TAILOR-MADE ALLOY CONSTRUCTIONAL STEELS

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Abstract

In this paper, a general account is presented of methods of substituting brains for excess steel in constructional applications in which steels are consumed in large tonnages. Attention is particularly drawn to the hardenability approach. The specific effects of common alloying elements in steels individually and in combination are outlined. The enhancement of hardenability by small amounts of boron is touched upon and it is emphasized that a little of two or three elements employed in conjunction in ' triple steels ' has often a more potent beneficial effect than the same total alloy content in steel of any one of the three alloying elements. The structural factors in hardenability which are often ignored, are discussed and consideration given to the question of finding the best techniques for securing uniform hardenability in the product of an ingot. The subject-matter has been discussed against the background of indigenous alloying elements and the most effective uses to which they could be put for present and future Indian requirements.

INCREASING specialization in the fields of application and emphasis on utilization of indigenous resources call upon the metallurgical ' back room ' boys to turn out new constructional materials as expeditiously and economically as possible. Although iron resources are plentiful in the world in general and in India in particular, the scarcity of critical alloying elements like nickel, tungsten and molybdenum is causing much thought to be given to conservation of alloys in constructional steels. The metallurgist must ' tailor ' his metallic values and in effect substitute brains for excess steel and alloying elements.

It goes without saying that, whatever efforts are made in other respects, the first requirement in the economic use of steels is that they should be used *as intended*. This may sound platitudinous, but it is still true today, even in the most advanced countries, that the main causes of waste of steels are the use of inappropriate material and the use of material of incorrect dimensions. A component or structure made of the wrong material may be completely useless, as may be one made with under-dimensioned steel. The excess weight in an over-dimensioned structure is equally infructuous. Dimensional control is easier to exercise than compositional control, but may, nevertheless, call for experts and specialized equipment in considerable quantities. Where a diversity of steels is employed, compositional control, prevention of mix-ups and sorting out those which occur are costly aspects. Steel stocks must be purchased to specifications and carefully segregated in store. For alloy steels, it may prove necessary to exercise the same care in the storage of the scrap arising during utilization of the steels as for the raw steel stocks.

Another point in connection with steel economy by reducing sections is the increased importance which must then be given to corrosion protection both prior to and after assembly into the component, machine or building. Equal life must be secured in the reduced section if economy is to result. Localized seats of attack, such as may be caused by cold-work in punching rivet holes etc., must in particular be guarded against. Use of light sections also emphasizes the need to avoid local stress-raisers, such as may arise from faulty design with neglect to provide adequate fillet radii, bad machining with non-removal of burr, etc., or from corrosion pitting. Use of thin, cold-formed sections will bring into prominence the need to avoid ageing effects which occur in all but very thoroughly killed steels. It will be seen that it is almost always the case that economy in the use of materials can only be bought at the price of more and higher quality technical control in the conduct of operations of manufacture and construction.

In the general engineering field, the possibility of saving weight depends on the nature of the component as well as on the available materials. Stiff, highly stressed components like studs fail when the stress reaches a level at which plastic deformation sets in. Design is, in fact, based on proof stress (or yield point for steels), and the section can be smaller the higher the proof stress. As between steels and other materials, the criterion of applicability is the ratio of proof stress to density. In ordinary carbon steel, the proof stress may have a value of 20 tons/sq. in., but simple heat treatment will bring the value to, say, 35 tons/sq. in., with good properties in other respects, while alloying plus heat treatment may give an applicable material which has a yield point of 80 tons/sq. in. and is thus serviceable to four times the specific stressing. This type of criterion is inapplicable in certain other applications, such as rotating shafts where fouling due to elastic bending is the dominant aspect, and stressed sheet construction where buckling is to be feared. In these cases it is the elastic modulus which is most significant, and this — as is well known — is subject to little variation in steels at room temperature whether as a result of heat treatment or alloying. There is thus no competition between steel and steel for such applications except as decided by price and incidental factors as corrosion resistance, ease of production in the desired form, or retention of properties unimpaired by ageing effects. Competition can be envisaged, however, between steels and alloys based on aluminium, titanium, etc.

In India, steel should not be used where aluminium will serve more economically, for example. Steel should also not be used, in the writer's opinion, where malleable or nodular cast iron would serve. Again, wear-resistant high-manganese steel such as the cast Hadfield steel should not be used where a low-alloy cast iron such as Nihard could equally well be employed. These cases could be multiplied, but the above will serve to indicate the general principles.

