RECENT DEVELOPMENTS IN ALLOY AND SPECIAL STEELS IN GREAT BRITAIN

TOM BISHOP

Metallurgical Editor, 'Iron & Coal Trades Review', and
Editor, 'Metal Treatment & Drop Forging', London

Abstract

As the availability of alloying elements for the iron and steel industry in Britain tends to stabilize, a review of the current developments in the alloy and special steel field reveals an interesting story of continual and healthy progress. Reference is made to some low-alloy high-strength steels, heat-resistant varieties, tool and die steels, magnetic types, and corrosion-resistant and composite steels, now in production.

IN the post-war era, the alloy and special steel industry of Great Britain was strongly influenced by alloy availability. Nickel, cobalt, tungsten and molybdenum were in very limited supply, and indeed the present situation shows by no means a return to an abundant flow. Nickel is still somewhat restricted, mainly owing to stockpiling programmes, although the molybdenum situation has improved, largely due to expansions at the Climax Mine in Colorado. Emergency specifications were resorted to for conservation of alloys in short supply, and, while some emergency steels were dropped, as alloys returned, much has been learned of techniques for production of other low-alloy varieties, and consequently some are being retained.

Indeed, the need to conserve imported and costly ferro-alloys as well as the difficulty in obtaining some of them at all has focussed the attention of several steel firms, Samuel Fox & Co., for example, on the development of leaner steels for given jobs. The aim has been to provide the user with the same properties for less alloy content and, therefore, to provide him with a cheaper steel. A considerable amount of work was done during the war on this subject, especially on direct hardening steels by taking into account the final section at the heat-treatment stage. A whole range of war-time substitutes have since become British standard steels. Some companies have never looked on these steels as substitutes and have progressively pioneered their use, especially in the motor-manufacturing trade.

During the Korean war, the actual shortage of nickel and molybdenum became very apparent and Samuel Fox & Co. immediately took steps to develop case-hardening steels with less of both these elements by giving some compensation in chromium. A complete new range of British standard steels (the En 350 series) was the outcome of this work in conjunction with other alloy steel makers and these steels were brought into use and adopted fairly widely, with a considerable saving in nickel. However, with the cessation of hostilities and the lifting of the restrictions on the use of nickel, the motor industry was quick to revert to the higher nickel-molybdenum specification again as their experience with the leaner steels had been, in fact, a little disappointing as regards impact values.

Interest has been aroused recently in a 0·5 per cent Mn, 0·5 per cent Mo case-hardening steel for gears etc., and trials on it are now in progress.

On direct-hardening steels, the development of induction-hardening has tended to further the cause of alloy conservation since only the surface layers are severely stressed

TABLE 1 — PROPERTIES OF SOME HIGH-STRENGTH STEELS

Quality	Equivalent En specification	0·1% proof stress, tons/sq. in.	Ultimate tensile, tons/sq. in.	Elongation, %	Reduction of area, %	Impact (Izod), ft.-lb.
G. 8	En 27	82	110	14·0	48	31
G. 11	En 25	81	102	14·0	50	24
G. 5 Spl.	En 24	88	126	12·0	35	20
H. 27	En 40C	84	118	14·0	40	30
R.D.M. 682	—	100	125	12·5	37	16
G. 1 Spl.	En 30B	78	112	14·0	47	42

while it could be shown that boron does increase hardenability, it does not do so enough to raise a steel to a higher category — e.g. it does not allow the use of a 1½ per cent manganese steel (En 15) to take the place of 1½ per cent manganese-molybdenum (En 16). Moreover, the investigation also showed that when boron-treated steels are not fully hardened, as is often the case, the impact value is then considerably lower than for similar steels not boron-treated. As a result, boron steels have not found much favour in Britain, apart from one or two special applications where it is possible that the user was already using a low-alloy steel where a plain-carbon quality might, in fact, have done the job in the first place.

Rare Earths in Steel-making

Although opinions differ as to the effect and degree of benefit of rare earth (e.g. cerium, lanthanum, etc.) additions in steel-making, it has been established that they have a worthwhile place in the manufacture of various types of steel[5]. They should not be regarded, however, as an antidote to bad melting practice, although they may help in improving heats which otherwise would be labelled ' off-colour '.

Most attention has been paid to the use of rare earth compounds in stainless and heat-resisting steels, but it is recognized that rare earth additions are of potential interest in other types of steel. This is mainly due to improved workability and it is emphasized that the advantages of rare earth additions in this connection are best appreciated by the consideration of the total savings in steel, fuel, labour, etc., along the whole fabricating line. In this way they offer distinct possibilities of increasing productivity by turning out more steel at lower cost. Much more work is needed, however, to establish the precise and optimum benefit in any one type of steel.

Lead-treated Alloy Steels

Lead may be added to alloy steels to improve machinability, to increase tool life and to provide better surface finish[6]. The motor industry, with their mass production methods, were quick to see the advantages that these steels had to offer and the adoption by them has been rapid since the war. The results have been pretty much as experienced with lead-treated mild and carbon steels, the lead addition having no effect on the heat treatment and little on the resulting mechanical properties. Recent experiences of users show savings in output times of up to 70 per cent in rough turning and 50 per cent in finishing. Increase in speed and feed of 50 per cent is common, with tool life up to 400 per cent in some cases. The following qualities are regularly produced with lead additions today:

in torsion and no great depth-hardening is needed. Still leaner alloy steels may now be required in consequence. In fact, even plain-carbon steels might be considered for some applications where low alloys had been used before.

