TECHNICAL NOTES

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

No. 560

A COMPARISON OF CORROSION-RESISTANT STEEL
(18 PERCENT CHROMIUM - 8 PERCENT NICKEL)
AND ALUMINUM ALLOY (24ST)

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In the selection of materials for aircraft application, it is not enough to make the selection on a strength-weight basis alone. A strength-weight comparison is significant but other factors must be considered, for while a material with a high ratio of strength to weight may be perfectly satisfactory for one use, it may be totally unfitted for another. It is essential, among other things, that the probable nature, magnitude, and direction of the principal stresses be given special consideration.

The following analysis has therefore been made with this in mind. An attempt has been made to cover insofar as possible the major, but not all of the points, that a designer would consider in the use of "18-8", as it is commonly referred to, and 24ST aluminum alloy, as applied to aircraft. 24ST was selected for this comparison as it has practically replaced 17ST for aircraft construction and it appears to have the best combination of properties of the alloys now available for this purpose. The cost of fabrication has not been considered.

MODULUS OF ELASTICITY

In view of the importance of modulus of elasticity in design, this characteristic will be taken up at this time prior to a discussion of the other items in which it is involved and of the other properties of the two materials.

The elastic modulus of 24ST is 10,300,000 pounds per square inch. This value is accepted by all designers and well supported by many tests. The modulus of elasticity of stainless steel of the 18-8 grade is not susceptible to precise determination. Some claim a modulus of 29,000,000 pounds per square inch for 18-8. This figure is not supported by tests made at Wright Field, the Naval Aircraft Factory, nor the National Bureau of Standards. These tests indicate the true elastic modulus to be approximately 26,000,000 and in some cases less. Assuming that the initial tangent modulus is 29,000,000, it would possibly be satisfactory to use this figure where very small unit stresses are involved but considering the range of stresses on the stress-strain curve for which the member would be designed, good engineering practice dictates the use of the lower value in the design of aircraft. Like other cold-rolled materials, the elastic modulus of 18-8 when cold-worked and not subsequently annealed, is difficult to define precisely because the stress-strain diagram of the material is not a straight line but a curve whose curvature begins practically at the origin. Tests indicate, however, that the curve can be straightened by suitable annealing and by proper prestressing and the proportional limit raised materially. The effect of this prestretching on other properties, especially fatigue and internal stress, is being studied.

IMPACT

By the conventional methods of impact testing material specimens at various temperatures, 18-8 appears definitely superior to 24ST. Its impact resistance varies from 35 to 29 ft.-lb. Charpy over a temperature range of from room temperature to -80° C. While test data on 24ST are not available as yet, it is anticipated that the Charpy value will not differ to any great extent from that of the 17ST value which is approximately 10 to 9 ft.-lb. (10 by 10 mm specimen keyhole notch, No. 47 drill). Results of impact tests made on any one material over a range of temperature are of value in determining the influence of temperature on that material. Impact results obtained with two or more materials differing widely in weight and other physical properties, however, should not be used as a basis of comparison of the suitability of the two materials for use in aircraft construction. In aeronautical service, the materials compete on a weight-saving basis as well as on the basis of strength and work of deformation.

The present methods of impact testing although they indicate what can be expected from a notched bar subjected to stresses to produce fracture, are not true indexes of the actual energy absorption power of materials. It is considered that the designer is more interested in the capacity of a member to resist injury when subjected to a suddenly applied load within or close to the elastic range than he is in the work done in fracturing the member. It is believed that resiliency, or elastic recovery from energy loads, would be more pronounced on materials of the same cross-sectional area with low moduli of elasticity than on those with high moduli when subjected to identical conditions of impact. The assumption is made that the work of deformation is equal to the energy of the blow. Considering the two formulas on page 42 of Johnson's "Materials of Construction" (reference 1) for stress under axial impact and for a beam under impact of a center load, it is apparent that the elastic modulus is a major consideration. These formulas are as follows:

$$W\ (h + e) = \frac{1}{2}\,\frac{S^2}{E}\,AL \qquad \text{(axial impact)} \qquad (1)$$

$$W\ (h + f) = \frac{1}{6}\,\frac{R^2}{C^2}\,\frac{S^2}{E}\,AL \qquad \text{(center load)} \qquad (2)$$