In these days most metallurgists approach steels with certain settled views. These include the following:

1. The development of the best combination of mechanical properties in steels is dependent on their having been fully hardened to martensite, tempered back to the desired strength and cooled quickly.

2. Provided the conditions at (1) are complied with, only carbon content is of significance, and the contents of alloy elements play their part primarily in deciding the sections in which full hardening can be secured.

3. The above points need certain reservations both as regards sub-zero and elevated temperature mechanical properties and do not in any case relate to specialized properties such as corrosion resistance, but the point remains that alloying elements are valuable in all these connections as well as under (1) and (2); alloy steels must, accordingly, not be left out of our thoughts when we consider steel production in India from the metallurgical viewpoint.

Alloy steel production in India in both the high-tensible category and heat-treatable constructional range is very limited. Considerable imports are being made of such steels and it is likely that, with increased industrialization, the demand for low-alloy steels in India will be about the same in proportion to the total steel consumption as in other steel-producing countries; if this proves to be the case, India will need some 300,000 tons per annum of low-alloy steels by the end of the Second Five Year Plan period.

As India has no nickel or molybdenum, there would be little merit in undertaking the production of nickel, nickel-chromium, nickel-chromium-molybdenum, or manganese-molybdenum steels or certain other types of steels which are standardized abroad. Rather, the demands should be met by production of manganese, chromium, chrome-manganese steels, etc. Of these, the straight manganese steels have certain disadvantages and are unlikely to meet exacting requirements when the steels are made with electrolytic manganese unless the present impressions are altered. It is, therefore, probable that the bulk of the alloy steel production in these classes will be of chromium-containing types and it is fairly certain that on an average the chromium content will be around 1 per cent; that is to say, there would be need for this purpose of some 3000 tons per annum of chromium or, say, about 4000 tons of ferro-chrome.

In the group of constructional steels, we are normally dealing with steels which are capable of being brought to an austenitic state by heating, so that we do not have to consider the effects of the alloying elements on the equilibrium diagram. Most alloying elements render austenite more resistant to transformation on cooling, with the result that, on cooling at a given rate, the formation of ferrite and pearlite occurs at lower temperatures or is suppressed, when bainite or martensite form, which on tempering give ferrite plus carbide structures. Of the alloying elements used some strengthen ferrite and some form special temper-resistant carbides.

Though the distribution of a particular element may depend on the amount and nature of co-existing elements, the general trends are summarized in Table 1, which indicates the normal amounts of the alloying elements present in the various categories of steel.

Manganese, chromium and molybdenum are the chief elements that promote depth-hardening. Nickel and silicon also help deep-hardening, although to a lesser extent. Phosphorus also promotes depth-hardening whilst sulphur and cobalt have negative effects.

Nickel is one of the most widely used alloying elements in steel. It dissolves in all proportions in the molten iron and forms a solid solution on cooling. Up to about 5 per cent, it increases tensile strength and toughness without decreasing ductility. Nickel also minimizes the tendency towards quench-cracking and distortion. Typical constructional steels contain nickel 3-3½ per cent with 0·3-0·4 per cent carbon, nickel plus chromium steels, e.g. 3 per cent Ni and 0·75 per cent Cr or 4·5 per cent Ni and 1·25 per cent Cr. These latter steels are oil or air-hardening types according to section. Case-hardening steels commonly contain nickel 1-5 per cent. In amounts exceeding 8 per cent, nickel is a constituent of many types of corrosion-resistant and austenitic stainless steels including the well-known 18 : 8 steel.

Additionally to section on hardenability, chromium imparts corrosion and wear resistance to steels. Along with nickel it provides a formidable array of stainless and heat and acid-resisting steels used for a multitude of applications.

Molybdenum as well as improving hardenability, strength and creep resistance (by stabilizing carbides), acts as an antidote to temper-brittleness encountered in Ni-Cr steels; it is commonly added up to 0·5 per cent. Owing to its powerful stabilizing effect on complex carbides, it retards the softening of a steel during tempering, permitting higher tempering temperatures and times with attendant beneficial results on stress-relief and mechanical properties. Molybdenum is also used as this basis in high-speed steels, replacing tungsten.

