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PROBLEMS INVOLVED IN THE CHOICE AND USE OF MATERIALS IN AIRPLANE CONSTRUCTION

By Paul Brenner

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INTRODUCTION

Careful selection and proper shaping of materials insure low weight, good strength and safety in operation. This requires a thorough knowledge and exhaustive study of materials. The present state of the problem of materials in airplane construction is studied below on the basis of data giving the principal characteristics of different materials and showing how they affect the form of airplane parts.

The problem of materials and of their transformation into airplane parts shows interesting aspects in the light of progress in aircraft construction. The originally prevalent opinion that materials of low specific gravity are required to build airplanes with a sufficiently low structural weight led to the extensive use of wood and fabric. At that time metal was used as little as possible. The increasing demand for economy and safety in operation brought the weak points of wood into full evidence, especially its small resistance to weather influences and deformation. Hence, the necessity of replacing wood by metal at least in certain cases. Welded steel-tube fuselages compare favorably with wood construction as regards strength and weight. The development of steel-tube construction was, however, greatly impaired by a prejudice against the reliability of welded joints, especially in wing construction. Their use is now practically confined to fuselages. The introduction of duralumin is one of the most important steps in the development of metal airplane construction. With the specific gravity of aluminum it

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*"Baustoffragen bei der Konstruktion von Flugzeugen." Zeitschrift für Flugtechnik und Motorluftschiffahrt, Nov. 14, 1931, pp. 637-648.

had the strength of the weldable steel tubes then in use. For the last 15 years full advantage has been derived from the possibilities afforded by this material. The use of duralumin in airplane construction has thus taken an unusual expansion. The new tendency to revert to steel construction is marked by the use of high-grade alloyed steel of 140 to 160 kg/mm² (199,130 to 227,575 lb./sq.in.) strength in thin strips shaped by rolling and joined by rivets. For several years this method of construction has been developed in England on the basis of systematic investigations in the field of materials, construction and design. In certain cases it offers great advantages over wood and light-metal construction, especially when highly rustproof chromium steel is used.

All three methods of construction are now in use. Light-metal airplanes are employed where great reliability in operation, resistance to weather and durability are required. In order to keep the price of sport airplanes, which are not yet built in quantity, within reasonable limits, they are preferably made entirely or chiefly of wood. England is practically the only country which has adopted all-steel construction.

It is difficult to predict the future trend of airplane construction, the problem of materials being affected by technical as well as by economical considerations. Much depends on whether the strength, uniformity and resistivity to corrosion of present-day materials are further improved or new materials with better characteristics are developed. The decisive influence, which progress in the field of material research and manufacture may have on the practical development of airplane construction, is clearly shown by the example of duralumin.

WOOD

Strength Characteristics

Wood is an excellent material for light parts subject to tension. Similar results can be obtained only with steel having a tensile strength of at least 200 kg/mm² (284,470 lb./sq.in.). On the other hand, the compressive strength of wood is much smaller than that of other high-grade materials used in light airplane construction, being only about half its tensile strength. Wood is preferable to metal for parts working under buckling stresses, so long as the external dimensions of the cross section remain optional and the stresses are below the limit of elasticity, since the low specific gravity of wood permits the use of large radii of inertia. When over-all dimensions have to be reduced in consideration of drag or lack of space, as for struts exposed to the air flow, materials with a greater Young's modulus (steel) are preferable. The small compressive and shearing strength of wood in the direction of the grain is detrimental in beams working in flexure. Besides, the excellent elastic properties of wood permit the stressing of wooden parts nearly to the breaking point without excessive permanent deformation.

The vibration strength of the woods used in airplane construction (pine, spruce, ash, walnut), as determined by fatigue bending tests, is rather small, being about 25 to 30 per cent of the static tensile strength. All the woods hitherto tested show a pronounced fatigue limit which is reached after not more than two million load alternations or reversals, and even sooner for softer species. (Reference 1.)

The irregularity of wood, due to structural differences resulting from changing conditions of growth, is prejudicial to its use in airplane construction. The tensile and compressive strengths of pine and spruce obtained in D.V.L. tests during recent years are compared in Figure 1. Although special woods are selected for airplane construction, their strength coefficients show considerable variation. The increase in the mean values with the specific gravity is roughly linear. A certain degree of reliability of the strength calculation of airplane parts may be attained with sufficiently small figures or by very carefully testing the strength of the wood before using it. The great irregularity in the strength factors can be partially eliminated by the well-known method of dividing the cross section into a large number of separate layers (laminas). This method, however, is applicable only to thick parts, especially spar flanges.

The strength characteristics of several woods used in airplane construction are given in Table I, including tensile, compressive, bending and shearing strengths parallel to and across the grain, as well as Young's modulus, the shear modulus and the fatigue bending strength.

Plywood is now the most important material for wood airplanes. It remedies completely or partly one of the main defects of wood construction, viz., the strength variation in different directions with respect to the grain. The tensile strength of plain wood is compared in Figure 2 with that of plywood, the three layers of which are arranged in different order and tested in various directions with respect to the grain. Plain wood has practically no strength across the grain (2 to 3 per cent of the longitudinal strength). In three-ply wood the longitudinal and transverse strength can be regulated at will by varying the thickness of the different layers (dash and dash-dot line). The diagonal strength, however, is always relatively small and therefore prejudicial to the use of plywood for spar webs or wing and fuselage covering. If the three layers are not glued at right angles but at angles of 60°, the strength distribution is uniform in all directions (dot line). Such plywood is not yet used in airplane construction. It would, in fact, be practically useless, since, on account of its dissymmetrical structure, it would warp considerably under changing conditions of humidity. This difficulty can, however, be overcome by using plywood with more than three layers. The results given in this report merely show that present-day wood construction can be further improved by developing the technical side of the material problem. The strength characteristics of birch and alder plywood, used in airplane construction, are given in Table II.

Joints

From the standpoint of strength and weight the method of assembling wooden parts by gluing, is the best. The shearing strength of cold casein glue is 60 to 80 kg/cm² (853 to 1137 lb./sq.in.). The full strength of wood can therefore be preserved by gluing sufficiently large surfaces. Scarfing prevents wooden joints from increasing the structural weight (fig. 3,b) and obviates the danger of additional bending moments capable of impairing the strength of the joint. A scarf ratio of 1/15 to 1/20 is used in airplane construction for pine.

On the other hand, disconnectable joints are extremely complex and comparatively heavy (fig. 3,c) owing to the difficulty of transmitting stresses from metal to wood.

Resistivity to Moisture

The strength characteristics of wood, especially the compressive strength, bending strength and Young's modulus, depend largely on its moisture content. Figure 4 shows the effect of the moisture content on the compressive strength and on Young's modulus of spruce. Both of these properties are inversely proportional to the moisture content up to the point of saturation of the fibers (20 to 30 per cent), beyond which they are not affected by a further increase in the moisture content. (References 21 and 22.)

The volume of wood changes with the moisture content, due chiefly to variations at right angles to the grain, which may cause undesirable deformation of wooden parts in operation. The crossed layers of plywood prevent swelling or shrinkage across the grain. Even plywood, especially thin sheets, may buckle or warp, owing to irregularities in the layers, inaccuracies of production, or local moisture absorption.

Wood has a tendency to adapt its moisture content to its surroundings. Precautions must therefore be taken to prevent variations in its moisture content, and especially increase of moisture in service, chiefly on account of the prejudicial increase in weight. Oil varnish is the principal means of protection against humidity in airplane construction. Its protective effect is improved by a preliminary treatment of the wood with paraffin. (Reference 2.) Under severe operating conditions (sea service, long exposure to rain in flight or on the ground) even this does not afford absolute protection, but more satisfactory results may be obtained by saturating the wood with water-repelling liquids. In this connection good results were obtained by tests with synthetic resinous substances. However, no saturation method suitable for use in airplane construction has yet been developed.

