Stainless Steel in Aircraft Construction

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The characteristics of a new material, commonly known as stainless steel, are considered, with facts and conclusions concerning its adaptability and suitability for use in aircraft construction. The type of steel discussed is called 18-8, by the proportions of chromium and nickel used. This material is selected because it is austenitic in character and is more readily procurable than some of its kindred alloys. The strength-to-weight ratios of 18-8 stainless steel are first considered in relation to comparable values from aluminum alloy, which is the most widely used metal in aircraft structures. This comparison is made using four criteria as representing the value of a material for structural uses. These criteria are (1) tensile strength, (2) the strength of columns, (3) the strength of members in bending, and (4) the deflection or stiffness characteristics. In this connection the finishes which are necessarily employed on aluminum alloy as corrosion preventives are charged against that material. It is considered that the use of paint on stainless steel is unnecessary except for external color requirements.

Fig. 1 shows a representative stress-strain curve taken from a specimen of hard-rolled 18-8 stainless-steel sheet material. Unlike ordinary steel, this material does not have a definite yield point. The limit of proportionality is rather low, after which the material yields along a uniform curve of decreasing slope. In defining a yield point for a material of this character it is necessary to select a point at which the stress-strain curve has deviated a definite amount from the straight line of Hooke's law. The amount of this deflection is somewhat arbitrary, but not entirely so. An attempt is made to define a value for the yield point so that when structures are designed using this value, the design load will be sustained without a permanent set of any of the members of the structure. A definition of such a value is taken at that unit stress under which the test specimen shows an extension of 0.002 in. per inch in excess of that which will be computed from Young's modulus of elasticity and the formula:

\[ \text{Unit stresses} = \frac{\text{Young's modulus}}{\text{Unit deformation}} \]

From reliable test data a minimum yield point of 140,000 lb per sq in. is obtainable from 18-8 hard-rolled material. This value may be used in design work and is believed sufficiently conservative to take care of material variations and an allowance for discrepancies between test results and actual failing stresses in built-up structures.

Fig. 2 indicates the cost in weight due to paint. Curve 1 shows the relation between the weights of painted and unpainted aluminum-alloy surfaces. Some 25 to 30 per cent is added to...
the weight of the gages of sheet usually employed on skin-covered structures such as monocoque fuselages and tail surfaces. Curves 2 and 3 show the relationships between painted aluminum alloy and stainless steel. The foregoing data indicate clearly that a saving in weight is possible when using stainless steel in so far as tensile strength ratios of actual deflection to calculated deflections in the two beams were almost the same (about 0.90), which indicates that the same load would have been held by the stainless-steel beam that was sustained by the aluminum-alloy beam had not the shear failure occurred first. Data on the strength of stainless-steel beams in bending and in combined bending and compression are too meager to be of value in drawing any definite conclusions. Within the near future, however, a rather systematic series of tests along this line will be completed.

Two beam sections, one of aluminum alloy 1 ft long and one of stainless steel 20 in. long, were made and tested in compression. Both specimens were of similar design and were made to represent sections of a beam for the same airplane. The aluminum-alloy member weighed 0.57 lb per ft and sustained a unit stress of 40,500 lb per sq in. in compression. The stainless-steel section weighed 1.098 lb per ft and held a unit stress of 128,000 lb per sq in. The factor \( e \) (see Table 1) computed from these tests based on equal weight is 1.21, indicating approximately a 20 per cent advantage in favor of stainless steel, even though this specimen was the longer one.

Beam members of similar design to the compression specimens previously described but of longer lengths were made and tested in bending. The aluminum-alloy beam is an efficient design as evidenced by the development of 47,700 lb per sq in. stress in bending. Owing to a shear failure experienced in the stainless-steel beam test, no ultimate bending stress was obtained. The ratios of actual deflection to calculated deflections in the two beams were almost the same (about 0.90), which indicates that the same load would have been held by the stainless-steel beam that was sustained by the aluminum-alloy beam had not the shear failure occurred first. Data on the strength of stainless-steel beams in bending and in combined bending and compression are too meager to be of value in drawing any definite conclusions. Within the near future, however, a rather systematic series of tests along this line will be completed.

\[ e = \frac{W_p}{W'} \times \frac{P/A_{dural} \times 2.83}{P/A_{alloy}} \]