Tungsten is an essential ingredient of high-speed steels owing to the great hardness it confers on steel after heat treatment and which is usefully maintained at high operating temperatures. Tungsten is also used for

TABLE 1 — DISTRIBUTION OF ELEMENTS IN VARIOUS PHASES AND THEIR AMOUNTS EMPLOYED IN COMMERCIAL STEELS

ELEMENT	DISTRIBUTION					AMOUNTS NORMALLY PRESENT IN COMMERCIAL STEELS AND SPECIAL FUNCTIONS
	Dissolved in ferrite	Combined in carbide	In non-metallic inclusions	Special inter-metallic compounds	In elemental state	
Aluminium	Al	—	Al_2O_3 etc.	AlxNy	—	0·01-0·06% for grain size control. Seldom used as ordinary alloying element except 1·3% in special nitriding steels and up to 5% in special heat-resisting steels.
Chromium	Cr ⟷	Cr	CrxOy	—	—	Under 1·50% in most structural steels. 0·50-4·00% in tool steels, larger amounts in still tube steels, 12-30% in corrosion-resistant 'stainless' steels.
Copper	Cu	—	—	—	Cu when > ±0·8%	About 0·20% in 'copper-bearing' atmospheric corrosion-resistant steels, up to 1% in high yield strength steels, 1-2% in steels for precipitation hardening.
Lead	—	—	—	—	Pb (?)	0·1-0·4% in both plain-carbon and alloy steels to impart free-cutting properties. It does not decrease the strength properties.
Manganese	Mn ⟷	Mn	MnS.MnFeO MnO.SiO_2	—	—	Over 0·25% and under 2% in most structural steels. 12-14% in austenitic castings.
Molybdenum	Mo ⟷	Mo	—	—	—	About 0·20% in constructional steels, smaller amounts in high yield strength steels; 0·50-1·50% in steels for high temperature service; up to 9% in tool steels.
	Ni	—	—	Ni-Si Compd.(?)		Usually 2·50-3·50% when used alone, and up to 5% in carburizing steels, 0·50-3·75% in complex steels. 8% or more added to corrosion-resistant austenitic Ni-Cr steels. Higher Ni in special alloy steels.
Phosphorus	P	—	—	—	—	Under 0·05% in heat-treated steels, around 0·10% in some free-machining steels, up to 0·15% in low-C high-strength steels.
Silicon	Si	—	SiO_2.MxOy	—	—	Very low in rimming steels, from 0·10 to 0·30% in most steels, around 0·50% in castings, up to 0·75% in high yield strength steels, 1-1·75% in graphitic steels, up to 2% in spring steels, still higher in low-C steels for electric uses.
Sulphur	S (?)	—	MnFeS ZrS	—	—	Under 0·06% in heat-treated steels, 0·10-0·30% in some free-machining steels in conjunction with high Mn.

TABLE 1 — DISTRIBUTION OF ELEMENTS IN VARIOUS PHASES AND THEIR AMOUNTS EMPLOYED IN COMMERCIAL STEELS — *Continued*

ELEMENT	DISTRIBUTION					AMOUNTS NORMALLY PRESENT IN COMMERCIAL STEELS AND SPECIAL FUNCTIONS
	Dissolved in ferrite	Combined in carbide	In non-metallic inclusions	Special inter-metallic compounds	In elemental state	
Titanium	Ti ↔	Ti	TixOy	TixNyCx TixNy	—	0·01-0·20% for grain size control.
Tungsten	W ↔	W	—	—	—	Very rarely used in constructional steels. Around 1-2% in steels for high-temperature service. 0·50-20% in die and tool steels.
Vanadium	V ↔	V	VxOy	VxNy	—	0·01-0·20% for grain size control and slight alloying effect. 0·25-5·00% in tool steels.
Zirconium	Zr	—	ZrO	ZrxNy	—	—

hot-die steels and other hot-working steels in amounts ranging from 2 to 10 per cent.

Vanadium is a good scavenger for steel, promoting soundness and cleanliness. It refines the austenitic grain size of the steel ensuring less susceptibility to grain growth at austenitizing temperatures compared with similar non-vanadium steels. It is used up to about 1·5 per cent in high-speed steels to improve the air-hardening property and the cutting efficiency.

The functions of titanium are practically identical to those of vanadium. In stainless austenitic steel, it acts as a carbide stabilizer owing to its very strong carbide-forming tendency and prevents weld decay through intergranular corrosion. The same effect can, however, be obtained by using niobium, alternatively known to columbium.