Constructional Steels

Recent advances have been made in the development and use of the so-called high-strength low-alloy structural steels. The strength of these steels, on the basis of the yield strength, is about 50 per cent greater than that of structural mild steel. The atmospheric corrosion resistance of some of them is a good deal higher also, and in general their weldability, notch toughness and workability characteristics are as good as, and indeed often better than, mild steel. A wide variety of such steels is available and a recent survey[1] gives trade names, with mechanical properties (including fatigue) and welding characteristics of steels of this type from many countries. A number of suitable alloying elements are available and these steels usually include two or three from the following: manganese, copper, silicon, chromium, nickel, molybdenum, phosphorus, and boron.

In the field of the fully heat-treated steels, due to an easing in the supply position of certain alloying elements, a wider use has been possible of certain En types. The popularity of certain of the emergency case-hardening steels (addendum No. 1 of B.S. 970) continues, and certain economies by virtue of the lower alloy contents are, therefore, still being made. When suitably heat-treated, these economy steels are satisfactory. Recently three new specifications have been added to the B.S. Aircraft Series, viz. S. 118 (55-ton), S. 119 (65-ton) and S. 120 (100-ton).

Extra-high-tensile Steels

It has been said that the theme of ferrous metallurgy requirements and developments of the last 15 years has been sung by the aircraft industry, and a fresh example is given by the latest demands in constructional and engineering steels[2]. There is a growing interest in air-frame and undercarriage parts in a steel having extra-high strength with adequate toughness, giving favourable strength/weight ratios and other characteristics. The minimum mechanical properties stated to be of interest in a typical aircraft requirement are:

0·1 per cent proof stress	85 tons/sq. in.
Ultimate tensile stress	120 tons/sq. in.
Elongation on 2 in.	6 per cent
Izod impact	20 ft.-lb.
Izod impact at −50°C.	10 ft.-lb.

It has long been known, of course, that at low temperatures of tempering, some steels possess very high tensile strengths, and the failure to make use of these has, in the main, been due to the feeling that such steels are in a highly stressed and brittle condition.

A recent report[3], from which the details of Table 1 have been taken, suggests that certain steels, suitably heat-treated, have attractive properties. The work is continuing, but it will be noted that certain compositions such as that of R.D.M. 682 (Table 1) give 0·1 per cent proof stresses of 100 tons/sq. in. with impacts of 16 ft.-lb. and though others give higher impact strengths, the proof stresses are lower. Experimental studies indicate that if quenched parts are sub-zero treated in liquid nitrogen, the tensile properties at room temperature are improved without much change in the ductility figures. Long tempering treatments have also been recommended.

Boron

An interesting study was recently concluded on the possibility of boron being used to raise the hardenability of direct hardening steels. One investigation by Samuel Fox[4] was very thorough. The outcome was that, En 24 — 1½ per cent nickel-chromium direct-hardening steel.

En 36 — 3 per cent nickel-chromium case-hardening steel.

En 39 — 4¼ per cent nickel-chromium case-hardening steel.

Low-alloy Steels for Corrosion Resistance

Certain low-alloy steels, without having the complete immunity from atmospheric corrosion of the stainless steels, are much more resistant in the open air than ordinary steel, say up to six times so. They owe their superior rust-resistance, not to the presence of an oxide film upon them, but to the fact that, although they rust at first like ordinary steel, the rust formed on them is more compact and less permeable to air and moisture, so that in time it builds up an effective barrier against further rusting. The simplest of these steels contain about a quarter per cent of copper and few have more than 2 or 3 per cent of alloying elements. Consequently, they are relatively cheap, and their potential output is unrestricted. One of the best is only about one-third dearer than ordinary steel. Moreover, because of their small alloy content, their possible output should not be limited by the availability of materials. The value of these steels has been fully confirmed by experience. Service trials on steel coal wagons on British Railways have already indicated that floor plates of such low-alloy steels will last at least twice as long as plates of ordinary steel.

A typical example of a high-strength, low-alloy steel, which has a superior resistance to corrosion (also good workability, high resistance to abrasion, impact, fatigue and good welding properties) is Cor-Ten steel. Hot-rolled plate and sheet (⅜ in. and thinner) in this steel has a yield point of 22 tons/sq. in. min., a tensile strength of 31 tons/sq. in. min., with 22 per cent elongation. The percentage composition is: C, 0·12 max.; Mn, 0·20-0·50; P, 0·07-0·15; S, 0·05 max.; Si, 0·25-0·75; Cu, 0·25-0·55; Cr, 0·30-1·25; and Ni 0·65 max. A further example will be described by another contributor at this symposium.