The casein glues now in use have only a limited degree of moisture resistivity. The binding strength of glued samples drops, after 48 hours' immersion in water, to about 30 per cent of its value in the dry state. (See "Bauvorschriften für Flugzeuge," 1928, No. 1132.) The moisture resistance of plywood is now being considerably increased by the use of adhesive films of artificial resin or cellulose acetate, instead of casein or albumin glues. These films are placed between the plywood layers and set by the action of heat and pressure. Plywood glued by this method is remarkably moisture resistant. (References 3 and 4.)

The characteristics of wood, especially regularlity and moisture resistivity, can be further improved. For the last two decades, however, wood research has lagged far behind metal research. If such active research had been carried on in connection with wood as with metals, the former would now probably have reached a much higher degree of perfection than it has.

At present the advantages of wood over metal are chiefly economic. Wood is a cheap material, easily workable at small cost. It can, moreover, be easily adapted to the requirements resulting from changes in design.

METALS

Metals are suitable materials for use in airplane construction owing to great regularity and permanency of form. They afford reliable data for strength calculation and permit increasing the accuracy of manufacturing methods, which is particularly important in the case of interchangeable parts. The metals under consideration (aluminum alloys, magnesium alloys, carbon steels and alloyed steels) are used in the rolled, stamped or forged state. Cast alloys can be used in only a very few cases, their mechanical properties not being even approximately so good as those of rolled alloys.

Refinable aluminum alloys are of special interest, duralumin being the best known representative of this group. All efforts toward developing other alloys with better characteristics than duralumin have hitherto failed. On the other hand, the properties of duralumin have been slightly improved during the last few years by a better composition and improved production methods. The ZB alloy (reference 5) used, among others, in the Zeppelin airship LZ 127, and the flying boat Do X, differs from standard duralumin alloys by having a higher limit of elasticity, yield limit and strength, its capacity of deformation being, however, slightly smaller. The characteristics of lautal (reference 6), another refinable aluminum alloy, most closely approach those of duralumin.

Magnesium alloys, the specific weight of which is only two-thirds that of duralumin, have hitherto been used in the form of the soft elektron alloy AM 503 for welded fuel tanks and certain other parts of minor importance such as engine, fuselage and landing-gear sheet-metal coverings, seats, inspection ports, etc. Attempts were recently made to use the stronger AZM elektron alloy for stressed airplane parts. The rivets are made of magnalium, an aluminum alloy with approximately 5 per cent magnesium, elektron being unfit for cold riveting on account of its brittleness.

The steels used in airplane construction may be classified as weldable and nonweldable. Owing to its good welding characteristics, unalloyed steel with less than 0.3 per cent C is commonly used for steel-tube construction and for fittings. Weldable steel of greater strength, especially chrome-molybdenum steel or steel with a higher percentage of C, is extensively used for this purpose. Welded fittings are now also made of Krupp's V 2 A austenite steel.

Unalloyed steels with approximately 0.6 per cent C and a small percentage of manganese have a strength of 75 to 85 kg/mm^2 (106,675 to 120,900 lb./sq.in.) and can be cold-worked. It is now used to some extent in Germany for riveted wing spars. Alloyed steels of much greater strength (199,125 to 227,570 lb./sq.in.) are used in England in the form of standard chrome-nickel steel or stainless chromium steel with more than 12 per cent of chromium. These steels can only be machined in the soft state. Refining after shaping requires special installations. (Reference 7.)

Strength Characteristics

The strength characteristics of the different metals are compared by determining the limit to which they may be stressed in use. While former methods of calculation covered only the breaking strength, it is now generally recognized that, in order to avoid excessive deformation, certain stress limits, considerably below the breaking point, must not be exceeded. It was found impossible not to exceed the limit of elasticity of the metal, since the definition and experimental determination of this limit involve considerable difficulties, the location of the limit of elasticity, when defined by a permanent set of 0.001

per cent of the measured length, being affected by constructional considerations which are beyond control. Besides, metals with a very low limit of elasticity, such as light metals which have given excellent results in airplane construction, would be greatly handicapped by this condition. The practice of considering the limit of elasticity as the permissible stress limit is losing ground, since it is impossible to prevent vibration ruptures simply by keeping within the limit of elasticity. Neither can the yield limit or the 0.2 limit be considered as the permissible stress limit, since the corresponding permanent set is already excessive. Hence, the maximum stresses in operation are often required to be somewhat below the yield limit. Thus, according to the latest airplane specifications, a safety factor of 1.35 is required in order to prevent the 0.2 limit from being exceeded. The same safety factor is required for the fatigue limit under frequently alternating loads.*

Increasing the elasticity, yield and breaking limits of metals by cold-working or heat-treating, which reduce the capacity for deformation, is limited in airplane construction by machining considerations. A certain minimum elongation is also required as compensation for differences in tension due to overstressing.

Tensile stresses.- The tension elongation curves for different metals used in airplane construction are plotted in Figure 5,a. The curves in Figure 5,b, in which the ratio of the tension to the specific gravity ($\sigma:\gamma$), is plotted against the elongation, afford a better means of comparison. When referring to the breaking stress (σ_B), this ratio is also called the "critical length." In both figures the top curve is for stainless chromium steel with a strength of about 170 kg/mm² (241,800 lb./sq.in.). This steel is of German make, annealed at 1020°C, air-cooled and tempered at 400°C.** As mentioned above, the elongation of this steel is smaller than that of other metals. It must therefore be worked in the annealed state. Elektron (7), at the bottom in Figure 5,a, is approximately equivalent to duralumin ZB (4) in Figure 5,b. According to Figure 5,b, the weldable steels (3 and 6) are the most

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*Specifications for airplane-strength calculations (DLA), draft of cover page No. 2.

**Steel with similar characteristics was used in the ill-fated British airship R.101.

unfavorable, yet welding offers the advantage of a great saving in weight over other methods of assembly (riveting, bolting, etc.).

Compressive and buckling stresses.- The compressive strength of metals greatly exceeds the practical requirements of airplane construction. The usually slender, thin-walled structural members collapse long before the full compressive strength of the material is reached. Since the minimum buckling strength of a member is a function of its slenderness ratio, the buckling characteristics of the various materials can be compared for different slenderness ratios. This comparison is made in Figure 6, where the ratio of the buckling stress to the specific gravity is plotted against the slenderness ratio $l:i$. A common Euler line is found for the elastic region, all the tested materials having roughly the same ratio of Young's modulus to the specific gravity. The curves for the inelastic region are partly obtained by calculation on the basis of distortion measurements for tubular compression members, according to Karman's method (reference 8) and partly by buckling tests. The superiority of chrome steel at small slenderness ratios can be fully utilized only when a certain ratio of wall thickness to diameter is not exceeded, local buckling of the wall being otherwise incurred. The buckling strength of thin-walled hollow bodies can be increased, however, by longitudinal corrugations. This feature, incorporated in the steel spar of an English airplane, is shown in Figure 7,f. Several typical spar types made of other materials are also shown for comparison. They illustrate the influence which the characteristics of materials, especially their specific gravity, have on the wall thickness and cross section of spars. The intricate structure of the metal spars is particularly conspicuous by comparison with the simplicity of the wooden spar.

Vibrational stresses.- The behavior of the above materials under the action of vibrational stresses differs widely. In Figure 8 the stress and alternating-load curves of different kinds of steel, duralumin, elektron and wood are plotted in the customary logarithmic manner. The curves are determined by fatigue bending tests with rotating cylindrical test bars and alternations up to 100 million. Below the pronounced fatigue limit, stresses can be withstood indefinitely by the tested steels (1 to 4). Wood behaves similarly (8). On the other hand, the tested light metals (5, 6 and 7) have no actual fatigue limit.

Their vibration strength decreases steadily with increasing number of load alternations.

The diagram in Figure 8,b is plotted with the ratio of the fatigue strength to the specific gravity (σ_W/γ) as ordinate, instead of the fatigue strength. In this case also the best figure is obtained with chrome-nickel-tungsten steel. In a comparison made for 100 million alternations, elektron (7) comes next and, far behind, wood (8), hard carbon steel (2), the two duralumin alloys (5 and 6) and lastly, the soft carbon steels (3 and 4).

