ALLOY STEELS — TECHNICAL AND ECONOMIC BACKGROUND

E. H. BUCKNALL
National Metallurgical Laboratory, Jamshedpur

THIS contribution is meant to serve as a general introduction to the symposium on Alloy Steels, which is being held at the National Metallurgical Laboratory, Jamshedpur, and which is hoped to encourage India to make and use alloy steels. As such, the first question which we must try to answer is, ' What are alloy steels ? ' This is a question which has not, so far, much been asked in India, yet one of which the answer should be of particular interest to industrialists and to those concerned, on the Government side, with determining and administering the iron and steel policy of India, as well as to the general public. The short answer is that alloy steels are steels with deliberately introduced quantities of elements other than iron or carbon or manganese (beyond 1·2 per cent). We hear a great deal about expansion of steel production in India and of measures aimed at economy in steel utilization, but at present this is mainly concerned with non-alloy grades of steel, although freer use of alloy steels should effect greater economies and limit somewhat the need for expansion of the Indian steel industry. It would also allow the development of more advanced engineering techniques than can at present be employed without resort to imported materials, and these would in turn result in achievements with lasting advantages.

In a sense all steel is an alloy; it is iron alloyed with carbon (to lower levels than in cast iron) and to some extent also with manganese and silicon, while accidental and undesirable trace amounts of phosphorus, sulphur and other impurities are also present. Mild steel, which is the main constructional material of the engineer, contains not more than 0·3 per cent carbon (often considerably less) and around 0·5 per cent manganese and 0·2 per cent silicon, with 0·05 per cent each of sulphur and phosphorus. Such a material has as-rolled a tensile strength of about 30 tons/sq. in. By normalizing or annealing it can be made slightly softer (and weaker) with compensating increases in ductility and toughness, but it cannot effectively be hardened by heat treatment. Certain other ' plain-carbon ' steels with higher carbon contents, such as about 0·6 per cent (railway rails) and 0·8-1·2 per cent carbon (carbon tool steels and spring steels), are normal products of industry, but are made on a smaller scale than mild steel. Some of these carbon steels have increased contents of manganese, as for example 1-1·2 per cent in ' medium-manganese ' rail steel. Such steels as-rolled are harder and stronger than mild steel and are, to some extent, amenable to further hardening by intentional heat treatment. Without heat treatment, a separate composition (which must be maintained within rather close limits) is required for each level of strength required; where the steels can be heat-treated this composition limitation tends to disappear, since a hardened steel can be tempered back to a variety of strength levels, permitting a single compositional type to serve a variety of purposes calling for varied strength. Unfortunately, the non-alloy steels have a number of features which stand in the way of their extensive use as heat-treated. Among these difficulties are: (1) even when carbon contents are increased to high levels, the sections in which plain-carbon steels can be hardened are quite limited — never exceeding a 1-inch diameter bar, or a plate with equivalent cooling rate; (2) hardening even in limited sections normally calls for a drastic type of quenching, which in conjunction with high carbon contents leads to distortion and cracking. While there are means of hardening which reduce these troubles, they are complex and expensive and of very limited application. On the other hand, alloy steel compositions can readily be found which will harden fully in quite large sections on much less severe cooling (as for example 6-inch bars air-cooled) without resort to high carbon contents; such steels lend themselves *par excellence* to heat treatment. Known as the alloy constructional steels, they form the main tonnage of alloy steels, constituting in some countries 5 per cent or more of the total steel output. A variety of alloying elements, and often a mixture of alloying elements, present to a total extent of about 5 per cent or less, may be used to build up such properties; the commonest additions being nickel, chromium, manganese and molybdenum. Some of the low-alloy types which are suitable for oil-hardening in moderate sections have less than 1 per cent total alloys. These alloy steels provide materials with strengths up to 100 tons/sq. in. or more, a level which can be attained in carbon steel only in the form of wire. They find particular application in engineering, especially in industries such as automobile manufacture.