Another new low-alloy special steel will now be mentioned. The possibility of catastrophic brittle failure must always be considered by engineers designing large welded structures, particularly those which may be required to operate at low temperatures. While much of the risk can be eliminated by proper attention to design and workmanship, there are instances in which there is justification for the use of material with less propensity to this type of failure than ordinary mild steel. To meet such requirements Colvilles Ltd. has marketed a special notch tough steel with good resistance to brittle fracture known as COLTUF steel. Practical experience has confirmed the superior toughness of mild steel with a high manganese/carbon ratio and a fine ferritic structure. A typical composition for this steel is: C, 0·13 per cent; Si, 0·15 per cent; S, 0·03 per cent; P, 0·02 per cent; and Mn, 1·1 per cent. The tensile strength of plates up to 2 in. thick falls within the range 28-32 tons/sq. in. A sub-zero temperature notch-bar impact test is carried out on every plate supplied.

Corrosion and Heat-resisting Steels

The post-war developments in corrosion and heat-resisting steels are quite phenomenal, especially in the latter category, spurred as they are by the ever-increasing demands of the gas turbine. For a full report on high-temperature steels and alloys for gas turbines, one of the best sources of information is Special Report No. 43 of the Iron and Steel Institute (July 1952), although advances have naturally been made since. The report contains 36 papers in almost 400 pages. It will be realized, therefore, that in reviewing recent developments in Britain in the relatively short space of the present paper, remarks must of necessity be cursory, and recent work carried out by the many alloy steel firms and research organizations cannot be fully covered. Indeed, the author extends his apologies to all those companies whose important work he cannot describe in this relatively short paper.

Stainless Steel

The work on alloy conservation already mentioned has not been confined merely to low-alloy steels, and research has been carried out into alloy steels[6]. In fact, the nickel situation since the war has necessitated the strictest economy of nickel. The difficulty in making worthwhile nickel reductions in austenitic steels, however, is very great if the resulting alloy is to be readily manufactured and used. Up to very recent times, most of the research on this subject has gone into the development of straight chromium ferritic steels containing 17 per cent chromium and low carbon (sometimes called stainless irons).

By good tool design quite a lot of complicated press work can take place with sheets made from these nickel-free steels and additional research was concurrently put in hand to improve the weldability of these ferritic steels, which are so prone to grain growth at temperature with resulting embrittlement. However, in spite of a fair amount of success in the promotion of the uses of straight chromium stainless steels in the sheet-fabricating industries, as soon as nickel restrictions were lifted after the Korean war, it is significant that most of the users immediately changed back to the austenitic qualities again. It seems that the market for these straight chromium type stainless steels is to be confined to fabricators doing work little more complicated than bending and roll forming, and if American industry is any guide, they will mainly find their use in the motor trade for the bright trim work on cars.

However, the basic problem of producing austenitic stainless steels capable of being fabricated and welded like the conventional 18/8 chromium-nickel types was not solved by this particular investigation. Very recently work has started again on types of austenitic stainless steels where some of the nickel is replaced by manganese together with some nitrogen, which is another powerful austenite former. The resulting alloys have fairly stable austenite at room temperature and as they are free from intergranular corrosion, they do hold out a prospect of providing a stainless steel which can be readily fabricated. However, much of this development work on these steels is yet in its early days, especially the hot-working characteristics do need to be explored some more, but it is expected that they will, nevertheless, find an increasing use in the future.

Many and great demands have been recently made by the chemical and petroleum industries, atomic energy plants and others, for corrosion-resistant steels. The wide range of well-known stainless steels has been satisfactory for most purposes. A highly corrosion-resistant austenitic alloy containing copper and molybdenum continues to be of considerable use in the cast condition, and recent developments have suggested that a forgeable material of this type can be produced.

As well as the stainless steels containing 17 per cent chromium, mentioned earlier, certain chromium-manganese stainless steels are in use, mainly in the U.S.A.[7] If a fully austenitic structure is required, using manganese and chromium alone, then the manganese content must be at least 13 per cent if the percentage of chromium is 13. However, alloys containing 18 per cent Cr with manganese in the range 6-14 per cent can be rendered austenitic by the addition of 0·1-0·15 per cent N and 2-6 per cent Ni. One grade in regular commercial production in the United States contains 15 per cent Cr, 16·5 per cent Mn, 1 per cent Ni, 0·15 per cent

N and 0·1 per cent C. Its properties are similar to 18/8 grades in most respects.

The hardening of stainless steel has also received a considerable amount of attention[2]. A number of such steels containing small amounts of some of the elements aluminium, titanium, copper, niobium and beryllium, can be suitably precipitation-hardened to give mechanical properties comparable with those of heat-treated constructional steels, combined with a good corrosion resistance. In severe conditions these alloys show, however, that their corrosion resistance has been somewhat impaired by the additions and heat treatment and they are also not completely non-magnetic.

No review of stainless steels would be complete without mention of the extra-low-carbon grades with their good resistance to weld decay. In Britain, the customer demand does not appear to be as high as in the United States, but some makers have mastered the technique of the production of such steels in the arc furnace with carbon contents of 0·03 per cent max.

One of the difficulties hindering the use of the stainless steels for structural purposes, apart from material cost, has been that the most corrosion-resistant members of the family have characteristically low values of yield strength and cannot be hardened by heat treatment, i.e. the austenitic 18/8 steels. This limitation applies particularly to transport engineering where economy of weight is of prime importance.