Aluminium is used as a deoxidizer in amounts up to 2-3 lb./ton to kill the steel and to control the inherent austenitic grain size. Nitriding steels for parts needing a high skin hardness may contain up to 1-3 per cent Al. Heat-resisting Cr-Al steels are also used which have aluminium up to 5 per cent.

Boron steels are of recent origin. As little as 0·003 per cent B added to plain-carbon and alloy steels increases the hardenability and improves their mechanical properties. Boron beyond 0·01 per cent, however, induces red-shortness.

The effects of copper have already been indicated in Table 1 and require no separate mention. The free-cutting properties acquired by adding lead are outstanding. Similar results can be secured with sulphur and also by incorporating selenium. This is commonly used in 18: 8 type of stainless steels.

This brief account of the influence of various elements has been aptly summarized by Bain in Table 2.

Boron

The additions of boron to constructional steel may be of interest to India although boron is non-indigenous. For steels in the range of 0·40 per cent C, an addition of 0·002 per cent boron is equivalent to 0·30 per cent manganese, 0·35 per cent molybdenum, 0·50 per cent chromium or 2·00 per cent nickel so far as hardenability is concerned. Many steels are being produced abroad with boron additions for uses such as of shafts, gears, springs, etc., in the

TABLE 2 — TRENDS OF INFLUENCE OF THE ALLOYING ELEMENTS ON STEEL PROPERTIES ACCORDING TO BAIN

	As dissolved in ferrite: Strength	As dissolved in austenite: Hardenability	As undissolved carbide in austenite: Fine grain, toughness	As dispersed carbide in tempering: High temp. strength and toughness	As fine dispersion of non-metallic: Fine grain, toughness
Al	Mild	Mild	None	None	Very strong
Cr	Mild	Moderate	Strong	Moderate	Slight
Co	Strong	Negative	None	None	None
Cb	?	?	Strong	Strong	None
Cu	Mild	Mild	None	None	None
Mn	Strong	Moderate	Mild	Mild	Slight
Mo	Moderate	Strong	Strong	Strong	None
Ni	Mild	Mild	None	None	None
P	Strong	Mild	None	None	None
Si	Moderate	Moderate	None	None	Moderate
Ta	Moderate ?	Strong ?	Strong	Strong	None
Ti	?	Strong ?	Very strong	Little* ?	Moderate ?
W	Moderate	Strong	Strong	Strong	None
V	?	Very strong	Very strong	Very strong	Moderate ?
Zr	?	?	None ?	None ?	Strong ?

*As a result of very slight solubility.

aircraft, automotive and machinery industries.

Boron and Standard Steels Compared

A comparison of boron-containing and molybdenum-containing steels which give equivalent hardenability to standard French grades has been made. The equivalence of boron to other alloying elements can be represented schematically as follows:

Carburizing Grades:

B 0·17% Mo = 0·3 Cr 0·6% Ni
B 0·25% Mo = 0·6 Cr 1·0% Ni

Through-hardening Grades (about 0·35 per cent carbon):

B 0·15% Mo = 0·4 Cr 1·00% Ni
B 0·30% Ni = 0·5 Cr 0·10% Mo

Low-carbon Grade:

B = 0·2 Cr 0·25% Mo

With medium-carbon steels, the effect of boron in improving mechanical properties is observed only when the section exceeds that in which the steel without boron will harden through, while in large sections the efficacy of boron diminishes. In carburizing steels, boron improves the core but not the case spalling.

Hardenability

Hardenability denotes the tendency of a steel to transform from austenitic condition on cooling to martensite with absence from softer decomposition products formed at higher temperatures. The following factors influence hardenability:

1. Mean composition of the parent austenite.
2. Homogeneity of the austenite.
3. Grain size of the austenite.

4. Undissolved carbides and nitrides in the austenite and possibly non-metallic inclusions.

The effects of alloying elements can be revealed in many ways such as TTT diagrams, quenching diagrams or diagrams depicting critical cooling rates.

The factors which increase hardenability are:

1. Dissolved elements in austenite (except cobalt) retard nucleation or growth of pearlite and for ferritic products form nuclei.
2. Coarse grain size of austenite which reduces number of centres for pearlite formation.
3. Homogeneity of austenite which restricts nuclei for ferrite formation.