W, weight falling

h, distance dropped

e, maximum deformation

S, maximum intensity of stress corresponding to deformation

E, modulus of elasticity

A, area of cross section

l, length

f, maximum deflection

It is therefore submitted that the tests on actual built-up structures, measuring deformation, and deflection under a suddenly applied load or by a drop test of the structure itself, are conducive of more accurate determinations of impact resistance within the range in which the designer is primarily interested than are the

Charpy or Izod methods of tests in common use. Under such conditions the apparent differences in the impact resistances of the materials as measured by the Charpy notched-bar test will lose their significance in design.

FATIGUE

Cold-rolled 18-8 can usually be relied upon to develop an endurance limit of slightly better than 50 percent of its ultimate strength in tension. The endurance limit of 24ST is approximately 14,500 pounds per square inch or about 24 percent of its ultimate. In view of the difference in these fatigue ratios, it is apparent that where fatigue alone is the controlling factor, 18-8 has the edge where identical shapes are concerned. In comparing the serviceability of two materials in structures subjected to repeated stress, consideration should be given not only to the fatigue limits but also to the stresses in a structure designed on a weight-saving basis. For direct tensile loading, on such a basis, steel evidently is superior to aluminum alloys when the fatigue limit of the steel is more than about three times that of the aluminum alloy. For resistance to repeated bending or torsion, however, this 3 to 1 ratio does not apply. In order to be superior to an aluminum alloy under repeated bending or torsion, the fatigue limit of the steel must now be at least five times that of the aluminum alloy.

INTERNAL STRESS

Materials such as cold-rolled corrosion-resistant steel, which obtain their strength by strain hardening, develop internal stresses as a result of this cold rolling. It is a condition in which the outer layers of the material are in a state of tension and the interior in a state of compression. This condition does not exist in properly heat-treated materials. In severely cold-worked 18-8, i.e., 180,000 pounds per square inch and above, this internal tension stress may reach an enormously high value. The objectionable features of such stresses are well known, particularly when the material is subjected to even slight corrosive attack. Tests conducted at the National Bureau of Standards for the Bureau of Aeronautics on tie rods, reveal that this stress in some cases was as high as 98,600 pounds per square inch on 1050 steel and between 120,000 and 128,000 pounds per square inch on 18-8. In the presence of such high internal stress, high tensile strengths in cold-drawn materials such as 18-8 tie rods really serve no good purpose for the higher the strength the greater the internal stress. Further, tests indicate that high tensile properties in such 18-8 are associated with minimum torsional fatigue resistance, a property which should be as high as possible compatible with adequate resistance to corrosion fatigue for investigation discloses that the majority of tie-rod failures have been due to torsional fatigue. It has also been demonstrated that slight corrosive attack will reduce the fatigue limit of materials containing high internal stresses. In light of the foregoing, it was concluded by the Engineering Experimental Station at Annapolis, that nothing is to be gained by the use of tie rods having a tensile strength greater than 160,000 pounds per square inch under conditions where torsional fatigue is encountered. The torsional fatigue of SAE 1050 steel and 18-8 tie rods is approximately the same but the corrosion fatigue of the latter is definitely superior. The corrosion-fatigue resistance of 18-8 was found to be approximately 10,000 to 12,000 pounds per square inch, whereas that of 1050 steel was about 7,000 pounds per square inch. The chief value of the former material for tie-rod use therefore lies in its superior resistance to corrosion fatigue.