The three known ways of meeting a requirement for a high-tensile stainless steel are as follows[8]: (1) martensitic transformation, (2) precipitation-hardening, and (3) cold-rolling or drawing. The first of these has until recently involved the disadvantage of somewhat reduced corrosion resistance and limited weldability, e.g. 13 per cent chromium steels and the 16 per cent Cr, 2 per cent Ni steels similar to 2S.80. No entirely satisfactory precipitation-hardening stainless steel has yet been produced in bulk. Cold work has, of course, been the most useful of these alternatives, as it can be applied to the 18/8 steels, and in this way it is possible to combine high strength with good corrosion resistance.

Meikle[9] has referred to possible new requirements of the aircraft industry, arising from the advent of very high speed aircraft, for skin materials to withstand temperatures in excess of 150°C., such as may be reached by kinetic heating at speeds greater than Mach 1·65. The corrosion resistance, high proof stress and Young's modulus values up to 300°C. of the 11-13 per cent Cr steels suitably heat-treated would make these an obvious first choice for high-speed aircraft.

Many claims have been made for precipitation-hardening stainless steels, including some which remain fully austenitic after hardening and others which must have a ferritic structure for the hardening to be effective. The fully austenitic group includes steels with relatively high carbon contents up to 0·5 per cent, and sometimes with additions of titanium and/or aluminium up to 3 per cent, or of beryllium or boron. These may fall short in terms of corrosion resistance on account of grain boundary carbide precipitation or because they are difficult to hot work.

The second group is mainly based on the 17 Cr, 7 Ni composition and an essential prerequisite of precipitation-hardening is to transform them to quasi-martensite, which for the present purposes will be called martensite, and then apply a final low-temperature hardening treatment at 350° to 550°C. These steels[8] are of particular interest because of their low carbon content and the possibility of producing sheets in a soft austenitic condition suitable for stretcher flattening and forming and of subsequently hardening the component at about 700°C. or less where distortion problems may not be prohibitive. Moreover, in comparison with the low-carbon 11 per cent Cr steels, the 17 Cr, 7 Ni steels offer somewhat greater resistance to corrosion in marine atmospheres. American steels of this type depend on the metastability of the austenite, characteristic of 17 Cr, 7 Ni steels, and on additions of up to 1 per cent of titanium and/or aluminium which permit precipitation-hardening of the low-carbon alloy martensite produced by a suitable intermediate heat treatment.

Effect of Tempering

Mr. Truman of the Brown-Firth Research Laboratories has described an investigation[10] in which a quantitative study was made of the effect of these treatments on three steels of differing carbon contents and it was found that corrosion resistance can be markedly affected by the tempering treatment.

Tempering temperatures below 400° to 450°C. appear to be safe, but above this temperature the corrosion resistance is lowered. The maximum effect occurs within the range 500°-650°C. Above this range the effect drops again, but in the case of 0·23 per cent and 0·29 per cent carbon steels, the materials do not attain the resistance of the 'as-hardened' condition. It is considered that the effect is due to chromium impoverishment resulting from the precipitation of chromium carbide and the carbon content has a determining control on the severity of the reduction of corrosion resistance. Thus, 0·06 per cent carbon material, unlike 0·23 per cent and 0·29 per cent carbon steels, was resistant to flowing tap water in all conditions. Moreover, although the 0·06 per cent carbon material did show a lowering of resistance to 3 per cent sodium chloride solution in the 500°-700°C. tempered range (maximum 600°-650°C.), its resistance after 750°C. tempering was comparable to that of the 'as-hardened' material. This was not the case with the 0·23 per cent and 0·29 per cent carbon steels. The attack was always of a pitting type and with the intermediate tempering temperatures was of a selective intercrystalline nature.

Clad Steels

In most of the corrosion problems encountered in chemical engineering, it is only the surface in contact with the corroding medium which need be of stainless steel or special alloy. It is, therefore, clear that if the strength portion of the vessel can be constructed of mild steel and a method can be found for protecting one surface, then such a process will have obvious economic advantages; hence many attempts have been made to manufacture clad metals.

Colvilles Ltd., for example, have introduced a series of clad steels under the trade-name of COLCLAD. These are now manufactured on a large scale by a process developed in their research laboratories. Clad steels do not only offer economic advantages, there are many other benefits to be derived from their use, e.g. where heat transfer is important. Further, because of restrictions on the weight of the ingot which can be satisfactorily cast in stainless steel, it is possible to manufacture clad plates in much larger dimensions and greater thicknesses than is practicable with homogeneous stainless steel. The wide range of qualities available from cladding is shown in Table 2.

The backing steel is normally of boiler quality, but an important feature of clad steels is that the cladding and backing material can be varied to suit individual service conditions.

Physical Tests — When broken in tension, the specimens behave as a homogeneous plate, there being no sign of separation. The results (examples given in Table 3) are usually slightly higher than would be expected from the backing material.

