a zone of metal in the condition of a casting and next to the latter a zone of annealed metal. Moreover, it often happens that the chemical composition of the matter in the weld zone is considerably altered from that of the parts welded; for example, it may be strongly decarbonized. All these concurrent influences vary greatly according to the material and the nature of the weld. Hence the fatigue strength of the welds has greatly differing values, ranging between 50 and 90 percent of that of the unwelded metal. Naturally, the higher values are found in the soft steels. It is expedient to base the fatigue strength, as well as the static strength, not on the original material but on that annealed by the welding. Then the differences are considerably smaller. The fatigue strength of welded carbon-steel tubes, as used in airplane construction (with unsmoothed welds) is 14 to 18 kg/mm^2 (19,913 to 25,600 lb./sq.in.). (See tables I and IV.) Cr-Mo-steel tubes yield somewhat higher values (reference 23). Apparently the original strength of welded tubes is relatively high (table I). Of course the values given are valid only when the weld itself is perfect. Otherwise they may be considerably smaller.

IX. CONCLUSIONS

The fatigue strength of a structural part is affected by very many factors which do not affect the static strength and are therefore disregarded in connection with the latter. All these conditions must be considered in fatigue tests. From the viewpoint of the designer there is, therefore, no fatigue strength to be based simply on the material. The structural form (increased tension at the cross-sectional transitions) and the character of the surface of the member must always be considered in judging the actual fatigue strength. The object of this work was to indicate the magnitude of these influences in the individual cases and to facilitate their estimation. In determining the fatigue strength with regard to these influences, it must be borne in mind, however, that the influences of the same order of magnitude, e.g., all those due to the nature of the surface, cannot be added according to their nature and have but little mutually strengthening effect on one another. On the other hand, the fatigue strength is reduced by large notches and cross-sectional transitions; for example, in addition to the influence of the surface. Hence, insofar as the effect of both influences is not determined in common, the reduction factors estimated for both influences are to be added algebraically, in order to determine the total reduction in the fatigue strength. In this way, with consideration of the known fatigue strengths, the most important of which for airplane and engine materials are included in this paper, the fatigue strength of the structural parts can at least be approximately estimated.

SUPPLEMENT

While this article was in press, a work by R. E. Peterson appeared (reference 24), which contains experimental results on the influence of the absolute magnitude on the fatigue strength of smooth and notched specimens. These data make it possible to estimate numerically the dependence of the notch effect on its absolute magnitude. Due to the great importance of these data in determining the fatigue strength of structural parts, they will be given briefly.

In smooth rods (without cross-sectional transition), the size of the specimen has no appreciable effect on the fatigue strength. The tests were made with specimen rods of 1.27 to 50.8 mm (0.05 to 2.0 in.) diameter and with steels of 0.20, 0.24, 0.44, and 0.57 carbon content.

In test specimens with cross-sectional transitions, however, the absolute magnitude has a very considerable effect on the fatigue strength. Figure 21 shows the relations for specimens with a transverse hole. For two series of tests a carbon steel containing 0.45 C, 0.79 Mu, 0.18 Si, 0.032 S, and 0.013 P was used, with $\sigma_{0.2}$ = 22.9 kg/mm² (32,570 lb./sq.in.), σ_B = 53.4 kg/mm² (75,953 lb./sq.in.) elongation (2 in.) = 32 percent, reduction of area = 50 percent, and σ_W = 23.2 kg/mm² (33,000 lb./sq.in.), the specimens having diameters of 1.27 to 50.8 mm (0.05 to 2 in.). A heat-treated 0.57 carbon steel was used for the third series of tests (strength data not given in the report). While the notch fatigue strength is 70 to 90 percent of the normal fatigue strength for very small specimens, it is only 40 to 60 percent for very large specimens. The relations are similar for other notch forms.

According to these tests and to theoretical considerations, it may be assumed that the notch effect in very large cross sections tends toward the value according to the theory of elasticity as the limit. Opposed to this, however, are the facts that, in plotting σ_W/σ_{WK} against the logarithm of the diameter of the specimen, the test points lie approximately on a straight line, and especially that the greater notch sensitiveness of the 0.57 carbon steel is just as pronounced in the large specimens as in the small ones. (With increasing approximation to the theoretical notch effect, the differences in the notch sensitiveness should gradually diminish.) Further researches will be necessary for clarifying these relations. It is certain, however, that, in estimating the notch effect, the influence of the absolute size of the structural members cannot be disregarded.

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TABLE I

Effect of Initial Tension on the Fatigue Strength

Material	Strength (kg/mm²)			
	σ_B	σ_W	σ_{+U}	σ_{-U}
Aluminum alloy* 0.99 Si, 4.28 Cu, 0.54 Mn	36	13	23	30
Magnesium alloy** 0.12 Si, 0.43 Zn, 6.30 Al	34	15	19	30
C-steel tube 28 by 1, smooth-drawn	54	22	39	-
C-steel tube, smooth drawn with 3 mm hole	54	10.5	19.5	29
C-steel tube, welded	46	15	29	-
Corrosion-resisting Cr-steel 1 mm sheet 0.34 C, 13.7 Cr, as delivered	75	33	57	-
Corrosion-resisting Cr-steel 1 mm sheet 0.34 C, 13.7 Cr, heat-treated	170	43	~53	-
Stainless austenite steel 1 mm strip, hard-rolled	116	42	75	-

*τ_B = 24 kg/mm², τ_W = 9.5 kg/mm², τ_U = 15 kg/mm²

**τ_B = 17 " τ_W = 7.5 "

(kg/mm² × 1422.35 = lb./sq.in.)

TABLE II

Fatigue Strength of Partially Finished Oroducts, etc.