In spite of the undesirable characteristics of corrosion-resistant steel and other strain-hardened steel for tie-rod purposes, the adoption of 18-8 in lieu of 1050 steel appears to have been a sound and logical step in the reduction of tie-rod failures. There are hundreds of airplanes operating with 18-8 tie rods, on which no troubles have been experienced. Accordingly, the material should not be condemned for this use because of reported failures on airplanes of known exceptionally high vibratory characteristics. It is questionable whether SAE 1050 tie rods, or tie rods made of other materials available in quantity, would perform any better under such conditions. The search for improved materials, preferably those which obtain their strength from heat treatment, should, however, be continued. Preliminary tests indicate that the 16-percent chrome - 1-percent nickel alloy seems to have possibilities for this use. This material obtains its strength from heat treatment.

It is believed that the effect of internal stress in thin sheet, although undesirable because of its indeterminate value, is not of especial moment, but in rolled bar such as used in the manufacture of tie rods, it should be removed. That the internal stress can be removed without adversely affecting the strength of the material, has been demonstrated. Tests are continuing at the National Bureau of Standards to determine and perfect the most practical method of overcoming this undesirable condition and to ascertain that this stress-relief treatment does not adversely affect other properties of the material, for the elimination of one objectionable feature may be accomplished at the expense of some other desirable property.

MAGNETIC PROPERTIES

Corrosion-resistant steel in the annealed condition is practically nonmagnetic; however, cold-rolled to the strengths required for aircraft applications, it is magnetic and affects the compass. This has been demonstrated in service. 24ST aluminum alloy has no appreciable effect on the compass.

EFFECT OF LOW TEMPERATURE ON PHYSICAL PROPERTIES

At low temperatures, i.e., -80° C., cold-rolled 18-8 appears to behave like many other materials which obtain their strength through strain hardening. Its tensile strength increases considerably as the temperature decreases. In one test it increased from 130,000 to 175,000 pounds per square inch accompanied by an increase in elongation. Its yield strength increases but slightly and in some cases it has been found to decrease. Recent tests conducted at the National Bureau of Standards for the Bureau of Aeronautics indicate this to be the case and check the results of tests on 18-8 reported in N.A.C.A. Technical Note No. 381 (reference 2). In this report it was shown that the yield strength dropped from a value of 114,600 pounds per square inch at room temperature to 112,400 pounds per square inch at -40° C. The endurance limit increases but the ratio of the endurance strength to the ultimate strength decreases. Impact resistance as determined by the Charpy method decreases generally with low temperature but for the material in some conditions of cold rolling it increases. Low temperature tests are now being conducted on 24ST and the results to date indicate that it does not possess any peculiarly undesirable characteristics at low temperature.

CORROSION RESISTANCE

The corrosion resistance of stainless steel is considerably overemphasized. As compared with other unprotected high-strength alloy steels commercially available, it is, however, in a class by itself. Reports of examinations of airplanes in which stainless steel ribs were used and which have operated under severe conditions, indicate that it must be protected in some way to resist the attack of salt water. One report revealed that after but 182 hours of flight time, the ribs were found to be considerably corroded. Attack was so deep in some cases that it could not be removed without scraping with emery cloth. On the other hand, no serious corrosion trouble has been reported with the 18-8 external interplane tie rods probably because they are wiped down periodically and attack does not have the opportunity to get under way because of their accessibility and consequent relative ease of maintenance.

In comparison with anodically treated and painted aluminum alloy, free of contact with dissimilar metals and installed under adequate drainage conditions, and with consideration of the thin gages in which 18-8 would have to be used, the use of 18-8 in inaccessible places in aircraft operating off salt water is not considered good practice.

STRENGTH-WEIGHT

Stainless steel has a specific gravity of 7.92, aluminum alloy (24ST), 2.79. The weight ratio is therefore 2.84. Navy Department Specification 47A10 for 24ST specifies a minimum ultimate tensile strength of 62,000 pounds per square inch. Accordingly, to compete on an equal weight-strength basis, stainless steel members must develop a minimum tensile strength of not less than 176,080 pounds per square inch. This, stainless steel can easily do. A review of material inspection reports reveals that the ultimate of 24ST is approximately 64,000 pounds per square inch. The specification value will, however, be considered in this discussion.