Bend tests are normally carried out with the cladding both in tension and compression and are usually capable of being hammered flat after bending. Such clad steels can be successfully hot and cold-formed, hot-spun and welded and gas-cut. They have been used in large quantities in the major

TABLE 2 — NOMINAL COMPOSITIONS OF THE COLCLAD SERIES OF CLAD STEELS

Type	Carbon, %	Chromium, %	Nickel, %	Other elements
14 Cr	0·12 max.	12·00 14·00	0·60 max.	—
13 Cr/Al	0·08 max.	11·50 13·50	0·60 max.	Aluminium 0·10-0·30%
18/8	0·10 max.	17·00 min.	8·00 min.	—
18/8 Ti	0·10 max.	17·00 min.	8·00 min.	Titanium not less than 4× carbon
18/8 Cb	0·10 max.	17·00 min.	8·00 min.	Columbium (Niobium) } not less than 10×carbon
18/10/2 Ti	0·08 max.	17·00 min.	10·00 min.	Molybdenum not less than 2·00% Columbium (Niobium) } not less than 5×carbon
18/10/2 Ti	0·08 max.	17·00 min.	10·00 min.	Molybdenum not less than 2·00% Titanium not less than 3× carbon
'AT' Nickel	0·05 max.	—	99·00 min.	—
'L' Nickel	0·02 max.	—	99·00 min.	—
Monel	0·15 max.	—	67·00	Copper 30·0% (nominal)

TABLE 3 — PHYSICAL PROPERTIES OF SOME COLCLAD STEELS

Type	Total plate thickness, in.	Percentage cladding, %	Tensile strength, tons/sq. in.	Yield point, tons/sq. in.	Elongation on 8 in., %
14% Cr	0·90	25	30·7	19·2	25
14% Cr	2·00	10	29·4	18·4	25
18/8 Cb	0·18	20	33·4	26·5	21
18/8 Cb	0·75	15	30·6	22·8	24
18/8 Cb	0·50	20	29·8	23·6	26
18/10/2 Cb	0·37	30	32·5	22·0	27
18/10/2 Cb	0·68	20	30·2	21·2	26
18/10/2 Cb	1·50	15	29·0	21·0	23

Backing steel in each case manufactured in accordance with British Standard Specification 14, 1942.

petroleum and chemical developments throughout the world.

High-temperature Service Steels

Steels for use at elevated temperatures constitute what is probably the most rapidly expanding section of the alloy steel industry. Temperatures and oxidizing conditions to be withstood vary from superheated steam (Table 4) to hot corrosive gases and ash in various types of gas turbine.

Samuel Fox & Co., for example, has been especially concerned with superheater tube steels for operation at 950°F. and a great deal of research work has gone into a 2¼ per cent chromium-molybdenum steel for this work, together with an 18 per cent chromium, 13 per cent nickel and 1 per cent niobium stainless steel for even higher temperatures and

TABLE 4—TYPICAL COMPOSITIONS AND HEAT TREATMENTS OF STEAM PIPE AND SUPERHEATER TUBE STEELS[11]

TYPE OF STEEL	C, %	Si, %	Mn, %	Ni, %	Cr, %	Mo, %	V, %	Nb, %	INITIAL HEAT TREATMENT
Plain carbon	0·12	0·15	0·60	—	—	—	—	—	Normalized 900°-950°C.
C-Mo	0·10	0·35	0·60	—	—	0·50	—	—	Normalized 940°C.
1% Cr-Mo	0·10	0·35	0·60	—	0·80	0·50	—	—	Normalized 940°C.
Mo-V	0·10	0·25	0·60	—	up to 0·50	0·55	0·25	—	Normalized 975°C. Tempered 690°C.
2¼% Cr-Mo	0·10	0·35	0·50	—	2·25	1·00	—	—	Annealed 940°C.
Austenitic (18/12/1 Nb type)	0·10	0·60	1·25	12·0	18·00	—	—	1·0	Air-cooled 1050°C.

power station designers have now a new form of creep tests for this work. These tests were devised to determine high temperature performance of bolt steels under constant strain conditions as opposed to properties under constant load (normal creep conditions). These relaxation tests provide better design criteria than normal creep tests, and in fact show that higher initial stress at constant temperature results in higher residual stress. The tests have also shown that reloading, i.e. retightening a bolt, results in even better relaxation properties.

Work at the National Physical Laboratory, at Teddington, Middlesex, England, on the determination of creep data for steels used in high-temperature steam power plant produced results[12] of 10,000-hr. creep tests carried out at temperatures from 500° to 800°C. on specimens machined from steam pipes and superheater tubes. Two and a quarter per cent chromium, 1 per cent molybdenum, and 18 per cent chromium - 12 per cent nickel - 1 per cent niobium steels, and also steam pipes of molybdenum-vanadium steel are being tested. Creep and relaxation tests taken in circumferential and radial directions from a specially made rotor forging in molybdenum-vanadium steel are in hand, and results of creep tests in the temperature range 530°-650°C. for periods up to 10,000 hr. indicate that the creep resistance is fairly uniform throughout the forging.

Tests to determine the relaxation properties of bolt steels have been continued for 10,000 hr. on molybdenum-vanadium, chromium-molybdenum and chromium-molybdenum-vanadium steels at temperatures in the range 450°-650°C.