The heat-treatable alloy constructional steels, though forming the largest single group of alloy steels, are by no means the only types which find industrial application. There are, for example, the alloy high-tensile steels, a group of plate and beam materials intended to be used as-rolled but with higher strength than the as-rolled carbon steels. Such steels, like the heat-treatable types, commonly have quite limited carbon contents and hence have better weldability than plain carbon equivalents. An outstanding steel of this type is ' Fortiweld ', a steel with 0·5 per cent molybdenum and 0·003 per cent boron, which combines a 40-ton yield point with the weldability of mild steel. Also within this group are the copper-chrome types which include Tata ' Tiscor ' and ' Tiscrom ' in which special resistance to corrosion is secured, as well as high strength.

So far all our references have been to wrought steels, but we should not forget that an increasing proportion of steel is being used as castings and that much of this (the majority, taking the world as a whole) is in alloy compositions. These include, as well as low-alloy types with 0·3 per cent carbon and the elements required to give the desired depth of hardening, various special types with particular properties developed to an unusually high level by means of higher alloy additions, e.g. heat-resistant castings, wear-resistant castings or non-magnetic castings. A special place among the wear-resistant castings is occupied by ' Hadfield manganese steel ' with approximately 12 per cent manganese. This material is so highly alloyed that instead of hardening when quenched in water it then fully retains its high-temperature austenitic constitution and does not transform to the hard constituent, martensite.

The wrought austenitic stainless steels have this characteristic to a higher degree; as sheets they retain the austenitic state on air-cooling. These usually contain chromium (typically 18 per cent) and nickel (8 per cent). High-silicon sheet steels which are used in the cores of transformers, on the other hand, retain at all temperatures the low-temperature structure of iron, ferrite. The same is true of straight chrome-irons, e.g. alloys with above 18 per cent chromium and very low carbon. Twelve per cent chromium steels, however, with carbon contents such as 0·2 per cent are, on the contrary, highly hardenable and thus serve for stainless cutlery. Amongst the higher alloyed wrought steels are many other types intended for specific applications dependent on special values of some physical property. For example, alloys of iron with 32 per cent nickel have practically zero coefficient of expansion and are thus of great service in measuring instruments; other related compositions have zero temperature coefficient of easticity and thus serve in watch and clock mechanisms.

After the above classes, we come to tool steels, which some industrialists in India apparently tend to think of as the only alloy steels warranting attention here with the possible exception of stainless steels. These tool steels comprise low-alloy and high-alloy types, ranging from slightly modified carbon tool steel compositions, through chromium die and hot-work steels, to high-speed steels, of which the best-known type contains 18 per cent tungsten, 4 per cent chromium and 1 per cent vanadium in conjunction with 0·7 per cent carbon. For special purposes up to 5 per cent cobalt may also be present. Such steels, and the 'carbide-tipped tools' which are a later development, depend on highly stable alloy carbides which retain strength and resistance to annealing at a red heat. Hence they can be used with feeds and speeds which heat up the tool to a temperature where carbon steel would fail.

To a large extent choice of materials by the Indian user at present depends on availability, which in turn depends on the indigenous steel-maker and/or on Government importation policy. It should, however, be acknowledged that the user or potential user has a very important point of view and that before he demands a material he will usually have satisfied himself that the material selected is a sound proposition both technically and economically. As may be appreciated from the foregoing, some alloy steels are in a very favourable position because they possess special attributes without which particular requirements cannot be met, e.g. stainless steels, high-speed tool steels, high-temperature steels for power plant and steels specially suited for low-temperature applications; but with the main body of constructional steels the merits have to be determined in terms of properties which are more or less common to all steels, though not always at the same levels. Many alloy steels are capable of showing better combinations of the ordinary engineering properties of strength, ductility and toughness than plain-carbon steels in a similar structural condition. The best combinations are invariably shown by steels which have been fully hardened and tempered; alloying allows such results to be secured in much greater sections and, as pointed out above, without distortion or cracking.