On a yield-strength basis, assuming a yield of 160,000 pounds per square inch for stainless, which value, tests indicate, can be obtained, and 40,000 for 24ST, its specification value, the area of an aluminum alloy tension member must be 4.00 times greater than that of the steel member for the ratio of the areas of the cross section vary inversely as the strengths. The ratio of weights will be:

$$4 \times \frac{\text{(weight per cubic inch of 24ST)}}{\text{weight per cubic inch of 18-8}} = \frac{4 \times 0.101}{0.286} = 1.41$$

In other words, in pure tension, an aluminum alloy member will weigh 41 percent more than a steel member to support the same load.

COMPARISON OF TUBULAR BEAMS MADE OF 18-8 AND 24ST

Hartmann, whose assumptions appear sound, N.A.C.A. Technical Note No. 378, (reference 3), shows that for equal over-all weight and equal beam strength, ignoring deflection, steel must have a yield strength 4.71 times that of 17ST aluminum alloy to compete on a strength-weight basis. Therefore considering, as before, the yield of 24ST as 40,000 pounds per square inch, the steel would have to develop a yield strength of 188,000 pounds per square inch. This value is considerably in excess of the 160,000 pounds per square inch value assumed for 18-8. This comparison has been made on the basis that the yield strength of the material is the limiting condition for the computed moduli of rupture $\left(f = \frac{Mc}{I}\right)$ and that there is no restriction on the outside diameter of the aluminum alloy member. In this case, assuming a yield strength of 160,000 pounds per square inch for the material in the stainless beam, the aluminum alloy beam will be the lighter of the two. If, however, size is a controlling factor, the aluminum alloy beam is at a disadvantage, for in some cases it is not always practical from an aerodynamic or structural consideration to spread the aluminum alloy out so that the metal is working at its highest efficiency.

Considering equal deflections,

$$E\ (24ST) \times I\ (24ST) = E\ (18\text{-}8) \times I\ (18\text{-}8)$$

By following through the formula developed in reference 3)

$$d(24ST) = \left(\frac{2.60}{1.03}\right)^{1/4} \times d(18.8)$$

$$= 1.26\ d(18\text{-}8)$$

$$d = \text{outside diameter}$$

i.e., for equal deflections with no limitations on the outside diameters, the outside diameter of the aluminum alloy tube must be at least 1.26 times the diameter of the steel tube. From the following formula the ratio of weights would be:

$$\frac{W(24ST)}{W(18\text{-}8)} = \frac{0.101}{0.286} \times \frac{d^2(24ST)}{d^2(18\text{-}8)}$$

$$= 0.36 \times 1.59$$

$$= 0.562$$

The aluminum beam, therefore, can be made 44 percent lighter than the steel tubular beam for the same span, load, and deflection when there is no restriction on the outside diameter.

If the outside diameters are kept equal, and assuming that the moduli of rupture are equal to the yield strengths, the inside diameters will vary as the yield strengths. The section modulus (I/c) of the aluminum alloy tube must be 4.00 times as great as the steel tube. Inasmuch as strength in bending is directly proportional to the section modulus multiplied by the unit stress, it can be readily shown that for equal strengths under this condition, steel definitely has the advantage on weight.