The vibration stresses, to which airplane parts are subjected in operation, are usually not simple fatigue stresses but supplement a static initial stress. The influence of the static initial stress on the vibration strength is shown in Figure 9. The admissible dynamic stress decreases with increasing static initial stress and is zero for the static yield limit. The admissible stress range given in the latest draft specifications is also plotted in the figure. It yields a safety factor of 1.35 against vibration rupture and exceeding the 0.2 limit, and a safety factor of 2 against a static tensile break.

The vibration-strength values for smooth cylindrical test rods cannot be readily used for the calculation of airplane parts on account of the stress increments at borings, abrupt changes of cross section, notches, bands, etc. which, in certain cases, may greatly affect the vibration strength of structural parts. (Reference 17.) These stress increments cannot be determined by elasticity calculations since, owing to inherent plasticity, materials can make up to a certain extent for stress differences. Each material has a different degree of sensitivity to stress increments, which can be determined experimentally by means of notched or banded test rods. (Figs. 10,a and 10,b.) Test results obtained with such rods are given in Table III. The vibration strength of the plain rod (without notch or band) is denoted by σ_W, that of the notched rod by $\sigma_{W\ notch}$ and that of the banded rod by $\sigma_{W\ band}$. The figures are given for C steel of approximately 54 kg/mm² (76,800 lb./sq.in.), Cr-Ni-W steel of 162 kg/mm² (230,400 lb./sq.in.), aluminum and elektron. The ratios $\frac{\sigma_W}{\upsilon}$, $\frac{\sigma_{W\ notch}}{\upsilon}$, and $\frac{\sigma_{W\ band}}{\upsilon}$ show that, for a smooth undamaged rod, the best σ_W values are obtained for Cr-Ni-W steel and elektron (8.85, 6.1, and 8.5).

Compared with the corresponding values for notched and banded rods, the light metals, especially elektron, surpass steel by their better notch resistance. This is important for the design of parts subject to vibration stresses in operation, on account of stress increments, especially in riveted joints. According to former tests (reference 1), wood has a good notch resistance. On the other hand, stress increments are usually better avoided with wood than with metal. (Fig. 7.) Particular attention is therefore called to wood as a material for parts working under vibration stresses.

Corrosion and Surface Protection

Metals are more or less subject to atmospheric influences and especially to the action of sea water which impairs their strength characteristics. Figure 11 is the stress-strain diagram of an unprotected duralumin sheet subjected for 48 days to the action of a 3 per cent table-salt solution, the corrosive action of which corresponds roughly to that of sea water. The strength and elongation are greatly reduced, while the mechanical energy of the corroded sheet is only about one-fourth of its original value. Corrosion may also have a considerable influence on the fatigue strength. (Reference 16.) The decrease in strength and ductility is caused by corrosion beginning at the surface and working gradually deeper into the metal. Typical examples of the corrosion of light metals by the atmosphere and by sea water, are shown in Figures 12 to 14 (microsections). In Figure 12 the corrosion is quite uniform. The decrease in strength is roughly proportional to that of the thickness under the corrosive action. The ductility is practically unaffected. Figure 13 shows deep pitting, resulting in loss of strength and ductility. In Figure 14 the corrosion follows along the grains, deep into the metal. The effect of this "intercrystalline" corrosion on the strength characteristics is disastrous. (Reference 10.)

According to the present state of corrosion research, the corrosive action is chiefly an electro-chemical process. With moisture and oxygen present, local galvanic cells are formed by irregularities in the chemical composition, grain, surface, etc., the anodes of these cells going into solution. Local cells are also formed by dissimilar external conditions, e.g., irregular ventilation of different points of the metal surface. According to corrosion tests (reference 9), the corrosive action is stronger at points of the metal surface where the ventilation is deficient. This explains why internal structures of metal-covered seaplanes, inadequately protected against sea-water penetration, often corrode more than external surfaces directly in contact with sea water and air. Several points found by experience to be particularly subject to corrosion are shown in Figure 15. Sea water concentrates chiefly in inaccessible corners of internal joints. The inside of the wing dries very slowly, owing to deficient ventilation and because the evaporated water is reprecipitated on the cooler metal surfaces. The evaporation and condensation of the water also changes continually the salt concentration at the points of corrosion, which is thereby accelerated.

In this respect, fabric-covered wings are better, since, on the one hand, the water-tightness of the covering can be increased to a reasonable extent, while, on the other hand, a good ventilation and drying of the inside of the wing is enabled by its perviousness to air. Practical experience has shown that, even under unfavorable conditions, the corrosive action is comparatively well withstood by the internal structure of fabric-covered wings.

The importance of corrosion in metal aircraft construction, at least as regards seaplanes, lies in the prevailing use of thin-walled parts which, when subjected to the same corrosive action, are destroyed faster than thick-walled parts. For the same speed of corrosion, the decrease in thickness and hence the loss in strength are inversely proportional to the wall thickness. Figure 16 shows the loss in strength of duralumin sheets of different thickness under the same conditions of corrosion. The continuous curve was determined experimentally and the dash-dot curve calculated on the assumption of an identical speed of solution. Under the given conditions of corrosion the 4 mm (0.16 in.) sheet loses approximately 3 per cent of its original strength, but the 0.5 mm (0.02 in.) sheet over 70 per cent of its strength. The theoretical curve shows a loss of only about 25 per cent for the 0.5 mm sheet. The marked difference between the theoretical and the experimental curve is attributable to the difference between the production methods of thin and thick sheets. (Different conditions of rolling and heat-treating, straightening of thin sheets after refining, etc.)

For these reasons the problem of corrosion and corrosion prevention offers much smaller difficulties in other fields, such as shipbuilding or bridge construction, where materials with greater wall thickness are used.

Thick sheet should be used in airplane construction wherever possible, especially for vital parts. Strong corrosion developed between the thin flange sheets of the wing spar of Figure 17,a - considerably reducing their strength. Corrosion resulted from infiltration of sea water between the insufficiently tight flange sheets, where deficient ventilation increased its corrosive action. The latter would have been lessened by using only a few thick plates instead of the many thin plates. (Fig. 17,b.) In this respect pressed or rolled section flanges or spars are preferable. (Figs. 17,c and 17,d.)

Another example of the influence of construction methods on corrosion is given in Figure 17,e. Hollow section strips are often riveted on the outside of floats and hulls to stiffen the covering. Inasmuch as rivet seams cannot be made absolutely water-tight, there is a possibility of sea water penetrating into the recess between the bottom sheet and the section strip where, owing to deficient ventilation, its action is highly destructive. The effect of this method of construction on the bottom sheet of a duralumin flying boat is illustrated in Figure 18. A hollow section strip was riveted to the bottom between the two left rows of rivets shown in the figure. Here marked corrosion ensued, while between the two right rows of rivets, where the bottom had been directly in contact with the sea water, the corrosion is scarcely noticeable. The inside of the hollow section strip was also strongly corroded. Ways in which these difficulties can be overcome are shown in Figures 17,f to 17,h.

Duralumin is the most corrosion resistant of the strong aluminum alloys, provided it is very carefully heat-treated and worked. Corrosion resistance may be greatly affected by small variations in the annealing temperature by subsequent heating or by internal stresses. (Reference 10.)

While it is comparatively easy to protect duralumin against weather influences by coatings, this means is, in the long run, inadequate against sea water. The life of oil, bituminous or cellulose dopes is very short under the severe conditions of operation at sea. Damage due to corrosion is prevented by frequent renewal of the dope and immediate repainting of defective spots. Material difficulties are thereby encountered, owing to the difficulty of access to internal structures. Attempts are therefore made to replace dopes by other means of surface protection or at least to improve their resistance. The most important methods of surface protection are briefly summarized below. More exhaustive accounts have been published elsewhere. (References 5 and 10.)