For many applications, liability to brittle fracture in service is an ever-present danger; accordingly, a steel may often be judged by the critical hardness at which it passes from tough to brittle in a standardized notch-impact test at a fixed temperature — the higher this critical hardness, the better being the steel. Alloy types in general, and some individual compositions in particular, which it is beyond the scope of the present article to detail, possess much higher critical hardness, in these terms, than can be secured in plain-carbon steels. Where fracture is a criterion of design, the attributes of hardenability (depth of hardening) and impact transition temperature should form the main bases for steel selection. The constructional engineer can be trusted to choose the combination of available alloying elements which allow him to do his job cheapest and best. Similarly, wherever design is based on yield point, alloy steels permit lower weight structures or greater security in structures of equal weight.

The engineer may argue that many, if not most of his designs are essentially based on elastic deflection and that Young's modulus is the only property that really concerns him. At room temperature, Young's modulus varies very little between the whole range of steels irrespective of composition or condition; he may, therefore, decide that alloy steels have no special merits so far as these applications are concerned. Such an argument would not, however, always be fully logical, since alloy steels can show to advantage even when design is based on Young's modulus. For example, an alloy steel often does not need to be accorded so high a factor of safety as mild steel. This is particularly the case where high deflection is permissible, but non-uniform deformation must be avoided; since the heat-treated alloy steels have no marked yield point, they do not exhibit non-uniformity of deformation. Again, in an alloy steel which can be put into one condition for machining and another for service, it is often easy to save in the gross weight of steel used for a component even if the finished net weight is unchanged. Further, alloy steels often reduce fabrication difficulties, as for example where they combine high strength with good weldability. Such advantages are particularly important in a country where technical skill is not always highly advanced and experienced labour is not much available, as must be acknowledged to be the case in India. It is often possible to make material fool-proof with small usage of alloying elements. That the tendency in advanced countries is now to reduce or even dispense with alloy contents for some purposes need not, and should not, be taken as an example in India at the present stage of development, although wasteful application of non-indigenous alloys would not, of course, be recommended.

Consideration of the prevailing price structure in countries where alloy steels are in relatively large production shows that the advantages offered by alloy steels may usually be secured at little monetary cost, which may be immediately offset by weight savings or may be recouped over a short period by reduction of working charges. The Climax Molybdenum Company of New York have recently developed this point of view very fully and effectively in their publication *Alloy Steels Pay Off* (New York, 1953), beyond which one does not need to go to appreciate the case for alloy steels. This publication comprises a general introduction of 29 pages followed by case histories of 60 individual examples where alloy steels have been found to pay, and establish the position where the 1952 U.S. deliveries of wrought alloy steels reach 5,151,381 tons plus 509,703 tons of stainless grades. The main grounds on which alloy steels are shown to pay are: longer life, greater pay load, lower operating costs, greater safety and less maintenance. These, of course, are not entirely distinct and separate features but merge to some extent one with another, but instances can be given where the feature cited is at least the main issue. For *longer life* an outstanding example is afforded by heat-exchanger tube assemblies. Three materials have been cited: carbon steel, chrome-molybdenum steel and stainless (type 304). For the two former 13-gauge tubes were necessary, for the last 16-gauge sufficed. With these tubes the safe service lives were: 1 year, 2 years and 20 years respectively. Despite the low-alloy steel costing 230 per cent and the stainless steel 1160 per cent above the carbon steel, the *costs per year* were in the reverse order, namely $ 3190, $ 2255 and $ 427 for carbon steel, low-alloy and stainless respectively, because of the increase in service life. An almost equally striking case may be made for expensive alloy steels for tools, e.g. the trimming tools used to clip the 'flash' from forgings, where a five times increase of life was secured for a very small initial extra cost, since labour was a higher fraction of cost than steel.