Factors which decrease hardenability are:

1. Fine austenitic grain size.
2. Undissolved carbides or nitrides, etc.
3. Inhomogeneity of austenite.

The proportion of an alloying element which is dissolved in austenite contributes towards increased hardenability and the portion which enters undissolved carbides is entirely inert and plays no further part in promoting increased hardenability; besides, it lends to shallow hardening effects owing to the restrictions it improves in grain growth.

Formulae that have been proposed and have fairly successfully been used predict hardenability by combining (actually multiplying together) the effects of individual alloying elements.

Bucknall and Steven[1] examined a series of 13 billets of En steels and found a distinct variation in hardening response in 7 billets, 3 having very soft centres, 3 fairly soft centres, and one a slightly hard centre. In an En 1 steel billet (manganese-molybdenum steel) the variation was particularly pronounced, the hardness 1 in. from the quenched end of Jominy bars varying from Rockwell C 46 to 36 according to position within the billet section. The effect is probably explained by dendritic segregation, the higher hardenability material at the outside being mainly derived from the columnar zone of the ingot which is substantially free from this effect.

Steels Based on Maximum Use of Chromium and Manganese in the Heat-treatable Constructional Ranges and Low-alloy High-tensile Structural Categories to Replace Nickel and Molybdenum

Thoroughgoing study of the effects of the individual alloys has resulted in a series of compositions for constructional steels distinguished by decreasing alloy contents. Nickel, in particular, has been conserved and to some extent molybdenum, without lowering the merit of the new steels for service; some, in fact, possess superior properties to the corresponding nickel-bearing steel. This evolution was pushed forward vigorously in U.S.A. and Germany. A wealth of information on German practice was contained in military intelligence reports and captured German documents. The general picture of Indian alloy steels may follow these German trends except where chromium is concerned, since India has fair chromite reserves.

The alloy structural steels are divided into case-hardening steels and through or semi-through-hardening steels differing in carbon contents.

German Pattern of Substitution in General

In order to avoid the use of scarce metals, the Germans were forced, during the war, to make significant changes in the compositions of many alloy steels. The outstandingly scarce alloying element was nickel, but molybdenum had to be reserved exclusively for high-speed tool steels. Tungsten was available for essential purposes, but very little cobalt or columbium was to be had. The broad picture was that at first, when nickel alone was scarce, chromium-molybdenum and chromium-molybdenum-vanadium steels were employed. Next, as molybdenum supplies became more difficult, the former steels were largely replaced by chromium-vanadium and manganese-vanadium steels. When chromium too became scarce, increased use was made of manganese steels with higher silicon contents.

As a supplement to nickel and nickel-chromium steels, chromium and chromium-molybdenum carburizing steels were standardized. These steels behaved quite differently from the nickel steels, especially in machining and heat-treating, and in pack-carburizing it was necessary to change from rapid-carburizing compounds to ones giving a milder surface-hardening effect. No difference, however, could be detected in salt bath carburizing response. Cr-Mo steels required a higher hardening temperature and more care was thus needed in avoiding distortion in complicated shapes, and also suffered from greater scaling of the surface. The appreciably better machinability and the higher hardness of Cr-Mo steels are important. In chromium-manganese steels hardening temperatures were the same and machinability better than in some of the Cr-Mo steels. Impact tests showed that machinable nickel-free and molybdenum-free steels are not far below Ni-Cr steels in toughness. The German development of heat-treating steels showed general similarities to the carburized steels. Eventually chromium-manganese case-hardening steels completely replaced nickel-chromium case-hardening steels.

Manganese Case-hardening Steels

The gradual evolution of manganese case-hardening steels took place in Germany and also in France in the following manner:

(a) Lowering the nickel contents of pre-war steels by substituting chromium or chromium plus manganese.

(b) Modifying the chromium-molybdenum and chromium-vanadium steels.

(c) Creating a chromium-manganese-molybdenum steel and Pater, a substitute without molybdenum.

(d) Introduction of a manganese-silicon steel when all other additions were scarce.

It should be possible, particularly with selected chromium-molybdenum-manganese steels, with a carbon content down to 0·16 per cent maximum as is common in nickel steels, to cover a range of core strength from 40 to 60 tons/sq. in. in section up to $1\frac{1}{8}$ in. dia., with other properties equal to those of nickel carburizing steels.