By the anodic process (reference 13) of Bengough and Stuart, a thin uniform layer of aluminum hydroxide, which is an excellent base for greases or paints, is applied by electrolytic treatment of the duralumin part in a solution of chromic acid. The advantage of this process over the galvanic method lies in the insulating action of the oxide layer which, owing to deeper penetration, affords a good protection even to intricate parts, hollow sections, joints, etc. Oxidation is a means of increasing the corrosion resistance of duralumin parts without materially increasing their weight. On the other hand, anodic oxidation methods are rather troublesome and expensive, especially when applied to large parts. When the treatment is confined to individual parts, prior to assembly, vital points of the finished structure (e.g., rivet heads) remain unprotected.

Plating of duralumin sheet with pure aluminum or noncuprous aluminum alloys (more corrosion-resistant) is another very efficient surface protection. The plating is welded on the two faces of the sheet by hot rolling. Cohesion of core and plating is further increased by heat-treating the rolled sheet since, during the annealing process, alloy particles of the core material are partially transplanted into the plating. The microsection of such a plated sheet 4 mm thick is shown in Figure 19 (magnified 150 times). Note the gradual transition from core to plating which insures perfect adherence of the latter to the core, even under strong deformation. Due to the smaller strength of the plating, the yield point and tensile strength of plated sheets are slightly below those of ordinary duralumin sheets. The bending characteristics, ductility, Young's modulus and vibration resistance are practically unchanged. (Reference 12.)

In addition to the direct protection of the core material, the corrosion-resistant coating also affords an electrolytic protection, since it is below the core material in the electrochemical series. Hence, points where the core is laid open, as along the sheet edges, are not attacked by sea water. (Reference 11.) As shown by Figure 20, the protection also extends to unplated rivet heads. The left of the two samples shown in the figure is standard duralumin sheet, the right "duralplat" sheet, the rivets being in both cases ordinary duralumin. In the corrosion test, the rivet heads of the duralumin sample were seriously damaged, while those of the "duralplat" sample were merely blackened, while remaining absolutely intact. The corrosion of the coating is stronger in the neighborhood of unprotected points. This, however, is of minor importance, since the mechanical stresses are chiefly transmitted by the stronger core material.

In accelerated corrosion tests with very corrosive solutions (3% NaCl + 0.1 H_2O_2), the surface was corroded even under the rivet heads. This, however, requires a period of time, during which ordinary duralumin riveting would be seriously damaged. Countersunk rivet heads obviate the danger of rivet loosening under the action of corrosion in the case of "duralplat" sheet. (Reference 14.)

All efforts must now tend toward improving the corrosion resistance of aluminum alloys. According to investigations made in recent years, the corrosion resistance of aluminum alloys is unfavorably affected by the addition of copper. The aluminum-magnesium alloys of the noncuprous aluminum group have an excellent corrosion resistance and good strength characteristics. The results of corrosion tests with magnalium alloy containing 7 per cent of magnesium and 0.5 per cent of manganese, in addition to aluminum, are shown in Figure 21.* The hard-rolled magnalium sheet had a strength of about 42 kg/mm² (59,750 lb./sq.in.) at about 11 per cent elongation. The measured Young's modulus of 700,000 kg/mm² (995,645,000 lb./sq.in.) is only slightly below that of duralumin. Considering that magnalium is approximately 6 to 8 per cent lighter

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*This alloy, known as "hydronalium," is manufactured by the I. G. Farbenindustrie A.G., Bitterfeld, Germany.

than duralumin, means are thus afforded for using softer sheets with better deformation characteristics. The figure emphasizes the much better corrosion resistance of magnalium as compared with that of the tested duralumin. If good sheets can be made of this material and easily drawn, edged, etc., magnalium alloys may be advantageously used in seaplane float and hull construction.

Elektron, in its present form, cannot be used in seaplane construction on account of its small resistance to the action of sea water. It has, however, hitherto given good results in landplane construction. The resistance of elektron to the action of sea water can probably be further improved by plating or by suitable heat-treating.

Carbon steels and low-percentage steel alloys corrode under atmospheric and sea water influences. They offer, however, some advantage over light metals, in that the corrosion usually spreads uniformly over the whole surface, local pitting being less frequent. Even steel may lose much of its strength and ductility under the action of corrosion. In general, paint adheres better to steel than to light metals and lasts longer. Steel parts can also be protected by the more resistant baked enamels, the use of which is not recommended for duralumin on account of the high temperatures required for baking. In England, complete steel wings are dipped, after assembly and careful cleaning of the surface, in a bath of thin enamel varnish and then placed in a hot chamber where the varnish is baked on at 120 to 140°C. (Reference 7.) This method is very simple and economical. The uniformity of the varnish coating is equaled neither by brush nor by spraying. Another advantage of steel is the possibility of easily applying galvanic coatings. Cadmium is very successfully used for this purpose. Owing to their small penetrating power, galvanic methods can only be used for the treatment of parts with comparatively simple forms.

No figures have been hitherto available on the weather and sea-water resistance of high-percentage chromium steels used to some extent in British aircraft construction. The resistance of these steels, if used on landplanes, would probably exceed the needs of present-day airplane construction. Experience will show whether rustproof steel may be used in seaplane construction entirely without paint or other surface protection.

Connections

The fitness of materials for airplane construction depends chiefly on the means used for assembling them. Riveting and welding are the chief means by which permanent connections are made in airplane construction. Welding methods are successfully applied only to soft steels with a small percentage of carbon and possibly small additions of chrome-molybdenum or manganese. In that case, steel tubes, sheets, etc. can be butt-welded with a minimum increase of structural weight and without materially reducing the strength of the welded points under static stresses. The resistance of welded joints to dynamic stresses is usually smaller. A microsection of an acetylene-oxygen welded steel tube is shown in Figure 22. (Reference 23.) The welded seam is on the left, followed by a wide section with very coarse crystals, while the return to the normal structure, unaffected by the welding temperature, is at the extreme right. The fatigue strength is unfavorably affected by these marked differences in the grain. The fatigue strength of welded steel tubes is only 50 to 60 per cent of that of seamless tubes. (Reference 15.) This accounts for the frequent fatigue ruptures of welded engine bearers. The grain differences at the welding point of small parts, fittings, etc., can be considerably reduced by adequate heat treatment. This method cannot, however, be extended to large units such as fuselages, wings, etc.

Duralumin and other refinable aluminum alloys are also weldable. Yet, the quality of the metal at the welding point is affected by the heat, the strength and corrosion resistance of duralumin being thus reduced. Welding of duralumin is therefore generally avoided in airplane construction. Electric spot welding affords a means of obviating this difficulty, the heat being thereby entirely concentrated at the welding point. An example of this method (magnified 25 times) is shown in Figure 23. (Reference 18.) The two sheets of 1 mm thickness are overlapped and welded between two electrodes applied externally. The modification of the grain is entirely confined to the lenticular welding area. Besides, the grain on the sheet surface is absolutely unaffected. The conditions for the application of such welding methods still require very careful investigation. Besides, the behavior of spot-welded joints under dynamic stresses has not yet been elucidated.

While the same material can be used for rivets and sheets in duralumin connections, the rivets connecting high-grade steel must be made of softer material in consideration of working. The advantage derived from the good strength characteristics of these steels for structural parts is thus reduced. Owing to the great sensitivity of hard steels to notching (Table III), the stress increments at the rivet holes may be detrimental under dynamic stresses. No systematic investigations of the fatigue strength of rivet joints have hitherto been made, but an idea of the sensitivity of various materials to notching may be gained from earlier test results.

SUMMARY

The good elastic and strength characteristics of wood are outweighed by very small form resistance, considerable water absorption and irregularity of structure. These defects can be obviated by better soaking methods, especially with synthetic resins, by the use of moisture-resistant glues and by improving the quality of plywood. A step in this direction was made by the introduction of glue films in plywood manufacture. In addition to its low cost, plywood offers the advantage of being easily workable and permitting simple structural forms on account of its small specific gravity and assembly by gluing. Wood can also be easily adapted to the changing requirements of progressive airplane construction.