The airplane is the standard example of *increase in pay load* being valuable. We may think of airplanes as being made from light alloys, but typically 15 per cent of the unloaded weight is in alloy steels. In the case of heavy truck chassis again it is reckoned to be worth dollars to save pounds of dead weight and this is easily done by using alloy steels. In one design of petrol transport tank wagon, alloy steels saved 1400 lb. of dead weight, allowing higher pay load and saving $ 300 per annum in delivery costs. This case overlaps into the field of *lower operating costs*, but the outstanding case here is that of land power stations. The progressive rise in steam temperatures and pressures which use of more advanced steels for boilers and turbines has permitted since 1900 has been responsible for a fall in the average coal consumption per kilowatt generated in the U.S. from over 6 lb. to approximately 1 lb., striking testimony to the power of special steels to allow increased efficiency. As regards *greater safety*, a clear case is that of pressure vessels, where deflection is of little consequence and design is based on tensile stress. With a given factor of safety (ratio of applied stress to yield point) of 1·83, a carbon steel could be used only to 18,000 p.s.i., but a suitable alloy steel could be stressed to 54,500 p.s.i. If one were content to lower the alloy steel working stress to double that of the carbon steel, a much increased safety factor would result. Moreover, as Climax Molybdenum point out, even when used at 54,500 p.s.i. the alloy steel has a much higher margin of stress (45,000 to 15,000 p.s.i.) separating the service stress from the yield point. Other cases of increased safety are easily envisaged, where corrosion is a serious factor in service and cannot adequately be guarded against with a non-alloy steel, but is automatically looked after in alloy materials. Such cases also involve lower maintenance. On the subject of *lower maintenance*, a striking case is that of the U.S. ' stainless steel ' trains, the Zephyrs, of which one-fifth of the weight is in stainless steel. According to our authority, ' Perhaps the biggest pay-off for the operators came in 1949 with the first major overhaul of the Denver Zephyrs after 13 years' operation and more than 4,500,000 miles of service (ordinary trains of carbon steel require such an overhaul after much shorter periods). There was no evidence of any corrosion of the stainless steel members of the Denver Zephyrs, but the carbon steel details (filler strips, partitions, conduit and junction boxes) had to be completely replaced. Otherwise the trains needed only renovation and redecoration. These trains had also shown outstanding advantages in pay load and reduction of operating costs.

In the face of such specific examples of the ' pay-off ' to be gained by the use of alloy steels, it is felt that no hesitation should be shown in making alloy steels available to the Indian engineer on the basis of indigenous production. By analogy with other countries, when steel production reaches 6,000,000 tons, an alloy steel potential of 300,000 tons ought to be provided for, of which about 30,000 tons might be stainless steels and perhaps a tenth of this in tool and special steels, the greater bulk being low-alloy constructional types. Some provision seems to be contemplated for stainless and tool steels at Bhadravati (The Mysore Iron & Steel Works) where ferro-alloy production is also in hand, but so far little thought has been given to making the constructional types in India, provision for these being made neither in the new Government steel plants nor in the expansion schemes of the present main producers. Since the special difficulties of alloy steel manufacture are well understood, it is felt that a real effort should be made to undertake the production of these steels in India, either by setting up a separate alloy steel plant or building up selected small producers, on the basis of indigenous resources, once Indian ferro-alloy manufacture has been taken up more actively — as is hoped shortly to be the position.

In the foregoing, apart from references to silicon steels, austenitic stainless steel, cutlery stainless, high-speed tool steel and Hadfield manganese steel, the case for alloy steels has been made in rather general terms. It now appears desirable, even in this introductory paper, to detail a little more closely the classes of alloy constructional steels believed to be required by India. Furthermore, since this contribution comes from a research establishment, consideration needs to be given to the extent to which research is called for in finding steels to meet the detailed needs.