Design data are also required on steels used for cast turbine casings, and data based on creep tests of a molybdenum-vanadium cast slab in the range 530°-650°C. for periods of up to 10,000 hr. have been obtained. Further work on similar cast slabs of other steels is contemplated.

A study of the effect of the addition of other elements on the creep properties of 7 per cent chromium steels has continued at the N.P.L. The effect of various amounts of carbide-forming elements has been studied and results of short-time creep tests have indicated that alloys containing additions of 2 per cent molybdenum and 0·5 per cent titanium have relatively good creep resistance. It is hoped that further work on alloys of this type will make it possible to develop a steel suitable for use in superheater tubes in power plants using steam at temperatures above 575°C.

At higher temperatures, considerable use has been made of the heat-resisting properties of chromium, and a material[13] containing 0·06 per cent carbon and about 20 per cent chromium, which possesses excellent resistance to oxidation scaling at temperatures up to about 1000°C., is used for parts which are not to be submitted to high stress. Such material can be pressed cold, but there have been a number of practical difficulties. However, a fairly wide use is now being made of the 17 and 20 per cent chromium irons for such applications as television cones, sink units and other pressed parts.

Of recent years, attention has been given to improving the creep resistance of the ferritic stainless steels[14], e.g. R.ex 448 (carbon, 0·1-0·2 per cent; chromium, 10-13 per cent; molybdenum, 0·6-0·9 per cent; vanadium, 0·1-0·2 per cent; and niobium, 0·3-0·6 per cent), whose short-time creep-resisting properties compare favourably with those of the stabilized 18/8 chromium-nickel austenitic stainless steels, but the evidence indicated that the ferritic steel becomes increasingly inferior to the 18/8 type when times of more than 1000 and 2000 hr. in the temperature range of 550°-650°C. are involved.

As a result of investigations on creep resistance and constitution of the H.R. Crown Max. type of steel, having a nominal composition of: carbon, 0·2 per cent; silicon, 1·6 per cent; manganese, 0·4 per cent; chromium, 23 per cent; nickel, 11·5 per cent; and tungsten, 3 per cent; it was found that the tungsten content could be reduced without serious detriment to the general properties. When the alloy shortage developed, it was decided that for certain applications the tungsten content of the H.R. Crown Max. type of steel could be reduced without affecting service performance and H.R. Crown 1, containing less than 1 per cent tungsten, was adopted for centrispun castings for use in aircraft.

A steel[13] containing approximately 0·25 per cent C, 17 per cent Ni, 16 per cent Cr, 2·5 per cent Mo, 7 per cent Co, and 1·8 per cent Nb, has been developed which possesses improved creep resistance as compared with previous austenitic steels, combined with good creep ductility and excellent forging properties.

Until comparatively recently, the rotating turbine blades themselves have in Britain been the exclusive province of the nickel-base precipitation-hardened alloys (Nimonics), but there are signs that other materials may supplant them for the most severe conditions. An iron-base alloy G. 42B (Jessop's) has already run successfully in one of the most advanced jet engines, and for operating temperatures exceeding 900°C. it is one of the strongest wrought alloys yet available. The properties of this alloy are given in Table 5, and it can be seen that for a life of 100 hr., which is more than adequate for fighter jets, a satisfactory working stress can be sustained at temperatures approaching 950°C.

This latest achievement with a relatively low alloy content (15 per cent nickel, 29 per cent chromium, 25 per cent cobalt, 32 per cent iron) has been made possible by an intensive development of the process of warm-working which was used for the manufacture of tens of thousands of turbine discs in Jessop G. 18B, of which G. 42B is a logical development. So far the alloy has only been used for the short-life jet engine, but already long-

TABLE 5 — STRESS-TO-RUPTURE PROPERTIES OF JESSOP G. 42B BLADING ALLOY

Temperature, °C.		750	800	850	870	900	950
Stress to rupture (tons/sq. in.) in	30 hr.	21·5	16·7	13·1	11·3	9·0	6·9
	100 hr.	19·3	14·4	11·0	9·0	7·1	5·1
	300 hr.	17·4	12·5	9·2	7·2	5·7	3·9
	1000 hr.	15·4	11·0	7·6	5·7	4·5	2·9

time creep tests up to 2000 hr. have been carried out, and the alloy may find use in the heavy gas turbine industry.

Other wrought turbine blade alloys are under development[12] and it is interesting to note here the increasing world interest in vacuum melting. Producers of special alloys in the United States and several firms in Europe have installed such equipment. One of the first commercial vacuum-melting installations in an English steelworks laboratory has already made hundreds of experimental melts.

In some of the stationary gas turbines, there are troubles with fuel ash, particularly from vanadium pentoxide, which limits the maximum temperature of operation. Troubles also emanate from peat and coke fuels, especially from sodium sulphate and chloride, which can be highly corrosive at elevated temperatures. There seems at present to be no metallurgical solution to these forms of corrosion, and would appear to be a field for future research in any country which would intend utilizing such fuels.