Duralumin has given excellent results in landplane construction. The difficulties arising from corrosion in airplanes used at sea can be successfully obviated by up-to-date methods of surface protection, especially by plating, artificial oxidation and structural improvements. Noncuprous aluminum alloys of the magnalium group may be successfully used in future for floats and hulls. The disadvantage of the small vibration strength of aluminum alloys is practically negligible, considering the comparatively small sensitivity of these materials to local stress increments at points of abrupt changes in cross section, notches, etc.

The strength characteristics of magnesium alloys, compared with their specific gravity are as good and in some respects better than those of duralumin. The good vibrational resistance of these alloys is particularly noteworthy. According to test results, their sensitivity to notching is slightly greater than that of duralumin. This is important for the construction of parts subjected to vibrational stresses in operation. The small sea-water resistance of magnesium alloys now available prohibits their use for seaplanes.

Soft steels with a strength up to 60 kg/mm^2 (85,350 lb./sq.in.) compare favorably with other aircraft materials since, being weldable, their connections are lighter than riveted and bolted joints. The advantage of welding is less for parts working under dynamic stresses, the vibration strength of the material being greatly reduced by grain differences resulting from autogenous welding (fatigue ruptures of welded engine bearers). The grain differences of small parts (fittings, etc.) can be compensated by suitable heat treatment after welding.

High-grade steel alloys with a strength exceeding 120 kg/mm^2 (170,700 lb./sq.in.) have high elastic and yield limits and great vibrational strength. The great sensitivity of these steels to local strain increments under dynamic stresses is detrimental, but can be partly overcome by better design and production methods. At present the use of rustproof chromium steel seems to be the best solution of the corrosion problem in seaplane construction.

To derive full advantage from materials used in airplane construction, their characteristics must be very thoroughly checked and carefully adapted to the requirements of design and construction.

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National Advisory Committee
for Aeronautics.

TABLE I. Mean Strength Coefficients of Woods Used in Airplane Construction
(Moisture content 12 to 14%)

Kind of wood	Direction with respect to grain	Static strength (kg/cm^2)				Young's modulus kg/cm^2	Mod. of shear kg/cm^2	Fatigue strength kg/cm^2*
		tensile	compressive	bending	torsional			
Pine at γ = 0.5 g/cm^3	lengthwise	~1000	~ 500	~ 700	~ 150	~110000	~ 7500	~ 250
	crosswise	~ 50	~ 50	–	~ 45	~ 4500	–	–
Spruce at γ = 0.4 g/cm^3	lengthwise	~ 800	~ 350	~ 600	~ 150	~ 95000	–	~ 210
	crosswise	–	~ 40	–	–	–	–	–
Ash at γ = 0.65 g/cm^3	lengthwise	~1300	~ 600	~1250	~ 260	~150000	~13000	~ 360
	crosswise	~ 125	~ 100	~ 180	~ 165	~ 16000	–	–
Walnut at γ = 0.6 g/cm^3	lengthwise	~ 1250	~ 680	~1400	~ 300	~140000	~15000	~ 420
	crosswise	~ 90	~ 120	~ 150	~ 150	~ 12000	–	–
Balsa at γ = 0.2 g/cm^3	lengthwise	~ 200	~ 180	~ 250	–	~ 35000	–	–
	crosswise	–	~ 18	–	–	–	–	–

(g/cm^3 x .036128 = lb./cu.in.)
(kg/cm^2 x 14.2235 = lb./sq.in.)

*With alternate bending stresses (circular bending).

TABLE II. Mean Strength Coefficients of Plywood Used in Airplane Construction (Moisture content 8 to 10%)

Kind of wood	Layers	Direction of face plies	Tensile strength kg/cm²	Young's modulus kg/cm²	Shearing strength* kg/cm²	Modulus of shear* kg/cm²
Birch $\gamma = 0.75$ g/cm³	1:1:1	lengthwise	~ 1000	~ 120000	~ 180	~ 10000
		crosswise	~ 450	~ 60000	~ 180	~ 10000
		diagonal	~ 300	~ 25000	~ 300	~ 40000
	1:2:1	lengthwise	~ 800	~ 100000	~ 200	~ 10000
		crosswise	~ 700	~ 90000	~ 200	~ 10000
		diagonal	~ 320	~ 30000	~ 350	~ 40000
Alder $\gamma = 0.6$ g/cm³	1:1:1	lengthwise	~ 750	~ 90000	~ 170	-
		crosswise	~ 500	~ 50000	~ 150	-
		diagonal	~ 300	~ 25000	~ 240	-

(g/cm³ x .036128 = lb./cu.in.) (kg/cm² x 14.2235 = lb./sq.in.)

*For determination of the shearing strength and the modulus of shear, plywood plates about 35 cm (13.78 in.) square were so mounted in hinged frames that, on the application of tensile forces at two diagonally opposite corners parallel to the edges of the frame, the maximum shearing stresses were produced. This arrangement is intended to represent the torsional stressing of the surface layer of airplane parts (wings, fuselage, etc.)

TABLE III. Effect of Stress Increments on the Bending-Vibration Strength of Metals

Metal	Tensile strength σ_B kg/mm²	$\frac{\sigma_B}{\gamma}$	Alternating strength w kg/mm²	$\frac{\sigma_w}{\gamma}$	Notch alternating strength σ_w kg/mm²	$\frac{\sigma_{w\ notch}}{\gamma}$	Band alternating strength $\sigma_{w\ notch}$ kg/mm²	$\frac{\sigma_{w\ band}}{\gamma}$
C-steel (St 48)	53.9	6.8	27.	3.5	18	2.3	15	1.9
Cr-Ni-W-steel	162	20.8	69	8.85	32	4.1	30	3.85
Duralumin 681 B	40.8	14.6	14	5.0	13.5	4.8	11.5	4.1
Elektron AZM	31.3	17.4	11	6.1	10	5.55		
			15.3*	8.5*	-	-	10*	5.55*

*According to D.V.L.
(reference 20)

(According to Ludwik,
reference 19)

(kg/mm² x 1422.35 = lb./sq.in.)

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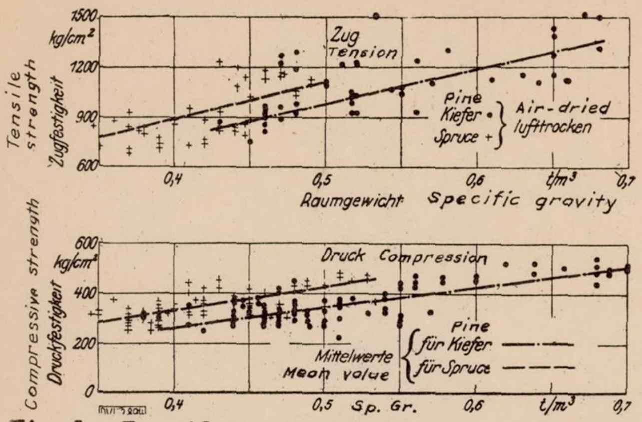

Fig.1 Tensile and compressive strength of pine and spruce plotted against their specific gravities (DVL tests).

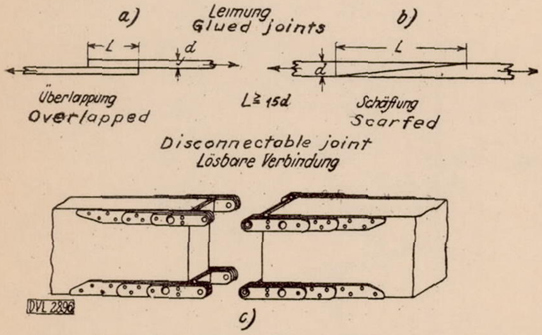

Fig.3 Joints of wooden parts:
a) overlapped,
b) scarfed,
c) disconnectable joint (spar joint).