According to the writer's view, the main classes of alloy constructional steels most wanted in India are the following:

(i) An alloy case-hardening steel with good core strength.

(ii) A steel of medium carbon content which will oil-harden in sections up to $1\frac{1}{8}$ in. diameter allowing use at 70 tons/sq. in.

(iii) A steel of similar carbon content which will air-harden in small sections and oil-harden fairly fully up to $2\frac{1}{2}$ in. diameter, allowing use at 70 tons/sq. in.

(iv) A steel of similar carbon content which will air-harden up to $2\frac{1}{2}$ in. diameter and oil-harden in larger sizes, allowing use at 80 tons/sq. in.

(v) A high-carbon alloy steel suitable for ball and roller-bearings.

To these might, of course, be added a variety of other specialized types including, for example, nitriding steels and a free-cutting variety (leaded) of the case-hardening steel. It is believed that availability of good steels representative of these classes would meet 90 per cent or more of the demands and potential demands for alloy steels and enable considerable advances to be made in engineering construction. The classes of steel enumerated form a series somewhat along the lines met by the British En series of steels covered by B.S. 961, but of a less ambitious and widely embracing nature. It will be seen that it is proposed to retain the feature of B.S. 961 by which use of given steels in a given tensile range is encouraged only in sections of defined cross-section in which the alloy content is economical. In U.K. and other countries, the standard steels in several of these classes make extensive use of alloying elements which are non-indigenous in India and it is a question for Government to decide as a matter of high policy whether to follow the lead of other countries and start the alloy steel industry here on the basis of these non-indigenous types. Such a policy would have the advantage that it could be implemented directly, without waiting for the results of research.

More probably, however, Government will decide to aim to use non-indigenous alloying elements sparingly or even to reserve them completely for cases where they are indispensable. How then would this affect the picture? Experience abroad during the periods of alloy shortage during and immediately after the war has thrown up steels which are more economical in alloying elements than, but at the same time fully equivalent in depth of hardening to, the standard steels. For these to be specified in India, all that remains to be done is to select the best types on the basis of their equivalence in resistance to low-temperature embrittlement and to control the early stages of production. One possible first selection of steels is referred to below:

(i) *En* 325 — Low-nickel-chromium case-hardening steel, suitable for a tensile strength of 55 tons/sq. in. Composition: 0·17-0·22 per cent C; 1·50-2·00 per cent Ni; 0·40-0·60 per cent Cr; 0·20-0·30 per cent Mo. This steel is refined at 850°-880°C. after carburizing and oil-hardened from 770° to 800°C. In $1\frac{1}{8}$ in. diameter it gives minimum 55 tons/sq. in. tensile strength in the core with elongation 15 per cent minimum and at least 35 per cent reduction of area.

(ii) *En* 18 — One per cent chromium steel, suitable for a tensile strength of 55 tons/sq. in. as $1\frac{1}{8}$ in. bar. Composition: 0·35-0·45 per cent C; 0·80-1·10 per cent Cr. The steel may be hardened from 850° to 870° C. and tempered between 560° to 700°C. If the composition is at the bottom of the range, water-hardening may be necessary, otherwise oil-hardening is satisfactory. In $1\frac{1}{8}$ in. bars, it gives minimum 55 tons/sq. in. tensile with 18 per cent elongation and 40 per cent reduction of area. In $2\frac{1}{2}$ in. bars it is still capable of giving a good combination of properties when hardened and tempered to a strength of 50 tons/sq. in. or less.