		σ_B kg/mm²	σ_W' kg/mm²	σ_W'/σ_W *
Grain (slag inclusions) Fatigue strength crosswise of grain	Steel (crankshafts)			0.7-0.9
	Duralumin (forging)			0.9
	Elektron (propeller)			0.8
Effect of mechanical treatment	Steel:			
	Grinding grooves { longitudinal			1.0
	Grinding grooves { transverse**	50-90		0.8-0.9
	Planing grooves { longitudinal			0.75-0.95
	Planing grooves { transverse***	50-90	25-30	
	Duralumin:			
	File scratch (smooth file) transverse			> 0.95
Fatigue strength of partially finished products	Duralumin:			
	Sheet	~ 40	10-12	
	Tubes and sections		9-9.5	
	Elektron:			
	Sheet	29	8	
	Tubes and sections		5-7	
	Steel:			
	C-steel tube, smooth-drawn	54	22	
	Stainless steel (V2A), 1 mm strip, as delivered - (smooth-rolled)	112	42	
	Corrosion-resisting steel (V5M), sheet as delivered (pickled)	121	44	
	Corrosion-resisting steel (V3M), sheet { as delivered, unworked	75	33	
	Corrosion-resisting steel (V3M), sheet { heat-treated, unworked	170	43	
	Cr-Ni-W steel sheet { as delivered, unworked	121	39	
	Cr-Ni-W steel sheet { heat-treated, unworked	162	39	

*, **, ***: See footnotes, next page.

TABLE II (cont.)

Fatigue Strength of Partially Finished Products, etc.

		σ_B kg/mm²	σ_W' kg/mm²
Fatigue strength of partially finished products	Steel (continued):		
	0.5 C spring-steel wire:		
	worked before heat treatment		72
	worked after heat treatment		43
	Cr-V spring-steel wire:		
	worked before heat treatment		67
	worked after heat treatment		50
Effect of corrosion	Previously corroded by exposure to salt-water spray for one month:		
	Stainless steel (V2A), as delivered (smooth-rolled)	112	43
	Corrosion-resisting steel (V5M), as delivered (pickled)	121	48
	Corrosion-resisting steel (V3M), heat-treated, pickled	170	27
	Cr-Ni-W steel, heat-treated, pickled	158	25
	Duralumin		~8
	Simultaneous corrosion and fatigue stressing (10 million periods at 50 Herz)		
	Steel	30-160	~12
	Duralumin		7-8
	Elektron		3.5

*σ_W' = reduced fatigue strength; σ_W = normal fatigue strength of polished specimens of full cross section.

**Also file scratches (smooth files)

***Also lathe grooves.

TABLE III

Effect of a Notch and of a Collar on the Bending and

Torsional Reversal Strength

Material	Tensile strength kg/mm²)	Bending reversal strength (kg/mm²)			Torsional reversal strength (kg/mm²)			According to
		Smooth rod	With notch*	With collar**	Smooth rod	With notch*	With collar**	
C steel (St 48)	53.9	26.0	18.0	15.0	15.0	13.0	11.5	Ludwik
Cr-Ni steel (VCN 35)	108	53.0	29.0	25.0	30.5	22.0	20.5	"
Cr-Ni-W steel (refined)	114	58.0	-	32***	38.0	-	30****	DVL
Cr-Ni-W steel (air-hardened)	162	69.0	32.0	30.0	37.5	26.0	-	Ludwik
Elektron (AZM)	34.6	15.3	-	7.3	7.5	-	-	DVL
" "	31.3	11.0	10.0	-	6.5	-	-	Ludwik
Duralumin 681 B	46.2	15.5	-	9.0	6.7	-	-	DVL
" 681 B	40.8	14.0	13.5	11.5	8.0	7.5	7.0	Ludwik
" 681 ZB	44.7	17.7	-	11.0	10.8	-	-	DVL
Silumin (cast)	19.6	6.0	6.0	-	4.2	-	-	Ludwik
Wood (pine)	14.0	4.2	~4.2 (~3.4)ˣ	>3.6	-	-	-	DVL

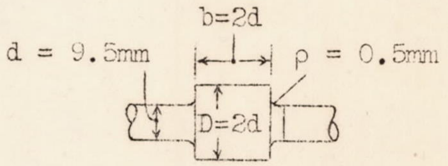
*Fourfold annular notch of 0.2 mm depth and 0.05 mm fillet radius (with a die for cutting metr. thread of 5 mm diameter).

**For form of collar, see sketch.

***Width of collar = d; ρ = 0.1 mm.

****Diameter of collar = 1.5 d; ρ = 0.3 mm.

ˣ45° notch of 4 mm depth.



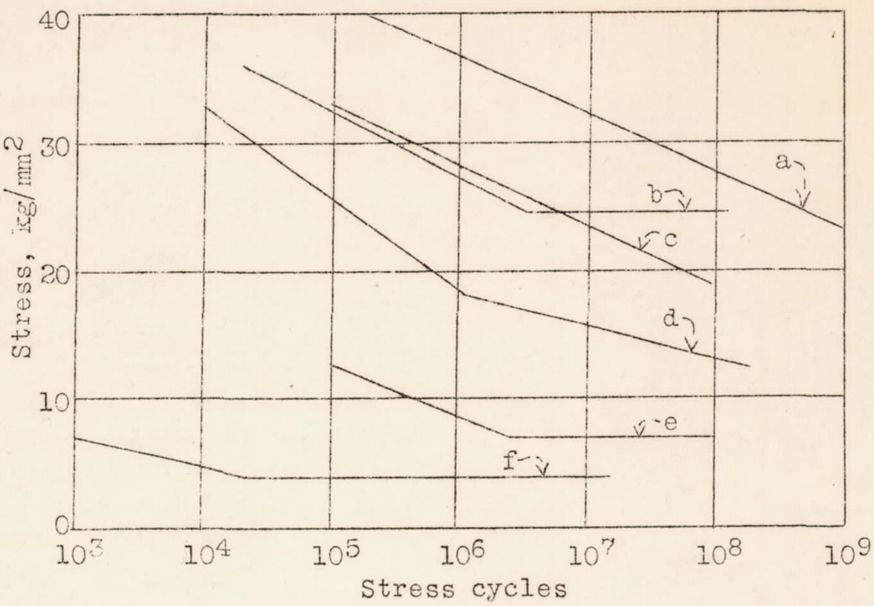
(mm x .03937 = in.)