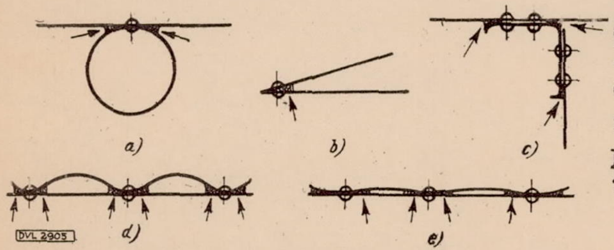

Fig.15 Points on seaplane parts from which corrosion usually spreads; (increased corrosion at points marked by arrows). a) junction of round tube with sheet-metal covering. b) trailing edge of wing and tail surfaces where the upper and lower coverings meet. c) junction point of sheets and angle strip. d) corrugated sheet riveted to a round tube or to a section strip. e) smooth sheet buckled by riveting to a round tube or section strip.

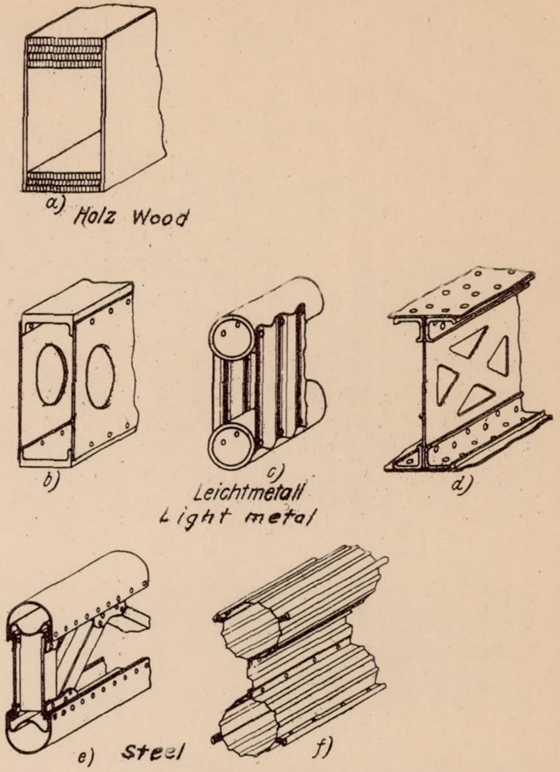

Fig.7 Influence of material on form of wing spar; a) wood: simple box spar: pressure flange stronger than tension flange, both laminated; plywood webs for shearing stresses; glued joints. b to d) light metal spars, usually of sheet-wall type, latticework rare; thick tubular or channel flanges. Webs of thin corrugated sheet or thick sheet with lightening holes; riveted joints. e and f) steel spars of very thin sheet; lattice type or the now more popular sheet-wall type with longitudinal corrugations. Riveted joints.

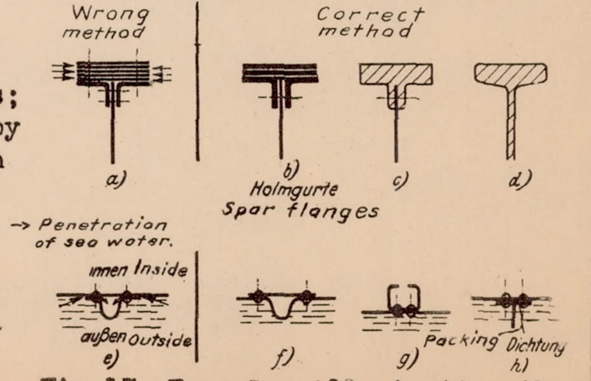

Fig.17 Examples illustrating the effect of design on corrosion.

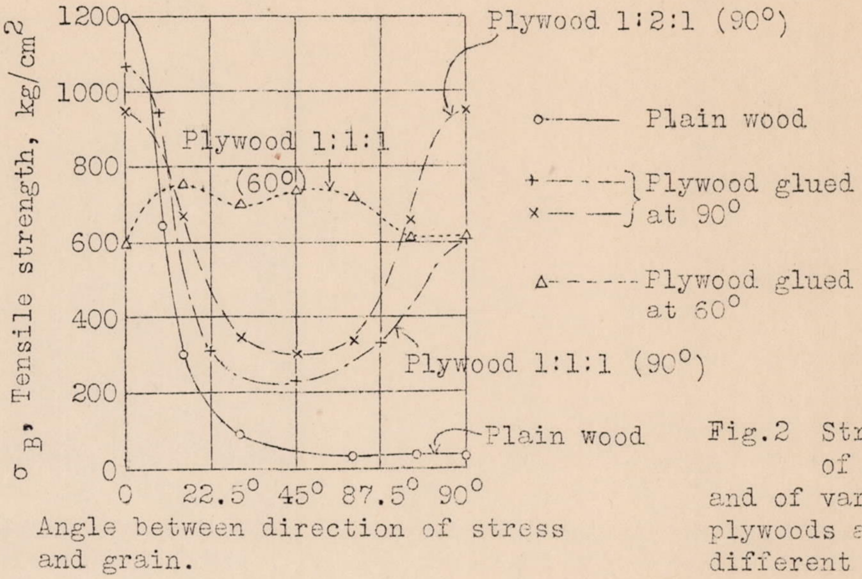

Fig.2 Strength of wood and of various plywoods at different angles to the grain (birch).

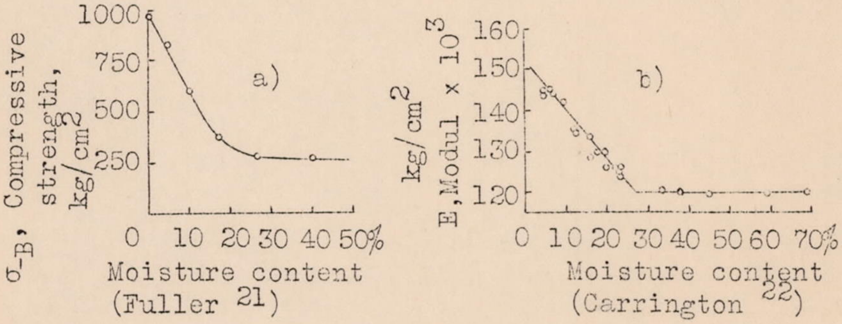

Fig.4 Compressive strength and Young's modulus plotted against moisture content of spruce.

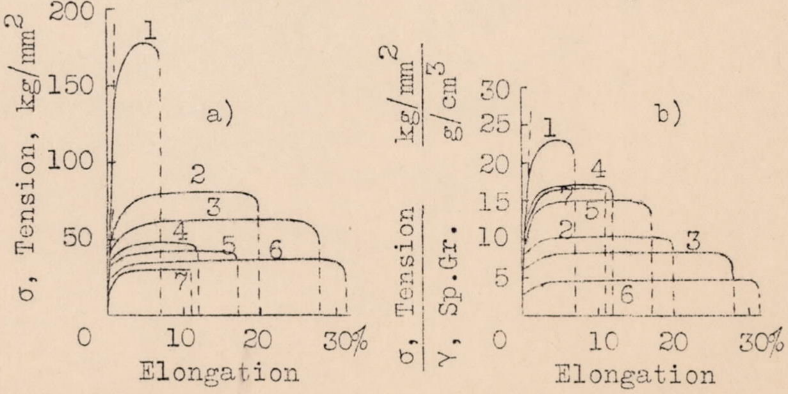

Fig.5 Tension-elongation curves of airplane materials:
1, Rust proof Cr-steel; 2, 0.6 C-steel;
3, 0.35 C, 0.53 Mn and 0.43 Si-steel (weldable);
4, Duralumin 681 ZB; 5, Duralumin 681 B; 6, 0.11 C, 0.48 Mn-steel (weldable); 7, Elektron AZM.

