STEEL VERSUS LIGHTER ALLOYS.

Paper read by Colonel N. T. Belaiew, C.B., (Member), before the Institution at the Engineers' Club, Coventry Street, W., on Friday, 7th November, 1924. Mr. H. B. Molesworth in the Chair.

I. INTRODUCTION.

COLONEL BELAIEW said :—

The recent researches and developments in the study and manufacture of light aluminium alloys have recently brought forward and placed at the disposal of the constructing engineer many valuable alloys of light weight and high strength.

The question arises, therefore, of comparing the properties of such alloys with those of steel. The question in itself becomes of a general importance for many constructional purposes, but for the present the most important battlefield seems to be that of *aircraft construction.*

The advantage of utilising a material of high strength, but of small density, seems fairly obvious in many fields, but it is in aircraft where the saving of dead-weight and of the mass to be set in motion seems to be of the greatest importance.

There is another and a very important consideration to be taken into account—the question of the so-called "local failure." For instance, as pointed out by Dr. Thurston, the most useful thickness for steel parts, if they were to compete with *wood* weight for weight, would be about 0.020 in. It is obvious that with such structures local failures might easily develop and become dangerous, before the full strength of the material should come into play.

It is very likely that such or like considerations weighed rather heavily on the minds of constructors when they, for a considerable period, felt inclined to stick to wood and forego the advantages of steel.

Even after the war, when (in 1918) over 1,000 all-metal machines were used by the Allies only, the advocates of metal construction had a rather stiff fight. They were able, of course, to point that " wood warps and cracks; is unsuitable for tropical climates; splinters easily in crash . . . . . is non-homogeneous; uncertain in strength and weight; weakens rapidly when exposed to moisture " and so on. (*Metal Construction of Aircraft.* By A. P. Thurston, D.Sc. Aeronautical reprints, No. 16, 1919, p.3). But as against this it was urged that steel is too heavy to be used in constructing efficient machines, and, when the latter fallacy was exploded, there still remained a lingering belief that a lighter material would be more welcome, as giving better guarantees against local failures.

Now, the advent of light alloys has done with the latter argument. For instance, if duralumin is used, corresponding parts become, weight for weight, three times thicker than those of steel. So it seems that the cycle has been completed, and that we, having abandoned the light but fibrous material—wood, for the sake of a more resistant but many times more heavy material—steel, are coming back to the use of lighter material, but this time a light metal alloy.

However, there is still that possibility that the necessity for lightness might have been over-emphasised and that a better insight into the actual conditions existing in various parts of a plane during flight would show that, under all circumstances, steel can safely hold its ground, and, for some special parts, can even be taken in preference to the lighter alloys. There is, in the author's opinion, some ground even for the suggestion that for some particular purposes of aircraft construction, steel parts possess some possibilities which up to now have rather escaped attention.

Therefore, in what follows, the author proposes to give a brief survey of the more important light aluminium alloys, and then to put forward certain suggestions with reference to steel.

II. LIGHT ALUMINIUM ALLOYS.

Light aluminium alloys have been scientifically investigated and brought into the foreground mainly by the National Physical Laboratory in this country and by the American Bureau of Standards in the States. Very valuable work has been done also on the Continent by the Belgian, French and German investigators, especially with reference to duralumin.

Duralumin is the best-known of the light aluminium alloys. Its composition varies somewhat. On the Continent the following composition was considered as representative :—

Cu.	3·5—5·5
Mg.	0.5
Mn.	0.5
Si.	traces to 0.5
Al.	the balance

The density of duralumin is about 2.8 and the tensile strength, after appropriate heat treatment will average 25 tons per sq. in. The elongation will be about 15 to 20 per cent.

The specific tenacity or the ratio of the ultimate tensile strength in tons per sq. in. to density (the weight of one cu. in.) will be about 250. The specific tenacity of a 25-ton steel is only about 90 and the specific tenacity of a 30-ton steel 105. This shows the importance of a low density and its influence on the "specific tenacity" or tenacity per unit of weight. For light aluminium alloys of the density of about 2.8, the specific tenacity is obtained by multiplying the figure for ultimate stress by the factor 10. For steel, on the other hand, this factor is only 3.5. In this way we arrived at the figures of 250 and 105 for the 25-ton resistance duralumin and steel.