TABLE IV

Influence of Notch Effects on the Fatigue Strength

	σ_{WK} kg/mm²	σ_{WK}/σ_W
Holes: in steel rods		0.5-0.6
" " tubes		0.32-0.54
" duralumin tubes		~ 0.44
" elektron tubes		~ 0.44
Keyed joint: effect of working (without notch effect)		0.65
Screws: commercial with		
σ_B = 55 to 70 kg/mm²,	(11) 17-22	
of Cr-Ni-W steel (σ_B = 150 kg/mm²),	31	
Nitrided,	42	
Riveted joints		0.3÷0.5
Welded joints		0.5-0.9
C steel sheets and tubes	14-18	
Cr-Mo steel tube	~ 21	

Translation by Dwight M. Miner,
National Advisory Committee
for Aeronautics.



a, Monel metal, σ_B = 63 kg/mm^2 b, 0.18%C-steel, σ_B = 47 kg/mm^2
c, Nickel, σ_B = 53 kg/mm^2 d, Refined dural.* σ_B = 46 " "
e, Pure aluminum, σ_B = 17 kg/mm^2 f, Pine wood (Kiefer), σ_B=17kg/mm^2

Figure 1.-Tension plotted against number of load reversals (in millions) for various materials.

*(681 B)

a, 0.11%C-steel, rolled. σ_B=68 kg/mm^2

b, 0.11%C-steel, standardized. σ_B=35 kg/mm^2

c, Copper, annealed. σ_B=23 kg/mm^2

d, Aluminum, rolled. σ_B=10.1 kg/mm^2

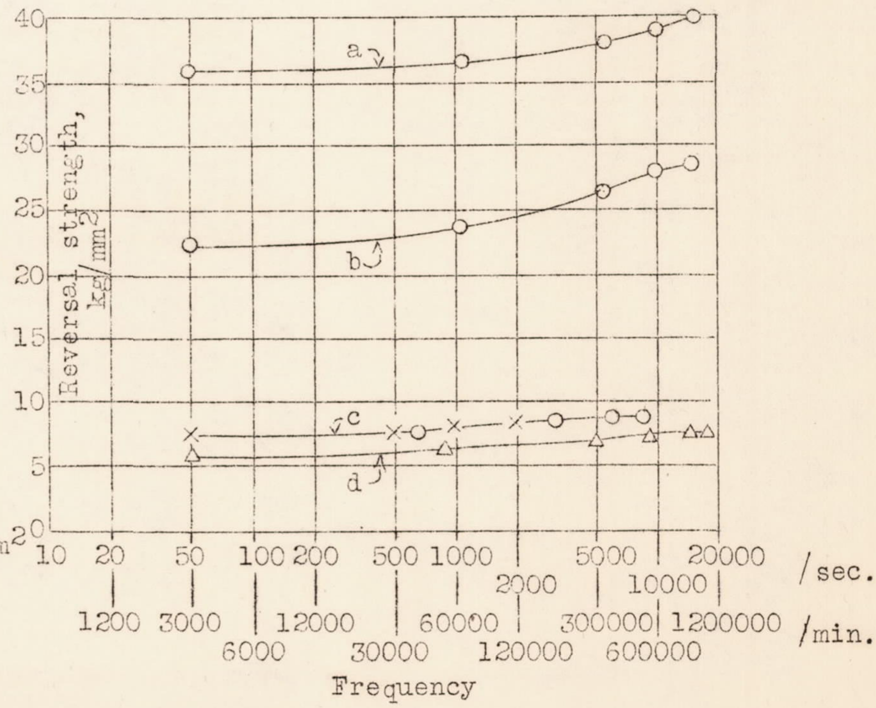


Figure 6.-Reversal strength plotted against vibration frequency.

Figure 3.-Fatigue fracture of a light-metal tube, starting from a hole.

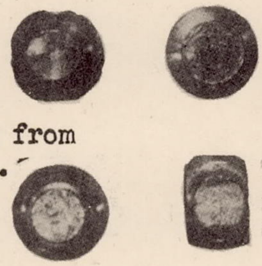


Figure 2.-Fractures of ball studs.

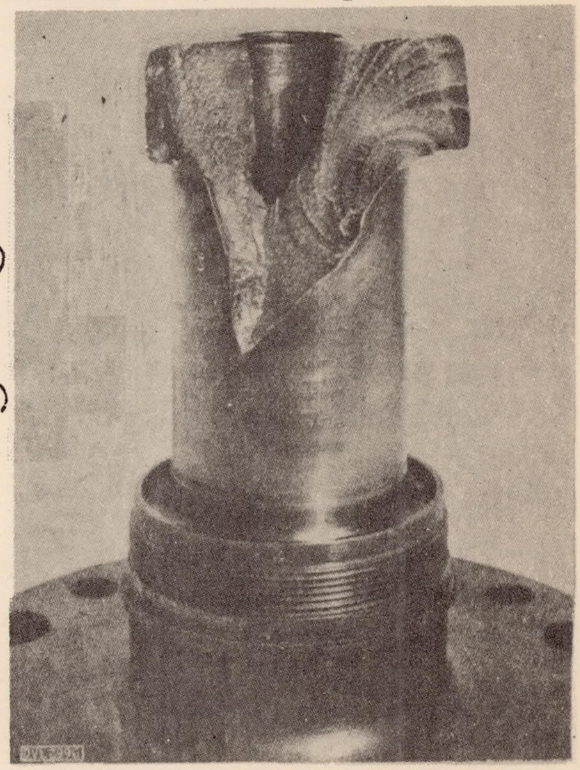


Figure 5.-Torsional fatigue fracture of a crankshaft.