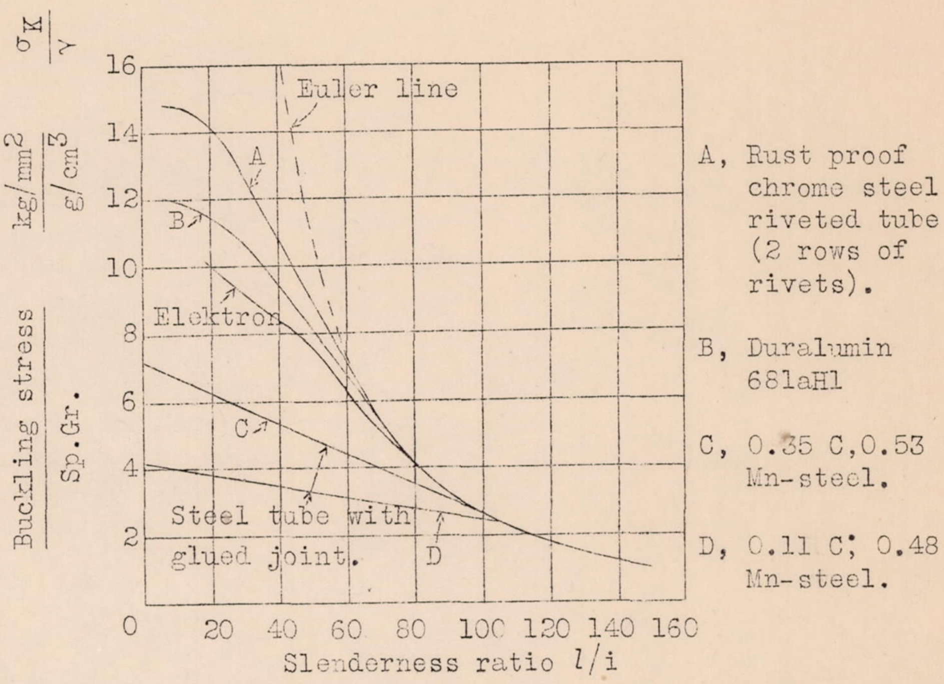

Fig.6 Comparison of airplane materials under buckling stresses.

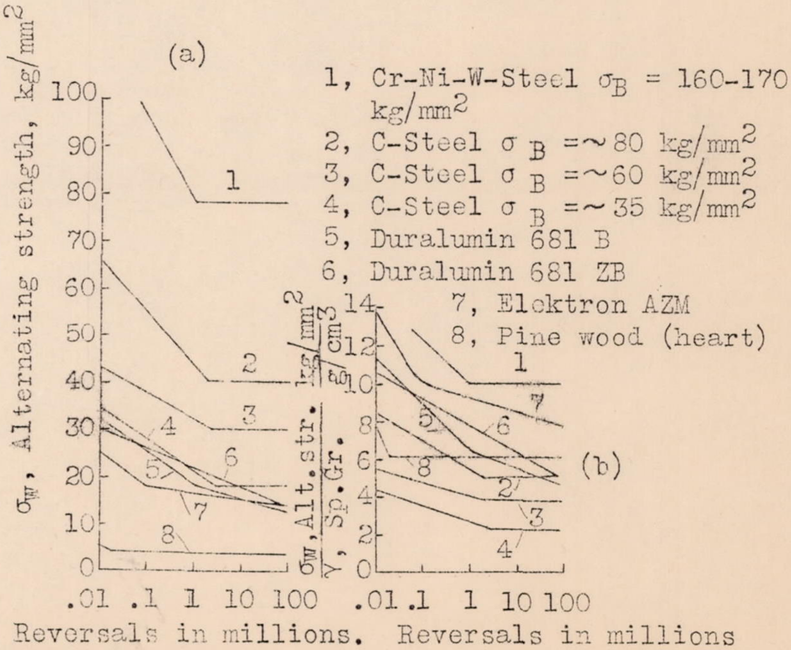

Fig.8 Alternation strength of aircraft materials plotted against the number of load reversals,

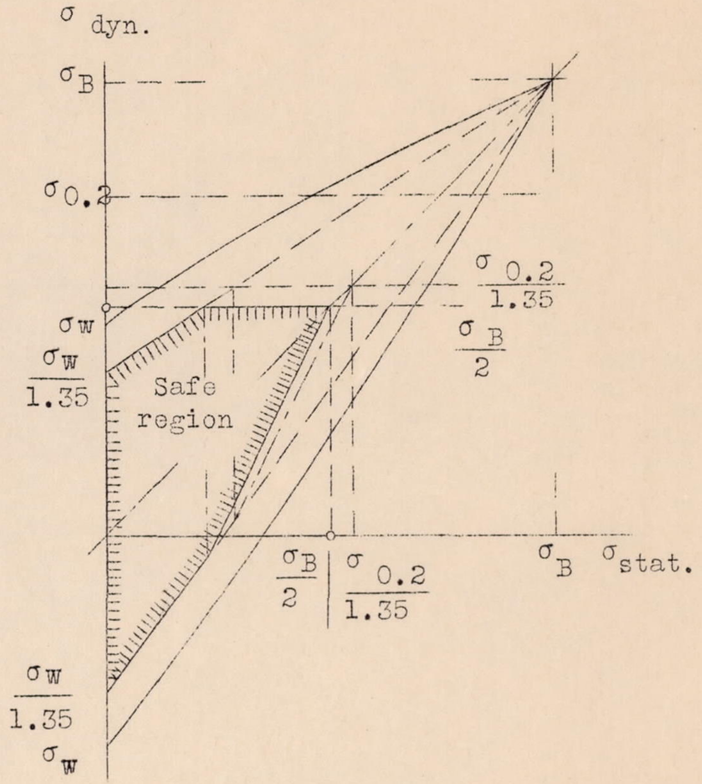

Fig.9 Vibration strength under initial static stress within safe limits.

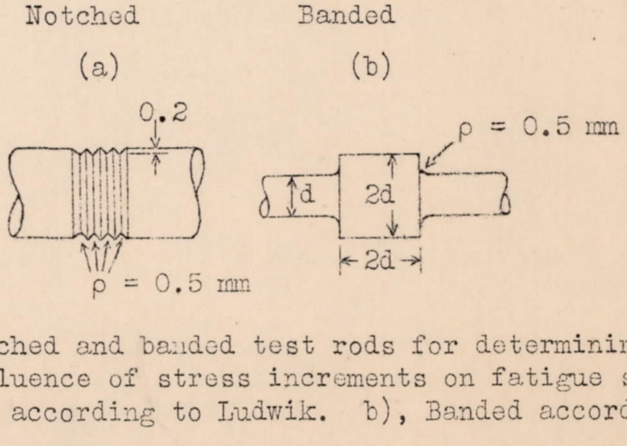

Fig.10 Notched and banded test rods for determining influence of stress increments on fatigue strength. a), Notched according to Ludwik. b), Banded according to DVL.

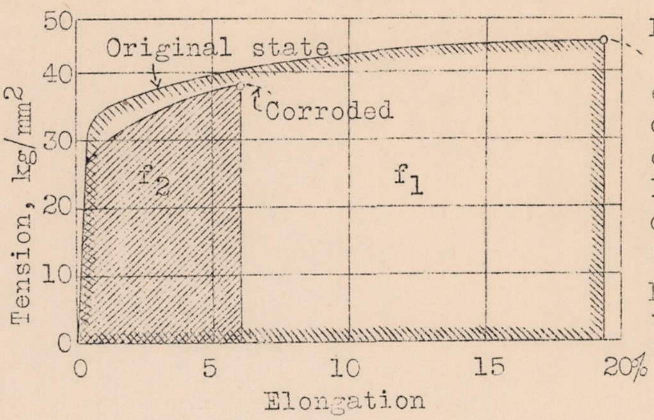

Fig.11 Decrease in strength and elasticity due to corrosion. Mechanical energy f_2 = about 1/4 f_1. Material: duralumin sheet (1 mm thick). Corrosion period: 48 days in 3% table-salt solution (DVL stirring method).