(iii) *En* 19 — One per cent chromium-molybdenum steel (or *En* 24, $1\frac{1}{2}$ per cent nickel-chromium-molybdenum steel). The first of these steels has the composition: 0·35-0·45 per cent C; 0·90-1·50 per cent Cr; 0·20-0·40 per cent Mo. It is oil-hardened from 850° to 870°C. and tempered between 550° and 720°C. In $1\frac{1}{8}$ in. bars it is capable of giving a tensile strength of 70 tons/sq. in. minimum, with 15 per cent elongation and 30 per cent reduction of area. As a $2\frac{1}{2}$ in. bar it will give a good combination of properties when hardened and tempered to 60 tons/sq. in. tensile strength. The second steel has the composition: 0·35-0·45 per cent C; 1·30-1·80 per cent nickel; 0·90-1·10 per cent Cr; 0·20-0·35 per cent Mo. It is oil-hardened from 820° to 850°C. and tempered below 660°C. The steel has somewhat greater hardenability than En 19 and may be used as $1\frac{1}{8}$ in. bars at the 80 ton tensile level with a good combination of properties, namely 14 per cent elongation and 25 per cent reduction of area minimum. The decision on a choice between the two steels, however, would mainly rest on the attitude taken to importation of nickel.

(iv) *En* 29 — Three per cent chromium-molybdenum steel. Composition: 0·15-0·35 per cent C; 2·50-3·50 per cent Cr; 0·30-0·70 per cent Mo; not more than 0·40 per cent nickel. This steel is oil or air-hardened from 890° to 910°C. and tempered at a suitable temperature below 750°C. It is suitable for use at 80 tons/sq. in. or even higher as $2\frac{1}{2}$ in. bars. It gives, for example, the following combination of properties when appropriately tempered: tensile strength, 100 tons/sq. in.; elongation, 10 per cent; reduction of area, 10 per cent minimum; at the same time it can be readily softened to below 270 B.H.N.

It is incidentally to a steel of this type, but at the lower end of the carbon range, that India would best turn if she required home production of armour plate for armoured-cars, tanks, etc. The purpose would be served either by rolled plate or castings, preferably the latter, since they are free from risk of 'discing' failure which follows on lamination of rolled plate which contains hair-line cracks.

(v) *En* 31 — One per cent carbon-chromium steel. Composition: 0·90-1·20 per cent C; 1·00-1·60 per cent Cr. This steel is hardened from 800° to 840°C. in oil or water and tempered at 130°-180°C. It occupies a unique position in the ball and roller-bearing field, developing great hardness and wear resistance when tempered as above; it may, however, be readily softened to below 230 B.H.N.

Such a series might, however, be regarded only as a half-way house, as some use would still be made of non-indigenous alloys. It might be possible by research to develop an equivalent series solely on the basis of the alloys indigenous to India. This is, however, something which has not yet been attempted, because in the other countries where substitute steels have been developed the shortages were not quite the same. This would be time-consuming and, even if the policy were adopted as the final aim, much remains to be said for two-stage implementation, where the first stage would be the 'half-way house' referred to above.

Additional to the research needed to define and prove steels for the applications listed above, there are other and more important fields of research on alloy steels which should be attacked in India. Possibly the most important is one referred to at some length in another paper in this symposium, namely finding how to secure consistent and uniform action by alloying elements as regards depth-hardening effects. With existing practice, it is by no means always the case that steels develop the hardenability to be calculated from their composition, and, quite often, rolled steel bars which have been heat-treated do not show smooth gradients of hardness across the section, as they should if the alloying elements act uniformly. Commonly, in fact, the centre of a bar is much less hardened than the depth-hardening characteristics of the outside steel would lead one to expect, while at intermediate positions undesirable peaks of hardness may occur. It is not yet clear whether it will be possible to find a sweeping solution to this source of embarrassment on the basis of new steel-making and/or pit-side practices, but, even short of this, an extremely useful position would be reached if among alternative possible steel compositions those were found in which the hardening differences referred to were kept to a minimum with existing practice. Another large field of research in alloy steels is concerned with the basis of mechanical property specifications and their relationship to service requirements, where complex stressing conditions are imposed, and in particular with demonstrating that steels made in India which have certain conventional mechanical properties are as good service-wise as any steels of the same strength made anywhere in the world.