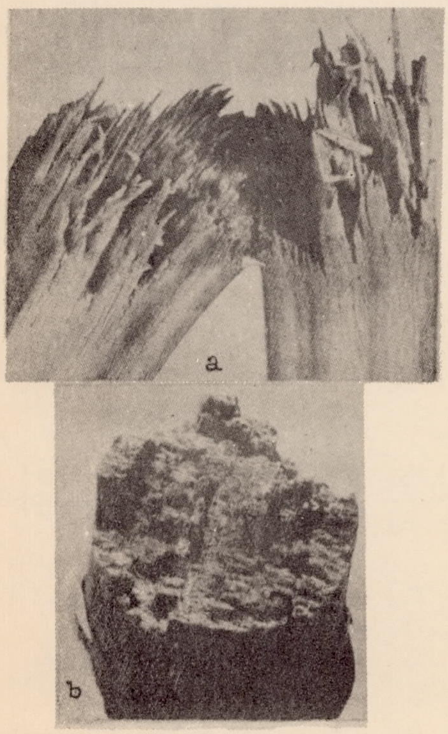


Figure 4.-Static (a) and fatigue (b) fractures of ash wood.

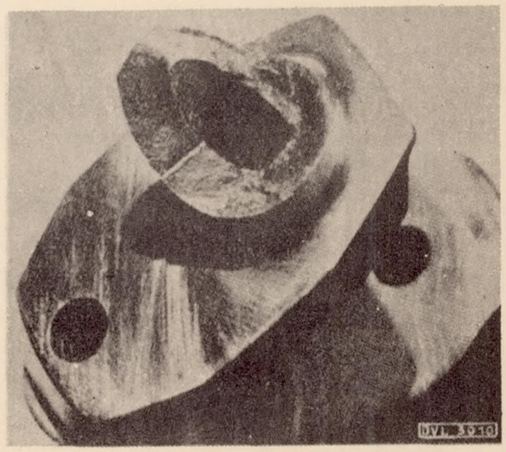


Figure 19.-Torsional fatigue of a crankshaft model, beginning at inner edge of oil hole.

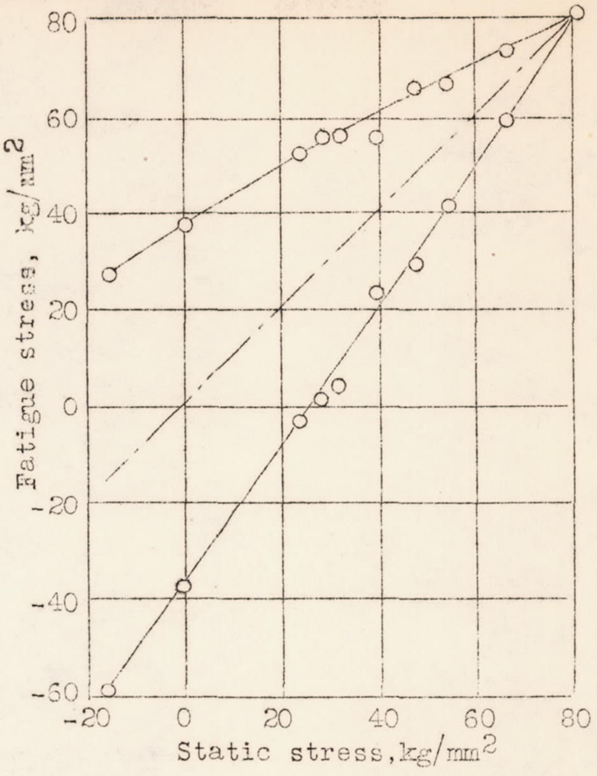


Figure 7.-Fatigue strength vs. initial tension.