**TABLE 1**

<table>
<thead>
<tr>
<th>Size aluminum-alloy tube</th>
<th>Area of tube</th>
<th>Weight per 100 in. length</th>
<th>Painted surface per 100 in.</th>
<th>Weight per 100 in. painted</th>
<th>P/A aluminum alloy</th>
<th>P/A stainless steel</th>
<th>( e )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/4</td>
<td>0.015</td>
<td>0.05113</td>
<td>0.51</td>
<td>1.09</td>
<td>0.568</td>
<td>44,000</td>
<td>1.360</td>
</tr>
<tr>
<td>1/4</td>
<td>0.049</td>
<td>0.1464</td>
<td>1.47</td>
<td>2.18</td>
<td>1.09</td>
<td>44,000</td>
<td>1.352</td>
</tr>
<tr>
<td>1/4</td>
<td>0.065</td>
<td>0.2393</td>
<td>2.63</td>
<td>3.27</td>
<td>1.85</td>
<td>44,000</td>
<td>1.320</td>
</tr>
<tr>
<td>2</td>
<td>0.095</td>
<td>0.5885</td>
<td>5.58</td>
<td>4.36</td>
<td>5.94</td>
<td>50 (28,000)</td>
<td>1.288</td>
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</tr>
</tbody>
</table>

**NOTES**

- Weight of painted surfaces:
  - 1 coat red oxide primer ........................................ 0.007 lb per sq ft
  - 2 coats navy gray enamel ...................................... 0.049 lb per sq ft
  - 1 coat aluminum bitumastic paint (inside) ................ 0.025 lb per sq ft
- Total ........................................................................ 0.072 lb per sq ft

- \( e = \frac{W_p}{W'} \times \frac{P/A_{dural} \times 2.83}{P/A_{alloy}} \)
- \( W_p = \) weight of aluminum alloy painted
- \( W' = \) weight of aluminum alloy unpainted
- \( W = \) weight of stainless steel
- 2.83 = ratio weight of stainless steel to weight of aluminum alloy
- Straight line \( P/A = 48,000 = \frac{W_p}{W'} \times 2.83 \)
- Euler \( P/A = \frac{2.83}{\varepsilon^2} \)

**Fig. 2 Comparison of Tensile Strength of Painted Aluminum Alloy With Unpainted Stainless Steel**

(Tensile strength of aluminum alloy, 55,000 lb per sq in.; tensile strength of stainless steel, 175,000 lb per sq in.)
Data which have been obtained at the present point in the research program, while not fully conclusive, do indicate that a saving in structural weight of 10 to 15 per cent is possible when using stainless steel except in long columns. Owing to the slightly lower modulus of elasticity of stainless steel—26,000,000 as compared with 29,000,000 for other steels—structures made from stainless steel may be expected to deflect about 11 per cent more than equivalent members of chrome-molybdenum steel or aluminum alloy. Recent research has indicated that by special processing it will be possible to improve the modulus of elasticity and to raise the limit of proportionality of stainless steel. From information gained, it appears that the structural characteristics may be improved as more is learned about the material.

The remaining factor to be considered by the designing engineer is the matter of making joints and fastenings. Practically we are confined to riveting and bolting or welding. A riveted or bolted-up structure of stainless steel, aside from the cost of the rivets and bolts and their insertion, would be very expensive because of the difficulty in drilling holes. Acetylene welding and electric-arc welding are as a general rule not suited for use in fabricating joints which are strong and resistant to vibrations, because of their detrimental effects on the structure of the material. Electric-resistance welding of stainless steel is now an established and a reliable process.

A brief discussion of the physical characteristics of 18-8 stainless steel and the adaptation of electric spot welding to its peculiarities will be given. This alloy is normally austenitic, which means that the carbon content of the material is dissolved in the iron somewhat as salt may be in solution in water. The maintenance of this condition is necessary for the material to have its normal physical properties and to be resistant to fatigue and corrosive attack.

Microscopic examination of a sample of austenitic metal shows that its structure consists of rather uniform crystals of rectangular section and that they are bounded by sharp, well-defined lines. When the carbon in this metal is merely mixed with the iron and is not in solution, the alloy is said to be non-austenitic. In this condition the crystals are somewhat separated by rather blurred and indistinct lines wider than in the austenitic metal. The material between the crystals is supposed to be carbon which has separated from the iron. This change in the character of the material gives rise to the term "carbide precipitation," analogous to the crystallization of salt from a salt-water solution. Apparently this change from an austenitic to a non-austenitic material takes place when the metal is heated to a temperature between 950 F and 1550 F and is held at this temperature for a sufficient length of time.