Steels on a Completely Indigenous Basis

Among the possible types of steels to be made in India on an indigenous basis, the following through or semi-through-hardening steels could be extensively developed.

The 'SAE' Type Alloy Steels— 1300 Series (Manganese Steels)

Generally these steels should be quenched in oil. They have high strength coupled with fair ductility and excellent resistance to abrasion. They are used extensively in the manufacture of heavy forgings because they have good forgeability and good response to heat treatment, particularly in large sections. They also have good notched-bar sensitivity values at high strengths.

Semi-through-hardening Grades — The principal uses of the steels in this series are in the manufacture of axle shafts, bolts, bolts for diesel engines, camshaft rocker levers, chains, cold-headed or forged parts, connecting-rod bolts for diesel engine, cranes, crankshaft forgings, differential gears, differential ring gears, forgings for aircraft, forgings for locomotives, etc.

Through-hardening Grades — The principal uses of the steels in this series are in the manufacture of axle shafts, truck axle shafts, trailer axles, bevel gears, bolts, camshaft rocker levers, clutch shafts, clutch spring bolts, connecting-rod bolts, crankshaft extension bolt, cylinder head studs, diesel engine parts, draw bench mandrels and punches, engine ring mounts, locomotive nuts, milling cutter bodies, oil pump shafts, piston rods, rock drill chucks, rocker arms, etc.

Chromium Steels

The steels of this series exhibit a combination of high strength and fair ductility. They are deep-hardening in an oil quench, have low distortion characteristics and do not decarburize at the surface of the part. The high surface hardness which these steels attain produces excellent wear resistance characteristics.

Semi-through-hardening Grades — The principal uses of this series are in the manufacture of automotive side gears.

Through-hardening Grades — The principal uses of steels in this series are in the manufacture of clutch shafts, transmission main shafts, automotive leaf and coil springs, steering worms, transmission gears and transmission spline shafts. They are also used for digger bucket teeth, machine tool gears, crusher jaws, etc.

High-carbon Chromium Steels

The steels of this series are used principally for ball-bearings, ball races, rollers and roller-bearings. They are characterized by high hardness and excellent wear resistance. Because of their susceptibility to quench-cracks, they must be handled very carefully, but can be treated to show a surface hardness of Rockwell C 63 to 65 and at that hardness have high fatigue values. Before machining or cold-working these steels require normalizing followed by a spheroidized anneal and slow cooling.

Through-hardening Grades — The principal use of this steel is for antifriction bearings of all kinds for the automotive, mining, farm implement and aircraft industries.

Chromium-vanadium Steels

The steels of this series are characterized by fine-grain structure, high strength and excellent ductility. In the lower carbon grades when used as carburizing steels they exhibit a hard, tough, wear-resistant case and a core structure which does not flake, powder or flow under pressure. They are better suited to single quenching than most other alloy steels and are readily welded. In the semi-through-hardening grades they exhibit high strength at temperatures up to 950°F. All the steels of this series have good machinability. They also have very low distortion characteristics when quenched either in oil or water.

In heavy sections these steels are used in the normalized and tempered condition, and they exhibit high strength, high ductility and an excellent tensile-yield ratio.

These steels are used in the automotive industry for differential pinion and side gears and leaf and coil springs. Hand chisels, hammers, pliers, screwdrivers and wrenches are made from this series as well as marine engine crankshafts, mill shafting, small crankshafts for pneumatic machines, valves and valve seats, etc.

Other general uses are for locomotive springs, oil refinery equipment such as bolts for high-temperature service, piston and plungers and parts for pressure vessels. In the machine tool industry this series of steel is used for gears, chuck jaw, precision lead screws spindles and tool holders and collets.

High-tensile Low-alloy Steels

The high-strength low-alloy steels are tonnage grades of steel possessing superior properties by the additions of small amounts of various elements. The strength of these steels as measured by the yield point is about 50 per cent higher than that of structural carbon steels. The resistance to atmosphere corrosion of some of these steels is four to six times that of carbon steels.

These low-alloy high-tensile steels comprise a specific group with chemical compositions specially developed to impart improved mechanical properties and greater resistance to atmospheric corrosion than are obtainable from conventional carbon structural steels containing copper. High-strength low-alloy steel is generally produced to mechanical property requirements rather than to chemical composition limits.