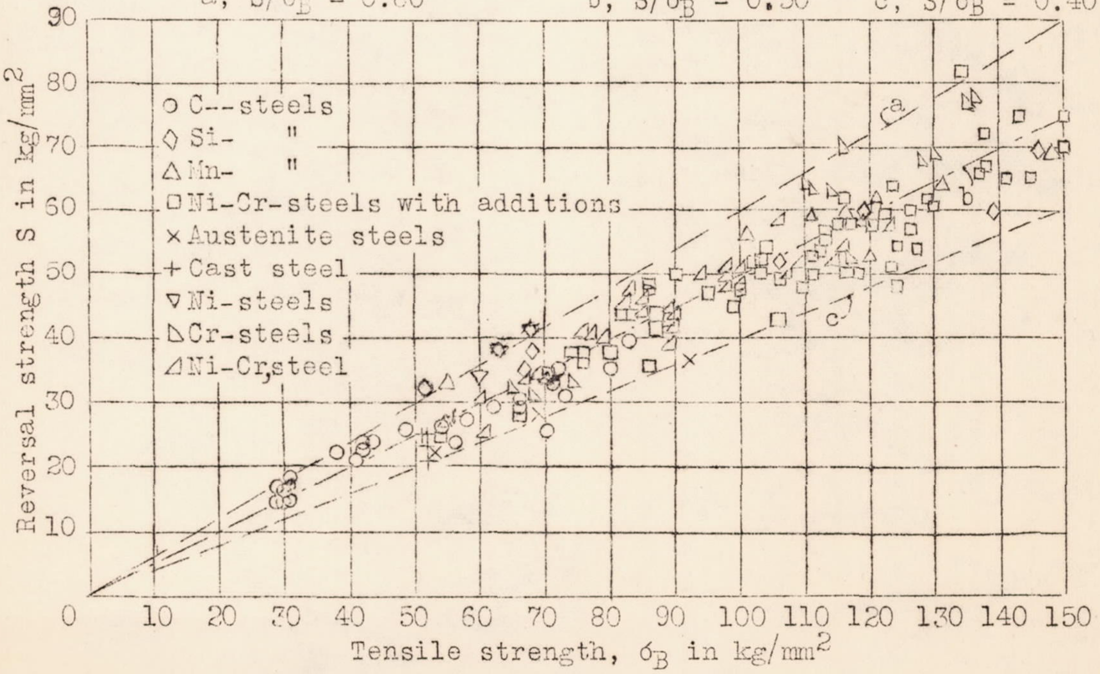


Figure 8.-Bending reversal strength vs. tensile strength.

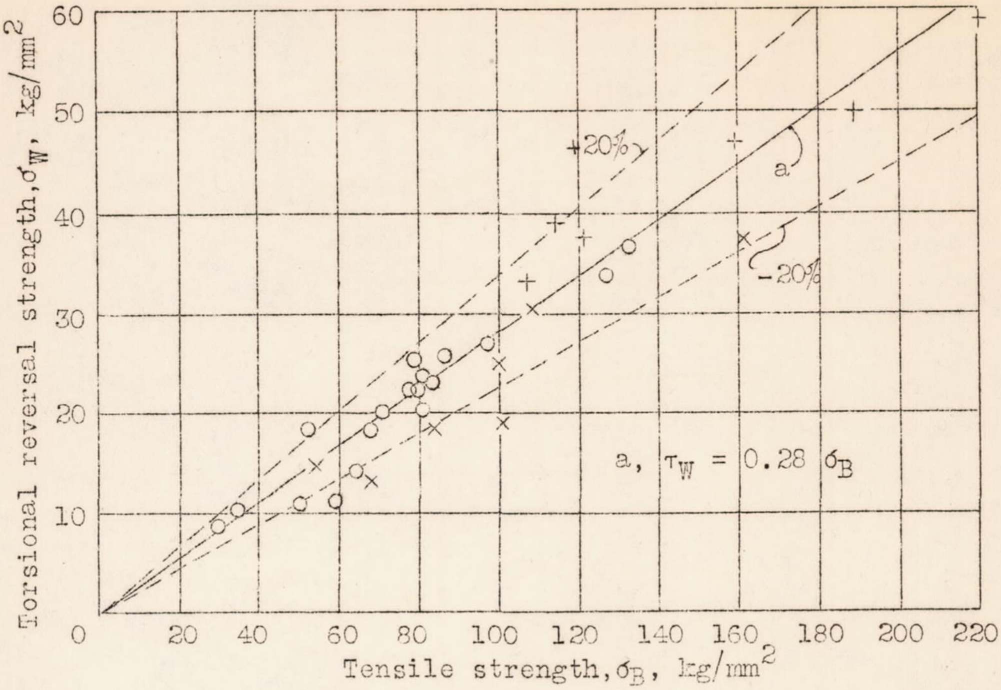


Figure 9.-Torsional reversal strength vs. tensile strength of steels.

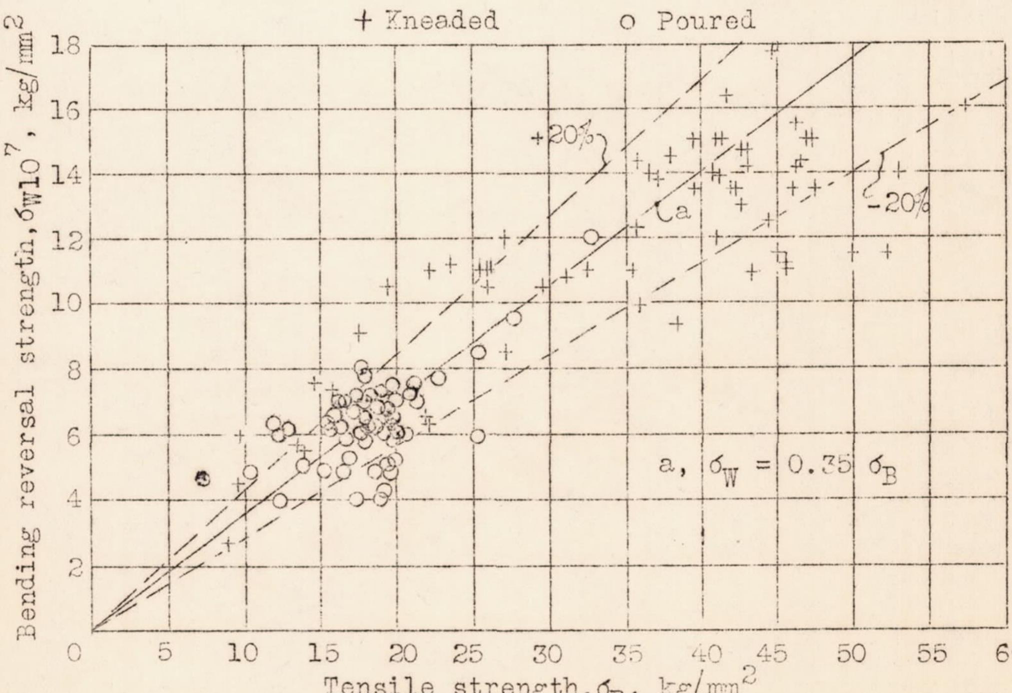


Figure 10.-Bending reversal strength vs. tensile strength of aluminum alloys.