The most remarkable phenomenon about certain aluminium alloys is their property of age-hardening. As shown by Wilm in the years 1903-11, duralumin can be appreciably hardened by quenching it from about 480-500° C. and by subsequent *ageing* at ordinary temperatures. It is interesting to note that the age-hardening property was first observed at Woolwich in an alloy of aluminium with 10 per cent. of zinc and a little magnesium shortly before Wilm published his first paper on the subject. (See Rosenhain's *Light Alloys of Aluminium,* and discussions, Dr. Moore, on Rosenhain.) Immediately after quenching, the metal is soft and plastic and may easily be forged, pressed or bent. Then the metal begins gradually to harden and very soon reaches the above-mentioned strength of about 25 tons and the elongation of 15 per cent. Further, the process continues to go on for a considerable time, the strength now increasing but slightly, and with a corresponding decrease of elongation. To sum up, and quoting Dr. Thurston, we can say that "the heat treatment of duralumin, instead of being a disadvantage . . . . is in actual point of fact the greatest assistance in the practical working of the metal." (*Metal Construction of Aircraft*, p. 8.) These properties of duralumin, in spite of some minor difficulties in working and some prejudice as to its corrodibility, have steadily worked for its popularity, and there is some information that the new Ford commercial planes are manufactured of duralumin.

The above-mentioned work of Wilm was continued in America by Merica, Waltenberg, Scott and Freeman (*Heat Treatment of Duralumin.* By Merica, Waltenberg and Scott. Scientific Papers of the Bureau of Standards. No.

347, 1919. See also Circular of the Bureau of Standards No. 76, on *Aluminium and its light alloys*), by Fraenkel, Seng and Scheuer in Germany, and by Rosenhain and his colleagues and co-workers at the National Laboratory. (The recent work on duralumin is summed up by Fraenkel and Scheuer in "Testing," No. 1, January, 1924, under the heading *The Researches on the Duralumin Problem.* Some references may be found there to the work of Guillet, Grard, Galibourg and other Continental workers). The former, working with copper containing alloys, ascribed the property of age-hardening to the separation from super-saturated solutions of the compound $CuAl_2$; the latter, studying the constitution of the aluminium-magnesium-silicon system, discovered that for any marked degree of age-hardening, a simultaneous presence of magnesium and silicon was necessary, and subsequently found the compound Mg_2Si. (*The Constitution and Age-Hardening of the Alloys of Aluminium with Magnesium and Silicon.* By Dr. Hanson and Marie L. V. Gayler. Journ. Inst. Metals, 1921, vol. 26, No. 2, pp. 321-395. See also the " Reports " to the Alloys Research Committee of the Institution of Mechanical Engineers, and, more particularly, the " Eleventh Report.")

A subsequent study by Miss Gayler proved that both Mg_2Si and $CuAl_2$ are responsible for the process, the former at ordinary temperatures and the latter at temperatures between 150° C. and 200° C.

The actual process of age-hardening is thus described as being due to the decreasing solubility of the intermetallic compound with falling temperature. It was also shown that the extent of the hardening taking place is proportional to the amount of the compound in solution at the moment of quenching.

It appears that the hardening is due to the precipitation from the supersaturated solution of minute particles of the intermetallic compound. The following coalescence of these particles into larger ones tends, subsequently, to reduce, somewhat, the so acquired hardness.

In practice, the first stage, that of increased hardness, is reached in about 100 hours after quenching at atmospheric temperature; the second stage requires a heating to at least 200° C.

In the course of a search for a light alloy able to retain its strength at comparatively high temperatures, a ternary magnesium-nickel-copper alloy ("Y") has been worked out by the National Laboratory.

The chemical composition of that alloy is :—

Mg.	1.5
Ni.	2.0
Cu.	4.0
Al.	the balance.

In the wrought condition the " Y " alloy is very similar to duralumin. In a cast and heated condition its maximum stress is about 20.0 tons per sq. in., with a corresponding elongation of 5 per cent. As the density of that alloy is 2.79, the specific tenacity is about 200.