These steels are generally intended for applications where savings in weights can be effected by reason of their greater strength and atmospheric corrosion resistance.

They are normally furnished as-rolled, as-annealed, as-normalized, or as-stress-relieved and are intended for use without further heat treatment except for preheating, post-heating or stress-relieving operations which are sometimes used in conjunction with metal-arc welding. They are generally available in the forms commonly supplied in carbon steels.

Some American standard compositions of high-tensile low-alloy steels are given in Table 3.

The development of low-alloy high-strength steels started with the introduction of silicon steel, which was soon replaced by steels with low additions of manganese, chromium and molybdenum to which part additions of copper were provided. Among several types developed, two have generally established themselves, one in which, besides copper additions, a medium manganese content is coupled with a moderate chromium addition; and the other with higher manganese contents, without chromium additions. The manganese steels are considered to be better weldable. Attempts have been made to develop good welding steels to have still higher strengths of 38 tons per sq. in. minimum and with yield strengths of more than 25 tons per sq. in., by a slight increase in silicon and manganese contents together with additions of titanium or vanadium.[2] This development has not yet borne fruit and could be further explored along with the effect of copper additions.

In comparison with the good welding straight manganese steels, the manganese-copper steels offer, for light-weight welded constructions, the advantages of an improved corrosion resistance and weldability, and, therefore, present a better solution for the light-weight coach construction. The structural steels produced at present (TISCOR and TISCROM) by the Tata Iron & Steel Co. Ltd. have a medium chromium and manganese content and may not develop optimum weldability. The former, with a higher yield ratio resulting from high phosphorus additions, has still less applicability for welded construction.

Tiscrom has an yield point of about 22 tons per sq. in. (min.), tensile strength of 37-43 tons per sq. in. and elongation 18 per cent ($\frac{3}{8}$ in. and over section) (min.) and satisfies the requirement of B.S.S. No. 548 I.R.S., M-23/48. Tiscor has an yield point of about 22 tons per sq. in. (min.), tensile strength 31 tons per sq. in. (min.), and elongation 20 per cent (min.), in addition to superior corrosion-resisting properties. These steels are claimed to have 50 per cent higher safe-working stress than mild steel, but, as far as it is known, their weldability is not so excellent.

Chemical Composition of Tiscrom
(For information purposes only)

	Per cent
Carbon	0·30 max.
Manganese	0·50-1·30
Chromium	0·50-1·10
Copper	0·25-0·60
Silicon	0·30 max.
Phosphorus	0·05 max.
Sulphur	0·05 max.

Tiscrom steel was extensively used in the construction of Howrah Bridge. Its

TABLE 3 — REPRESENTATIVE HIGH-STRENGTH LOW-ALLOY STEELS

Data given, except for noted exceptions, are for plate ½ in. thick in the hot-rolled condition

BRAND NAME	COMPOSITION, PER CENT											YIELD PT., MIN., p.s.i.	TEN. STR., MIN., p.s.i.	MIN. ELONG.	PRODUCRE
	C	Mn	P	S	Si	Cu	Ni	Cr	Mo	Zr	Al				
Aldecor	0·12 max.	0·15-0·40	0·08-0·15	0·05 max.	0·35-0·75	0·35-0·60	—	—	0·16-0·28	—	—	50000	70000	a22%	Republic Steel Corp.
Cor-Ten	0·12 max.	0·20-0·50	0·07-0·15	0·05 max.	0·25-0·75	0·25-0·55	0·65 max.	0·30-1·25	—	—	—	50000	70000	a22% f18%	U.S. Steel Corp. Republic Steel Corp. Sharon Steel Corp. Greer Steel Co. Algoma Steel Corp.
Republic Double Strength	0·12 max.	0·50-1·00	0·04 max.	0·05 max.	—	0·50-1·00	0·50-1·10	—	0·10 min.	—	—	50000	70000	a22%	Republic Steel Corp.
Dynalloy	0·15 max.	0·60-1·00	0·050-0·100	0·05 max.	0·30 max.	0·30-0·60	0·40-0·70	—	0·05-0·15	—	—	50000	70000	a25%	Alan Wood Steel Co.
Hi-Steel	0·12 max.	0·50-0·90	0·05-0·12	0·05 max.	0·15 max.	0·95-1·30	0·45-0·75	—	0·08-0·18	—	0·12-0·27	50000	70000	b-c	Inland Steel Company
Mayari-R	0·12 max.	0·50-1·00	0·06-0·12	0·05 max.	0·10-0·50	0·30-0·70	0·25-0·75	0·40-1·00	—	—	—	50000	70000	f18%	Bethlehem Steel Co.
N-A-X High Tensile	0·08-0·15	0·50-0·75	0·04 max.	0·05 max.	0·60-0·90	Resid.	Resid.	0·50-0·65	—	0·05-0·15	—	50000	70000	c	Great Lakes Steel Corp. Republic Steel Corp.
Otiscoloy	0·15 max.	0·90-1·40	0·08-0·13	0·04 max.	0·10 max.	0·30 min.	Resid.	Resid.	—	—	—	50000	70000	a-d25	Jone & Laughline Steel Corp.
Tri-Ten	0·25 max.	1·30 max.	0·045 max.	0·05 max.	0·10-0·30 max.	0·30-0·60	0·50-1·00	—	—	—	—	50000	70000	a22% f18%	U.S. Steel Corp.
Tri-Ten 'E'	0·25 max.	1·30 max.	0·045 max.	0·05 max.	0·10-0·30 max.	0·20 min.	0·50-1·00	—	V 0·02 min.	—	—	50000	70000	a22% f18%	U.S. Steel Corp.
Yoloy	0·15 max.	0·60 max.	0·05-0·10	0·05 max.	—	0·75-1·25	0·50-2·00	—	—	—	—	50000	70000	a22%	Youngstown Sheet & Tube Co.