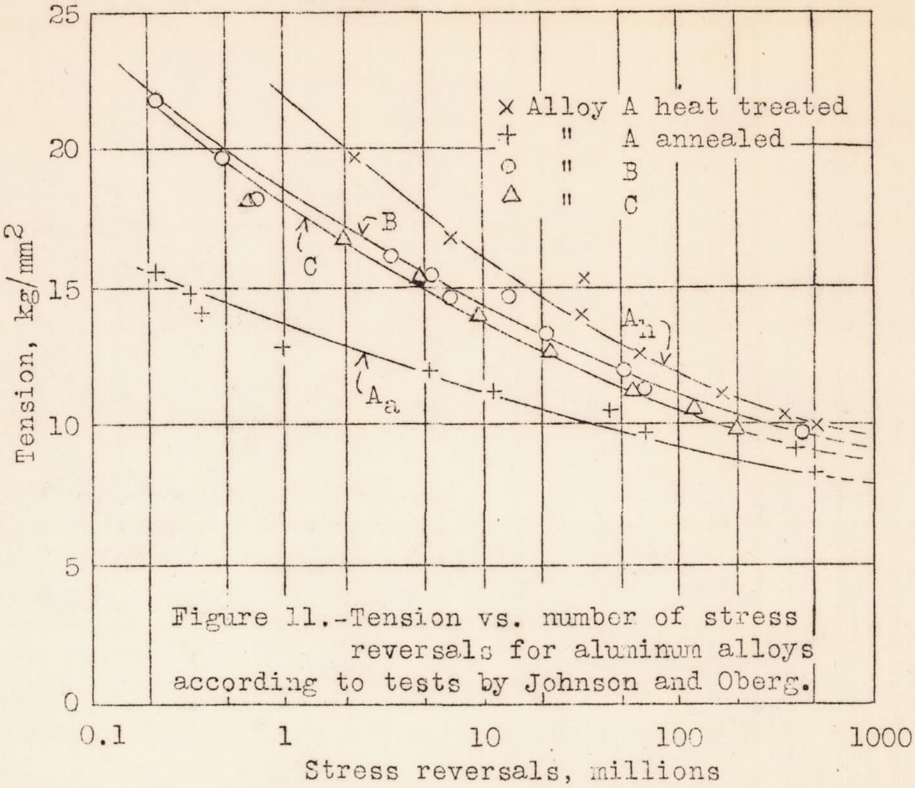


Figure 11.-Tension vs. number of stress reversals for aluminum alloys according to tests by Johnson and Oberg.

Alloy A heat-treated, with 4.01 Cu 0.22 Si 0.73 Mn 0.57 Mg; σ_B=41.6 kg/mm²
" A annealed, with 3.94 Cu 0.16 Si 0.67 Mn 0.58 Mg; " =23.7 "
" B with 3.90 Cu 1.24 Si 0.39 Mn 0.57 Mg; " =46.5 "
" C with 4.42 Cu 0.82 Si 0.83 Mn 0.00 Mg; " =41.1 "

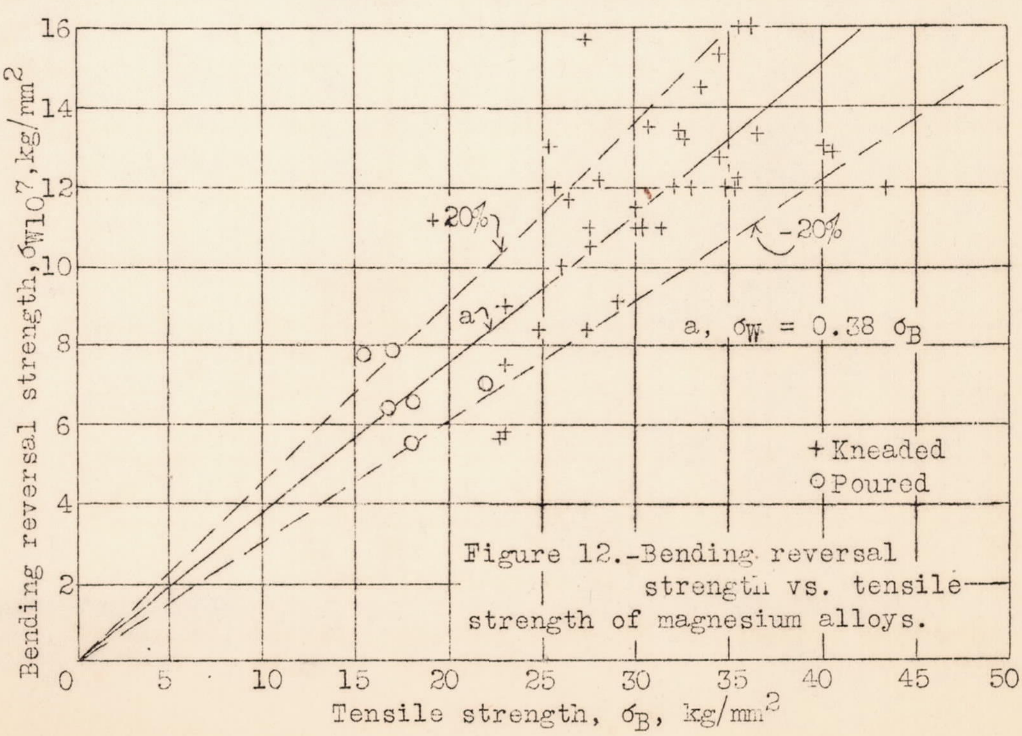


Figure 12.-Bending reversal strength vs. tensile strength of magnesium alloys.