COMPARISON AS COLUMNS

A comparison of the two materials as columns would be an exhaustive study in itself for it involves a number of factors which should be considered for an accurate analysis. A review of the National Advisory Committee's reports on its investigation of thin-walled cylinders in compression is abundant evidence of the various factors involved. It can be concluded, however, that for short columns, steel has the weight advantage. In the long-column range, and provided there is no restriction on the outside diameter, 24ST has a marked advantage over the steel. Under such conditions the slenderness ratio of the aluminum alloy member will be less than that of the steel, and the material can be more economically distributed. If, however, there is a restriction on the outside diameter because of aerodynamic or structural considerations, the steel tube will be the lighter of the two. No attempt will be made to discuss the exact weight savings possible by the use of either material under the conditions stated. It is desired to point out, nevertheless, that the peculiarities of the stress-strain characteristics of 18-8, particularly in the elastic range, are not especially favorable to its use under axial compressive loads for it is not a simple matter to predict whether the member will fail by plastic yielding of local buckling. In other words, it appears extremely difficult to determine what d/t ratio should be used to prevent local failure. Tuckerman, of the National Bureau of Standards, in his recent Edgar Marburg Lecture (reference 4), very ably sums up the problem by saying: "However great the complications, the structural problem of light-weight construction retains the same basic character. It is the problem of securing the best possible balance between plastic yielding, dependent upon the strength density ratio of the material and major and local elastic instabilities dependent upon its modulus density ratio and finally the transitions between these, dependent upon an accurate knowledge of its stress-strain curve."

STRESSED-SKIN COVERING

In the case of stressed-skin structures, failure is liable to result from local buckling. Under such conditions the more rigid structure will as a rule withstand local failure more satisfactorily than a thin structure of relatively low rigidity. To compete on a weight basis, high-strength steels must employ approximately one-third of the material allowable for aluminum alloys. Although the modulus of elasticity of such materials is about three times that of the aluminum, the form factor, which is, to a great extent, based on the bulk of the material used, more than compensates for the difference in the inherent rigidity. Fleetwings, Inc., has advocated carrying the majority of the stress in stringers, using the skin largely as a restraining influence on the stringers. This company has designed and built stainless-steel wing structures of reported high efficiency, using this scheme. It is believed, however, that the same ingenuity extended in the direction of aluminum alloy would yield equally efficient structures.

With the continued increase in speed, and the resultant increase in air pressures, it is believed that fabric for wing covering will be eventually supplanted by metal covering. The trend at present appears to favor the use of metal, at least from the leading edge to the rear beam. With the advent of metal covering it will be necessary to choose between steel and aluminum for the entire wing structure; for the use of composite structures of steel and aluminum, because of corrosion hazard, is not the best practice for severe operating conditions. That metal covering is definitely in the picture, cannot be denied.

All things considered, and in the absence of more extensive data on load-carrying capacities of stainless-steel structures, it is believed that aluminum alloy at present offers the best combination of properties for fabricated structures of stiffened sheet and for columns. For highly stressed fittings carrying lugs, good design and psychological consideration point toward the use of steel forgings, heat-treated subsequent to forging. Where pure tension is the primary controlling factor, such as in wires and cables, aluminum alloy obviously cannot compete with other available materials. The structural advantages of high-tensile steel for practically all primary applications, however, cannot be dismissed, even though it may require protection against corrosion. The optimum steel should be one with a good stress-strain curve, uniformly high mechanical properties, and properties capable of reasonably accurate determination. Stainless steel, as it is now available commercially, does not meet these requirements, and it is doubtful as to whether production methods can be devised to make it so without increased expense to the consumer. It is believed that the material should be one which obtains its strength through heat treatment and not through cold working.

Bureau of Aeronautics,
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REFERENCES

1. Johnson, J. B.: Materials of Construction. John Wiley & Sons, New York, 1919, p. 42.

2. Russell, H. W., and Welcker, W. A., Jr.: Endurance and Other Properties at Low Temperatures of Some Alloys for Aircraft Use. T.N. No. 381, N.A.C.A., 1931.

3. Hartmann, E. C.: Comparison of Weights of 17ST and Steel Tubular Structural Members Used in Aircraft Construction. T.N. No. 378, N.A.C.A., 1931.

4. Tuckerman, L. B.: Aircraft Materials and Testing. Proc. of Am. Soc. for Testing Materials, vol. 35, pt. 2, pp. 3 to 46, 1935.