In general, stainless types of materials are being used increasingly for both gas and steam turbines. For multistage land gas turbines, materials may range from stainless iron with and without molybdenum to austenitic steels[13], e.g. FCB(T)* and 326 steels (*see* Table 6). Nimonic alloys are also used, of course. Turbo-blowers built on gas turbine lines are using 467 steel extensively. Aircraft gas turbines use Nimonic almost exclusively. Steam turbines use lots of stainless iron with limited use of stainless iron plus molybdenum. There is a limited use of austenitic steels, for martensitic steels are preferred. It is likely that complex martensitic steels such as the 448 already mentioned may be used in the future in gas and steam turbines for temperatures of the order of 550°C. Turbine discs in all newer designs use a complex martensitic stainless steel.

Land gas turbines are using austenitic steels of the FCB(T) and 326 types or MoV type steels. Austenitic steels in large masses such as solid rotors are still very difficult to produce. The largest austenitic steel rotor in the world was produced in 326 steel by Brown-Firth. The dimensions were as follows: 33 in. body dia. by 73 in. body length; total length 197 in. and weight as forged 11½ tons.

Austenitic steels with creep properties superior to 326 are available, but it is unlikely as yet that they will be used for, say, rotor shafts in view of the difficulties likely to be encountered in manufacture. Where

TABLE 6 — TABLE OF COMPOSITIONS OF ALLOYS FOR GAS TURBINE BLADES[14]

MATERIAL	ANALYSIS, PER CENT										
	C	Ni	Cr	Mo	W	V	Co	Nb	Ti	Cu	Al
Nimonic 80A	0·05	77·0	20·0	—	—	—	2·0 (max.)	—	2·50	—	0·5-1·8
Nimonic 90	0·10 (max.)	Rem.	18·0-21·0	—	—	—	15·0-21·0	—	1·80-2·70	—	0·8-1·8
S. 816	0·40	20·00	20·0	4·0	4·0	—	44·00	4·00	—	—	—
G. 32	0·27	10·50	19·1	2·2	—	3·00	46·60	1·40	—	—	—
R.ex 448	0·10-0·20	—	10·0-13·0	0·6-0·9	—	0·10-0·20	—	0·30-0·60	—	—	—
FCB(T)	0·10	12·00	18·0	—	—	—	—	1·20	—	—	—
362	0·25	17·00	16·0	2·5	—	—	7·00	1·80	—	—	—
337	0·20	17·00	16·0	3·0	—	—	7·00	—	0·80	3·00	—
R.ex 467	0·20	9·50	14·5	2·0	—	—	—	—	0·80	2·50	—

built-up rotors are used, e.g. discs welded together, the manufacture of discs as against solid rotors is easier, but the welding together of the discs is a difficult proposition.

Ferritic (or martensitic) rotors are not particularly limited as to size of forging, but of the steels commercially available to date, metal temperatures must be limited to about 525°-550°C. Forty in. dia. solid rotor shafts have been made. Steam turbine rotors are exclusively ferritic. To date, the MoV type represents the highest level of creep resistance available for this purpose. The 448 steel is being used for the smaller gas turbines (e.g. Ruston Hornsby type, Napier turbo-blower and W. H. Allen type).

For further information on high-temperature steels and alloys, interested metallurgists are recommended to study the Iron and Steel Institute Special Report No. 43.

Tool Steels

In the field of tool steels, the influence of alloy availability has played an important part in the post-war period[13]. Many of the high-alloy high-wear type of high-speed steels are often adaptations of older, well-known varieties, and are characterized by a high alloy content, especially of cobalt and/or vanadium, sometimes associated with carbon contents of up to 1·5 per cent.

A steel with 2·5-3·0 per cent molybdenum, 3 per cent vanadium and 2·5-3·0 per cent tungsten proved to be satisfactory for planing and milling cutters and for twist drills, rivalling steel with 1-1·5 per cent vanadium and 18 per cent tungsten, but its lack of toughness prevented its use for fine drills. A steel with 1·6 per cent vanadium and 9 per cent tungsten is said to be equal to one containing 1 per cent vanadium and 18 per cent tungsten for drilling and milling. Cobalt-coutaining steels are preferably reserved for heavy turning, where hardness at red heat is required; 3-5 per cent cobalt is usually adequate, higher contents being necessary only for special uses. Steels with high vanadium content are recommended for tools subject to heavy wear.

For many cold-working applications such as blanking, pressing, punching, etc., the well-known ranges of tool and die steels can be said to be adequate for most production runs, and development of new types has not received much attention until quite recently[2]. With the growing use of cold extrusion, especially for steel parts, and of thread rolling, new demands have arisen. Not only are high compressive strength and wear resistance needed, but toughness (i.e. freedom from chipping tendencies) must be adequate. For the punch in cold-pressing operations, high-speed steels based on tungsten and on molybdenum, but having a lower carbon content than usual, are being used with success. High-carbon, high-chromium steels with molybdenum and vanadium additions are also recommended, especially for thread rolling.