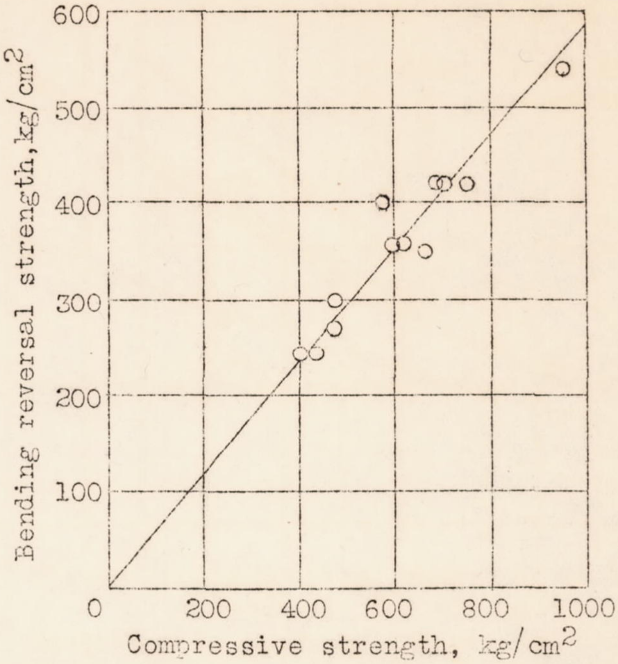


Figure 13.-Bending reversal strength vs. compressive strength of woods.

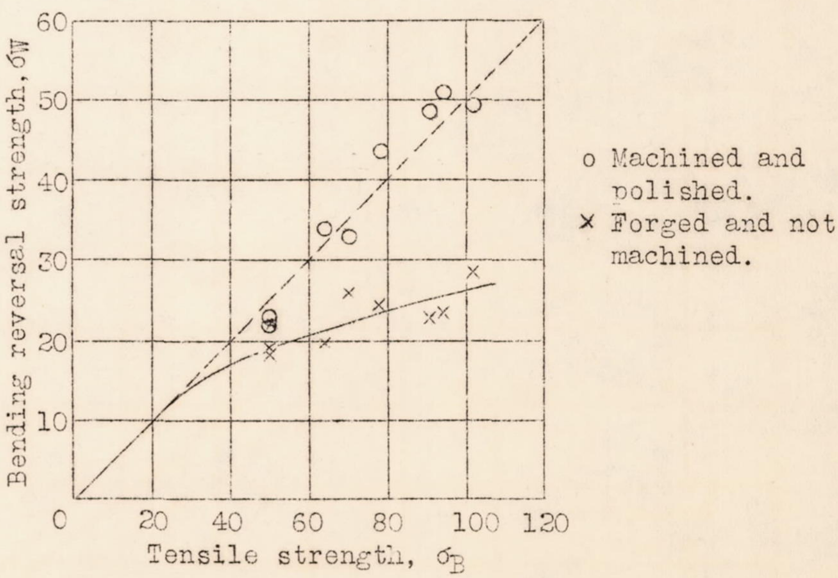


Figure 14.-Effect of surface decarbonization on the bending reversal strength of forged test specimens.

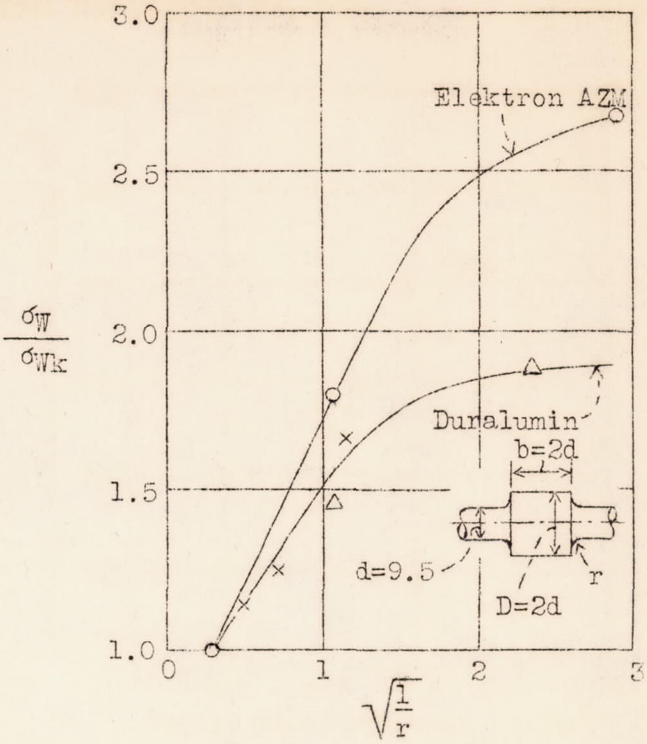


Figure 15.-Effect of the fillet radius on effective increase in tension.