Like duralumin, " Y " alloy must be subjected to heat treatment to develop its latent mechanical qualities. According to Rosenhain, " the ' Y ' alloy does not appear to offer any special difficulties in casting in either sand or chill moulds, and is valuable in regard to strength at high temperatures, elasticity, improvement of properties by heat treatment, and resistance to corrosion, as compared with most other available light alloys." (*Light Alloys of Aluminium.* By Dr. W. Rosenhain. Empire Mining and Metallurgical Congress. Section D: Non-Ferrous Metallurgy. London, June 3rd-6th, 1924, pp. 1-24.) It must be further pointed out that a valuable achievement with reference to light alloys is the increased fatigue range when cast. Whereas the usual figures were about ± 3, they have been increased now to ± 7. In wrought alloys that range is up to ± 10. Thus the safe range of stress has been materially increased.

The high conductivity power of aluminium and its alloys makes them invaluable for pistons and like parts, and we are told, besides, that higher values for ultimate stress and elongation than those already mentioned are shortly to be expected. " The application of the age-hardening process to certain *wrought* aluminium alloys has led to the attainment of tensile stress of 30-40 tons per sq. in. in an alloy of density 3.1 grms. per c.c." (*Light Alloys of Aluminium.* By Dr. W. Rosenhain, as above, p. 3.) The specific tenacity of such an alloy would be about 365.

All these properties tend to make the light aluminium alloys more and more popular with the designer; as to the constructor and manufacturer, there still seems to be a certain uneasiness as to the resistance to corrosion and to the permanence of their stability. An exhaustive reply to these doubts may be found in the recent papers read before the Institute of Metals, in the " Reports " to the Alloys Research Committee, and, more especially, in the address on " *Light Aluminium Alloys,*" read by Dr. Rosenhain before the section of non-ferrous metallurgy at the Empire Mining and Metallurgical Congress.

III. THE IMPORTANCE OF A CORRECT FIBROUS STRUCTURE.

It has been rightly said that engineering progress depends upon the fullest utilisation of the best available material for any given purpose. After having paid an appropriate tribute to the newcomers in construction—the light aluminium alloys—the author would like to revert to the domain of iron and steel and to make certain suggestions showing what a vast field to explore still remains in the seemingly so well-known and simple iron-carbon diagram.

In a paper read before this Institution in 1920 on the "Structure of Steel" (Journ. of the Inst. of Aeronautical Engineers, Vol. I, No. 3, 1920, pp. 14-23), the author pointed to certain important factors occurring during crystallisation and influencing deeply all the posterior structures and properties of any steel article.

This important factor is the dendritic crystallisation of steel occurring during solidification and resulting in the formation of comparatively large *macroscopic* dendrites. Every such dendrite is a unit, both from the crystallographic and the chemical point of view. The crystallographical unity of the dendrites is destroyed during the subsequent cooling by various processes occurring in the austenitic area, but the chemical non-homogeneity remains intact throughout the whole life-history of the alloy, and in the cooled specimens may be revealed by macroetching. (Figs. 1, 2, and 3.)

Forging or stamping or any other mechanical treatment does not destroy either the existence or the substance of any dendrite, but, on the other hand any such treatment distorts these units in its own way, and alters their shape in accordance, and in proportion to, the work absorbed by the specimen. (Figs. 4 and 5.)

Now, as mechanical treatment alters the shape of the ingot, the original dendrites are getting more and more distorted, their outer shape and outlines become more elongated, and their main axis gets more and more twisted. Finally, the now elongated and twisted dendrites become like fibres in the texture of some woods, and the whole arrangement, when revealed by macroetching, becomes distinctly fibrous. As already pointed out, the chemical unity of such fibre-dendrite remains intact, and the mechanical properties of every fibre will be different in respect to its main axis. Conversely, mechanical properties of a finished article will be anisotropic and will differ as to the direction of the main axis of the fibre.

As is to be expected, the elongation will be much lower in an equatorial than in a longitudinal section. Therefore it is of the utmost importance that the axis of the fibre be placed in such a relation to the axis of the specimen, say of a shaft, as to insure the full benefit such a fibrous structure affords.