For the extrusion, forging, pressure die-casting, etc., of metals, a wide variety of hot-work steels is available — some, in fact, are quite new and their full capabilities are not yet known. For the extrusion of non-ferrous metals, the dies are generally made of steels such as the 10 per cent tungsten, 5 per cent chromium-molybdenum-tungsten, 5 per cent chromium-molybdenum-vanadium and 6 per cent tungsten-nickel-chromium types. When extruding copper alloys, however, the conditions of service involve more severe temperatures and abrasion, and a steel containing 12 per cent tungsten, 12 per cent chromium and a cobalt-base creep-resisting alloy, has given good results. The use of a creep-resisting alloy as a hot-work material is an interesting though logical development.

High-speed Steels

One problem that is being tackled energetically is the reduction in friction between the high-speed steel and the workpiece. A step in this direction is the use of steam tempering, which is being used to an increasing extent for drills and similar components. After the tools have been hardened, tempered and ground, they are loaded into a steam atmosphere at about 350°C., and after one hour of such treatment gradually brought up to a temperature of 550°C. with the steam turned off. The tools then have a blue finish, and it is this surface which has the antifriction properties. Whether such a finish is better than certain proprietary chemical finishes has yet to be finally proved, but steam-tempered drills are certainly better than those having no surface treatment. Another treatment is one in which the surface layers of the tools are sulphurized in a salt bath — increased lives of taps and drills are claimed.

The analyses for high-speed steels are legion and, broadly, the 18 per cent tungsten type is the most important general purpose alloy, although the picture is changing. It should be stated here, however, that a comparison of British practice with that of other countries shows great differences[15]. The contrast with the U.S.A. is very marked. In the U.S.A. 18 per cent tungsten has been largely abandoned in favour of Mo-W and Mo steels. For the first five months of 1954, 82 per cent of total deliveries were accounted for by these types, chiefly 8½ per cent Mo 1½ per cent W ('M-1'); 5 per cent Mo 6¼ per cent W ('M-2'), and 8 per cent Mo ('M-10'). 'M-2' is used most, representing 42 per cent of the total, but substantial quantities of 'M-1' with 21 per cent and 'M-10' with 14 per cent are also produced. The two latter are cheaper, but some manufacturers consider them superior for certain tools, notably drills.

It is easy to understand the American's preference for molybdenum-based high-speed steels. The reason is mainly cost. Generally speaking, the use of 18 per cent tungsten is considered extravagant. Further, its price is unstable and the violent fluctuations over the last few years have caused heavy losses to large users. Even if equal prices for molybdenum and tungsten are assumed, it is obvious that the savings made in reducing tungsten from 18 per cent to 6¼ per cent or 1½ per cent or eliminating it altogether are substantial. Added to this, molybdenum is only about half as heavy as tungsten. Molybdenum high-speed steels are, therefore, lighter than 18 per cent tungsten and the same weight of steel will yield between 5 per cent and 7 per cent more tools. There is no question of lower quality. It cannot be seriously argued that inferior steels could have established themselves universally in the U.S.A., but in any case, tests in Britain and Europe have confirmed that molybdenum high-speed steels, correctly heat-treated, give performances at least equal to 18 per cent tungsten. For certain tools, notably drills and hacksaws, some results are superior. Although the 5-6-2 and 6-6-2 compositions are in regular production in Britain, there is quite a long way to go before the full economic and technical advantages of molybdenum high-speed steels are reaped.

Further data on the 18/4/1 type of tool steel are provided at this symposium by Ineson and Hoyle, of the British Iron and Steel Research Association.

Manganese Steel

There is practically a *status quo* in the field of hard-wearing manganese steels for crushers, rail points, etc. — in spite of much competition from other wear-resisting materials, and many efforts to improve manganese steel by modifying its composition, the alloy originally cited by Hadfield still holds its own in resistance to conditions of impact and high pressure—a great tribute to its inventor. Austenitic manganese steel contains essentially about 1·2 per cent C and 12½ per cent Mn, and has to be correctly heat-treated.

Magnet Steels

In the specialized field of magnets, as ever, new demands have stimulated the development of steels and alloys which have greatly enhanced magnetic properties and permit a greater economy both of weight and volume. A steel containing 35 per cent cobalt represents the maximum magnetic performance obtainable in carbide-containing materials which can be forged and machined before hardening, but the general trend at present is towards the use of higher efficiency alloys of the iron-nickel-aluminium-copper-cobalt series, which is rather outside the terms of reference of the present paper. A brief reference might be made, however, to the Columax alloy of this type (Swift, Levick & Sons Ltd., Sheffield) which is claimed to possess the highest magnetic energy per unit of volume yet achieved in commercial magnetic alloys. It is manufactured by a special process which replaces the equiaxed crystals of the normal cast alloy by long columnar crystals in a preferred direction coincident with the direction of magnetization of the magnetically heat-treated and finished magnet.

Conclusion

In a review of this type, it is impossible to examine fully the vast field of all aspects of alloy and special steels. Nothing has been said, for example, of manufacturing methods such as continuous casting, steel extrusion, planetary-well rolling, oxygen lancing techniques, use of radioactive isotopes, or testing methods. The special steels required for nuclear power production will form their own ever-increasing field of study. The current research and development work now being vigorously pursued in Great Britain in alloy steels is, no doubt, some years ahead of present routine production. It is hoped, however, that sufficient has been said here to give at least some indication of the recent developments in progress in special and alloy steels.

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