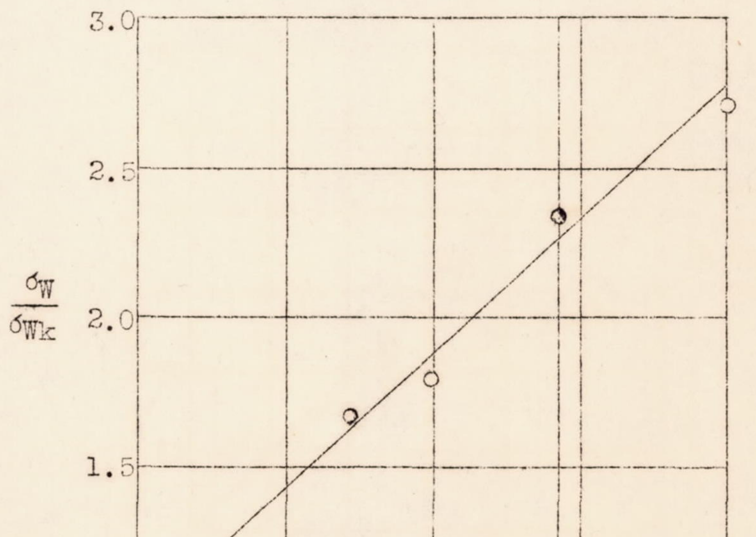


Figure 16.-Influence of depth of notch on effective increase in tension. 60° V-notch with 0.05 mm (0.002 in.) fillet radius and 0.1 to 0.8 mm (0.004 to 0.031 in.) depth. Cr-Ni steel (VCN 35) with a strength of 108 kg/mm^2 (153,614 lb./sq. in.)

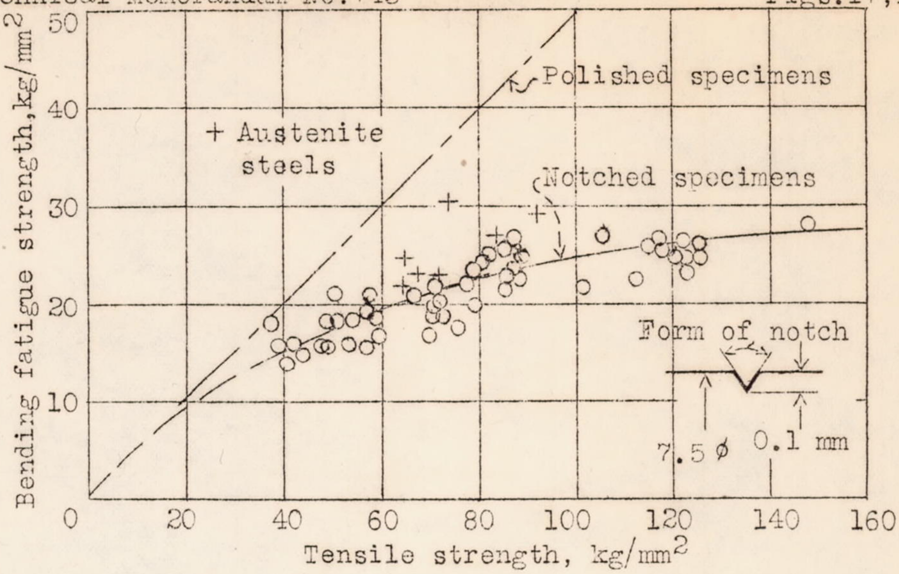


Figure 17.-Notch sensitiveness and tensile strength of steel according to Houdremont and Mailander. Bending reversal strength vs. tensile strength.

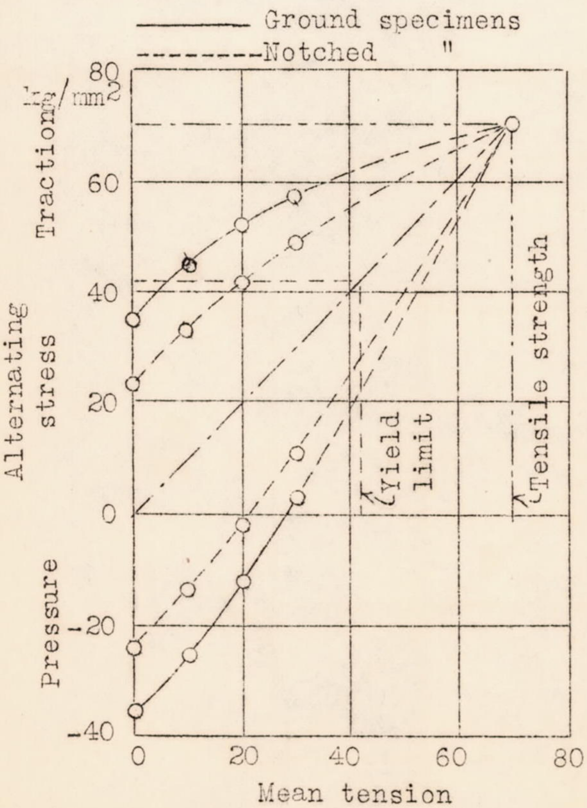


Figure 18.-Notch effect in fatigue stressing with initial tension (according to tests by Schenck).

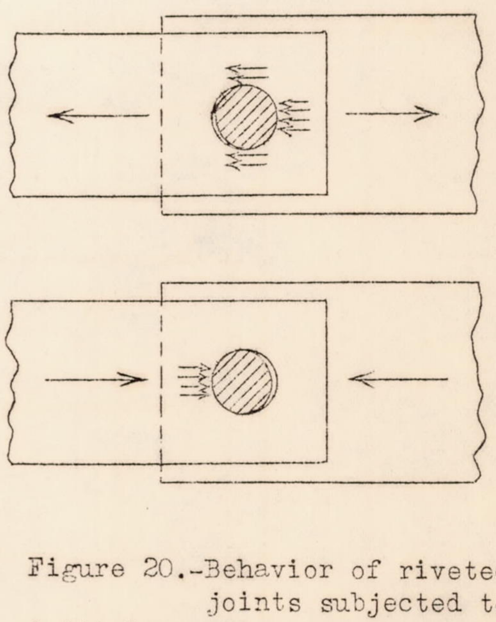


Figure 20.-Behavior of riveted joints subjected to initial tensile and compressive stresses (diagrammatic). With initial tensile stress (above) the edge of the hole is under tension. With initial compressive stress (below) the forces are transmitted directly to the sheet.