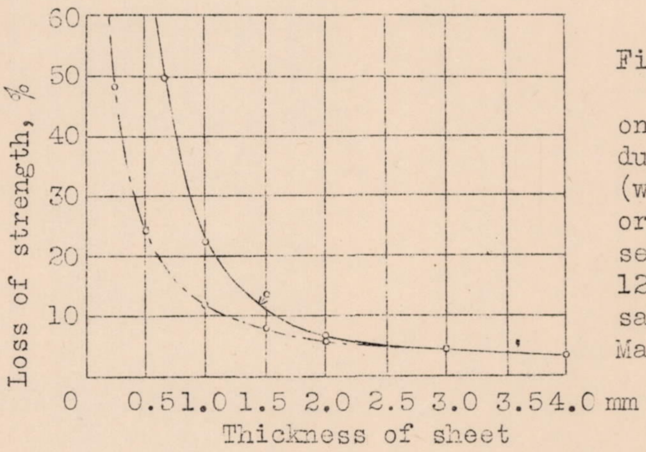

Fig.16 Influence of sheet thickness on loss of strength due to corrosion (with respect to the original cross section). 120 days in 3 % table-salt solution. Material: duralumin.

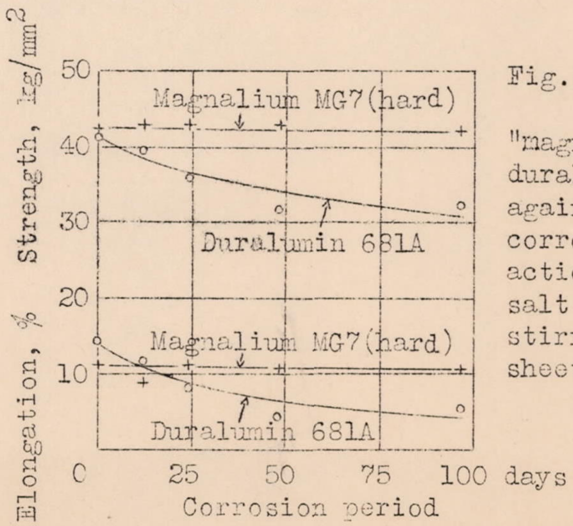

Fig.21 Strength and elongation of "magnalium", harder than duralumin 681A, plotted against the time of corrosion. Corrosive action by a 3% table-salt solution (DVL stirring method), sheet thickness: 1.0 mm.

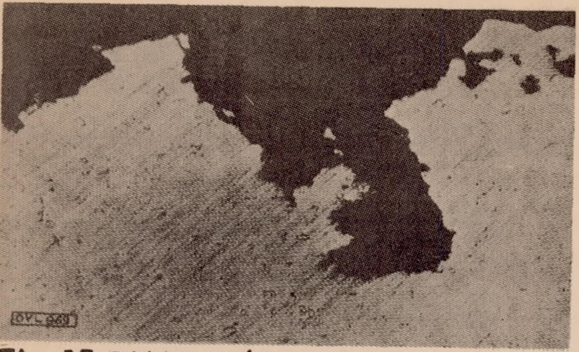

Fig.13 Pitting (deep local corrosion)

Figs. 12,13, 14 Microsections of corroded light-metal sheets. Magnified about 120 times.

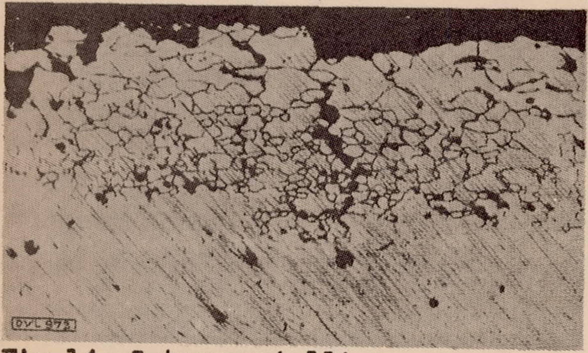

Fig.14 Intercrystalline corrosion (following the grain contours).

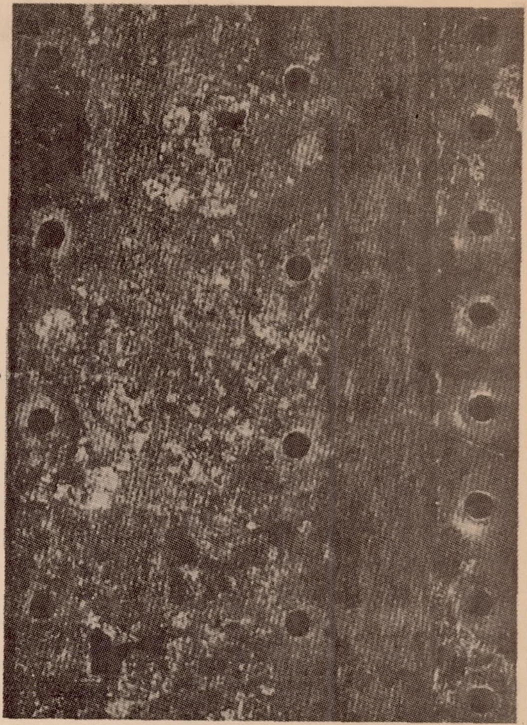

Fig.18

Fig.12 Uniform corrosion.

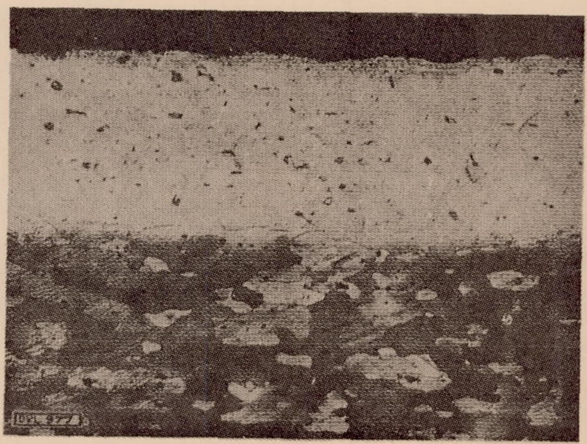

Fig.19

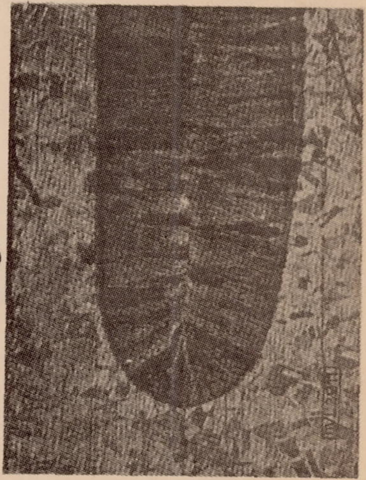

Fig.23

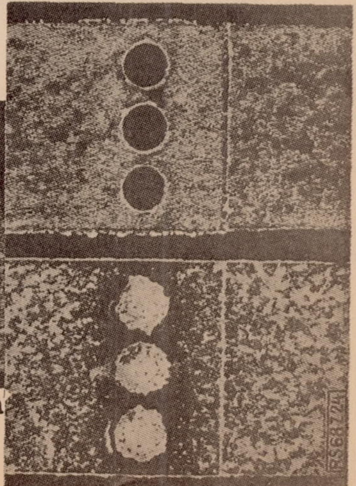

Fig.20

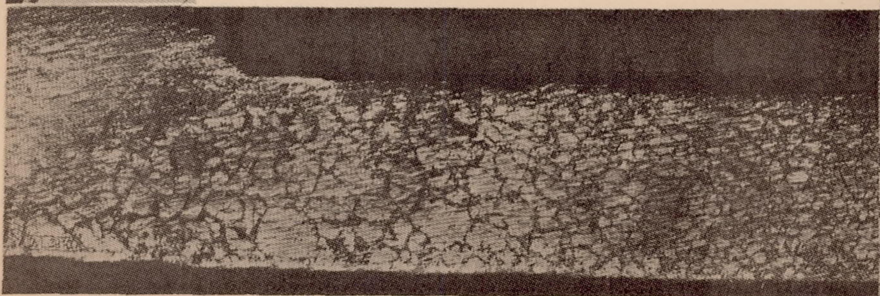

Fig.22 Acetylene-oxygen weld of a steel tube. (Note marked grain differences).