The more stringent are the specifications and the more costly the materials, the more limited becomes the constructor as to the weight of the billet and of the finished article, and the more inclined would he feel to take full advantage of all the latent possibilities of his material, and the more perfect as to design, weight, and mechanical excellence, will the finished article be.

Such or like circumstances prevailed in days of old in India and Persia, where the material, the cake of Indian crucible steel, was precious, and where the " specifications " as to the finished article—the sword, the helmet—were exacting. Under such circumstances no waste of the precious material was to be dreamed of and, on the other hand, every nerve had to be strained to get all that could be got out of the material in the mechanical excellence of the finished article. As the author put it in another paper (*Crystallisation of Metals.* 1923. London University Press), a process has been steadily evolved by which the dendrites of the cake were hammered out into a perfect maze of interwoven fibres.

After forging and a final heat treatment, every blade, every article, was macroetched by some vegetable acid, and both the manufacturer—the smith—and the customer, be he a warrior or a trader, could and would examine the structure of the finished article, admire its perfect fibrous watering or scoff at the unfortunate worker.

The most common and rather despised pattern of the fibrous structure was that of logitudinal veins of the Syrian blades. Such structure was called " sham," and consisted of parallel running stripes or ronces. A more skilful forging and a larger amount of carbon would produce a wavy or a motley watering; there not a single straight line would be left, and every fibre would seem wavy like running water. Finally, in blades, the essence of excellence would be attained in the " kirk-nardubán " with its forty vertebræ of splendidly-arranged fibres. (Figs. 6 and 7.)

Just one hundred years have elapsed now since Anossoff, at the Zlatoust works was applying the knowledge of the eastern Damascene process to the melting and forging of high carbon steels. About fifty years have passed since Tschernoff brought some of the Anossoff's blades to the Oboukhoff works in St. Petersburg; it is also nearly twenty years since, following in his teacher's steps, the author first tried to draw the attention of steel manufacturers and steel users to the splendid possibilities of the Damascene process and to the importance and possibilities offered by the use of the fibrous structure of steel, and how that " fibre " was taken full advantage of in the " dark ages " by the old Indians and Persians.

From time to time the author has been able to follow the progress of the macroetching and see it applied to some finished articles, like crankshafts and various drop-forgings—a most satisfactory, and quite a " Damascene," procedure. But what about the structures revealed? And what structures aimed at? At the best a watering was produced showing parallel running wavy strips which the Oriental would unmistakably call "sham." The author is quite aware that the forging of a crankshaft is an entirely different proposition from that of a blade, and that the ideal structure for the latter is not a "kirk-nardubán"; but still there must be an "ideal" watering to be aimed at for every article, and from such a point the problem seems even not to be considered.

So let us try and direct our energies towards the settlement of the "fibre problem," which, in its essence, is the problem of the old watering. In one of our early materials for aircraft construction—wood—we had that fibre already. In our next material—steel—we were longing for it. So, for instance, Major A. R. Low, discussing Dr. Thurston's paper on "Metal Construction of Aircraft," suggested "that the best results might be obtained by imitating as closely as possible the internal structure of wood." Let us do it. We had it in the Damascene steel already. We may get back to it not only in carbon steel, but in rustless steels and, some time, in light aluminium alloys.

DISCUSSION.

Lieut. Olechnovitch:—I quite agree with the author that steel cannot be beaten for many parts of aircraft. Being a man of more practical than theoretical knowledge, I always look at every matter from the former point of view. Therefore it seems to me that steel construction should in many respects be preferred to lighter alloys. For example, such an important process in the construction of aircraft as autogeneous welding, is more reliable in steel than in any of the aluminium alloys; also the question of repairs is much simpler when steel is used. We had before this Institution last year, an extremely interesting paper, by Mr. Fokker, regarding steel construction, and I think his ideas are of great value.

Colonel Belaiew has touched on the question of stainless steel as an aircraft material, and I wish to point out that this steel deserves much more attention and use than at present. During the last two years I have had an opportunity of studying and experimenting with stainless steels, and found them extremely good. Regarding the strength of this particular steel, the accompanying tables may be of some interest. (Fig. 8.)

The steel was oil-quenched from 950°C. and tempered to the temperatures indicated. The sample of the steel tempered at 500°C. is most interesting, and also shows the importance of the proper heat treatment of the steel.