At about 950 F the carbon is completely dissolved in the iron. Upon raising the temperature, carbon begins to precipitate. This precipitation takes place at an increasing rate until a temperature of 1200 F is reached. Above 1200 F the rate of carbide precipitation becomes less, until at 1550 F it stops entirely. If the temperature is carried on up above 1550 F, the carbon gradually goes back into solution and the alloy returns to its normally austenitic condition. If the metal, once more in its most desirable state, can be cooled sufficiently rapidly, it will pass through the critical temperature range just described without carbon leaving the solution again. This quality is of very great importance in selecting a method of welding the material.

Acetylene or arc welding, as all know, is a process of fusing two pieces of metal at the points where they are to be joined in such a way that the metal is melted and caused to flow together. During these processes a considerable mass of material is melted and cooled rather slowly. During this cooling an ideal condition is produced for carbide precipitation to take place. Electric spot welding is a more desirable method, since only sufficient metal is melted to form the spot. Under ideal conditions a weld is made by pressing the two or more pieces of metal together and at the proper time allowing just sufficient current to pass between the electrodes to bring the metal to the fusing point. At this instant the pressure applied causes the fused metal to flow together, thus forming a homogeneous and firm bond between the plates. Because of the small amount of metal which has been melted and also because of the fact that the adjacent metal has not been heated, the molten spot cools very rapidly, so that the carbide precipitation does not have a chance to form.

To obtain welds of suitable quality and reliability for aircraft production it is necessary to make use of equipment somewhat more advanced in its development than the average power-driven spot welder used in commercial work. In spot welding there are three main variables:

1. Pressure of the electrodes on the work
2. The amount of current
3. The time of current application.

The pressure can be adjusted to the amount required by varying an electrode compression spring, which is ordinarily furnished with a machine. The current is easily adjusted by changing the setting of a control, which also comes with the welding machine. The timing control is more difficult and requires a special device. It is necessary to make resistance welds in as short a time as possible for several reasons:

1. High-speed production
2. Minimum oxidation or scaling

As previously explained, carbide precipitation, as well as distortion and warping, is held to a minimum when the heat is confined to the actual welding area, and this is possible only if the welding time is very short. If welded in a short enough time, it is theoretically possible to generate the necessary heat at the location of the weld, fuse the surfaces together, and allow the heat to be conducted rapidly away by the surrounding metal and electrodes after the weld has been completed without heating the outer surface of the sheets to an injurious temperature. It is not only necessary to complete the weld in a very short space of time, but it is also necessary to synchronize the make and break of the weld with points on the alternating cycle curve which pass through zero, or at the times when no current is flowing owing to a reversal of the cycle.

The reason for beginning and ending a welding operation at times of zero current flow is to avoid arcing when the electrodes are making or breaking a contact. The formation of an arc is a cause of oxidation and burning of a weld.

Each cycle of the sine wave representing a 60-cycle current takes a time of 0.0167 sec. If it is possible to weld in even cycles or half cycles, then the question of timing control is solved both as to accuracy of the duration of each weld and the fulfillment of the requirement of starting and stopping of a weld at exact instants when no current is flowing.

Actually with suitable equipment it is possible to make welds in one-half-cycle increments. Theoretically it is best to use this amount of time for all welding and vary the amount of current in direct ratio to the thickness of the parts being welded. Practically, however, a machine of normal capacity is not large enough to supply the needed current for welds on heavier gages, so that it is necessary to increase the time, using several cycles, so that the total amount of electrical energy dissipated at the weld is approximately the same as would be the case with the shorter welding time and more current.

The most satisfactory device for controlling the application of
He only needs to know the strength per spot for each gage of material. The strength of a spot varies in a fairly definite relation with the thickness of the thinnest of the material being welded. In stainless-steel sheet-metal construction equivalent to thin aluminum alloy such as wing and tail-surface covering material, the strength of a spot weld is about double that of the most efficient size rivet in aluminum alloy. This advantage gradually diminishes on the heavier gages in which the strengths of welds and rivets are comparable.

Manufacturing Costs

It is not possible with available data to present any accurate figures to show the difference between the costs of aluminum-alloy and stainless-steel construction. However, it is possible to make some comparisons between the various processes involved so that a fairly definite conclusion may be drawn as to the relative merits of the two methods.

Normal forming and cutting operations are much more difficult and costly on stainless steel than on other commonly used materials. For this reason such operations are simplified and avoided as far as possible in designing stainless-steel aircraft parts. For the most part, shapes are made by a drawing process producing simple forms, but conforming to known principles.

Current to a weld at the proper instant, definitely measuring a predetermined time in even cycles of current, and stopping the weld at the proper time, is an electrical rectifier known as the thyratron contactor. The figures and microphotographs illustrate some of the results obtained with a device of this kind applied to a spot-welding machine as the time-control medium. Fig. 3 illustrates welding periods in terms of cycles of current. The symmetry and uniformity of these records show clearly the accuracy of control. Fig. 4 shows the results obtained by using long and short periods of dwell. The center spots were welded with 60 cycles or 1 sec time. A zone around these welds has been heated to the critical temperature at which carbide precipitates, so that these are not good welds. At the top of the photograph are three welds made with 12 cycles. These welds are more uniform in quality and appearance due to the more rapid heating and cooling periods. At the lower left side of the picture are four welds made in 1 cycle each. These welds are of excellent quality, without carbide precipitation or discoloration of the metal. Fig. 5 is a section of one of these welds magnified 500 diam. The excellence of the grain structure is noteworthy.

When using electric spot welding, the designer does not need to think in terms of rivet-shearing strength and bearing area.
for their structural efficiency. Because of the high density of the material (the same as ordinary steels) it is necessary to use it in thin gauges in order to build structures of comparable weights to wood and aluminum alloy. A thin sheet inherently lacks stiffness normal to its own plane. For this reason it is considered necessary in order to take full advantage of this metal as a structural material to resort in general to the principle of using frequent stiffeners in such a manner as to keep the flat-sheet element widths down to low values, and further to make use of frequent supports along the lengths of the members to keep the column lengths down to low values.

Owing to this method of design with additional formers and stiffeners, it is believed that probably four times the number of spots will be used compared with rivets in aluminum-alloy construction. The cost of drilling, inserting, and heading operations on aluminum-alloy rivets has been compiled from actual time records for the three operations shown in Table 2. A comparison of the cost of spot welding is made based on the rate of speed in welding which has been obtained in work of a similar nature to that which employs the rivets.

This comparison indicates a great advantage in favor of spot welding considering only the present application of the method. The possibilities of spot welding may be more fully realized by considering what may be done using production methods. It is within the realm of possibility to produce 75 ft of linear welding per minute, making four spots per inch, which amounts to 3600 spots per minute, making four spots per inch, which amounts to 3600 spots per minute. At such a speed it would of course be necessary to properly feed and guide the work through the machines. It is also necessary to take care to prevent abrasion and scratching of the metal while in process of fabrication, and the use of sharp marking tools is prohibited.

The visual differentiation between annealed and high-strength steeled rivets was in some way used in production. One instance has recently been experienced of a very costly mistake in which improperly heat-treated rivets were in some way used in production. The visual differentiation between annealed and high-strength stainless steel is pronounced enough to avoid confusion, as annealed steel may be purchased with a dull pickled finish, whereas hard-rolled material is bright.

The physical properties of 18-8 steel are derived from cold working, and it does not respond to any sort of heat treatment except normalizing. Therefore this phase of manufacturing when using this metal is eliminated except for such normalizing as is considered to be necessary.

In the author’s experience a very costly item in aluminum-alloy construction has been the rejection and reworking made necessary by wrongly drilled holes, elongated holes, and bad rivets. The use of stainless steel and the spot-welding process obviates these difficulties to a large extent as no holes are required and a lesser degree of care is required in spacing the welds than is the case with rivets.

Next in importance to the saving effected by replacing the riveting process by welding is the practical elimination of the elaborate finishing operations on aluminum alloy and other steel construction. Anodizing at approximately 25 cents per square foot and sand blasting and painting at approximately 20 cents per square foot are
almost entirely eliminated when using the stainless steel.

Summarizing the probable advantages of stainless-steel construction from the airplane manufacturer's viewpoint, the method should yield lighter structures for equal strength and should materially reduce construction costs. The outstanding factors in costs are the use of electric resistance welding and the reduction of costly finishing processes. From the operation standpoint the foregoing considerations lead to greater operating economy through increased pay loads and reduced maintenance costs, particularly the item of continually renewing protective coatings.