Notes — All of these steels, in thicknesses up to and including ½ in., are capable of at least meeting A.S.T.M. Standard Specimen cold band of 180° over a diameter equal to the thickness of the material.

a — Per cent elongation in 2 in., A.S.T.M. Standard Flat Specimen.

b — $\frac{1,500,000}{\text{T.S.}}$ min. per cent elongation in 8 in., A.S.T.M. Standard Flat Specimen.

c — For thicknesses under $\frac{3}{16}$ in., 22% min. elongation in 2 in., A.S.T.M. Standard Sheet Specimen.

d — For thicknesses under $\frac{3}{16}$ in., 25% min. elongation in 2 in., A.S.T.M. Standard Sheet Specimen.

e — Typical values for ½ in. plate, 27% in 8 in., A.S.T.M. Standard Flat Specimen.

f — Per cent elongation in 8 in., A.S.T.M. Standard Flat Specimen.

distinctive characteristics are high yield point and ultimate tensile strength with good ductility, high resistance to corrosion and good workability in the as-rolled condition.

The atmospheric corrosion resistance of Tiscor is 4-6 times that of ordinary mild structural steel and 2-3 times that of corrosion-resistant copper steels. The high resistance to corrosion particularly distinguishes Tiscor from other low-alloy high-strength structural steels.

Tiscor is used in the as-rolled condition without any heat treatment and can be readily fabricated by the same methods and equipment as used for mild steel with very minor changes in operating details.

Chemical Composition of Tiscor
(For information purposes only)

	Per cent
Carbon	0·10 max.
Manganese	0·10-0·40
Chromium	0·70-1·10
Copper	0·30-0·50
Silicon	0·50-1·00
Phosphorus	0·10-0·20
Sulphur	0·05 max.

Considerable work has been done on the development of low-alloy high-strength steel in other countries, but the main direction Indian investigation may profitably follow would be to find compositions readily weldable and possessing adequate strength resulting from suitable air-cooling transformation characteristics and adequate corrosion resistance under Indian tropical conditions. Such compositions may include more extended use of manganese than hitherto done, based on manganese-silicon-titanium combinations with or without copper and chromium. Their weldability and corrosion resistance under Indian conditions will have to be investigated very thoroughly. A suggested combination is given below.

	Per cent
C	0·15-0·19
Si	0·40-0·80
Mn	1·40-1·60
P	0·035 max.
S	0·035 max.
Cr	0·30-0·60
Cu	Optional

Low-alloy molybdenum-boron steels to be discussed later on in this paper have better weldability than Tiscrom, but are likely to be inferior in corrosion resistance. The issue of molybdenum, however, may be debatable under Indian raw material conditions but is worth serious consideration. Introduction of molybdenum to 0·20 per cent C and 1·6 per cent Mn (maximum) steels will tend to depress the temperature of transformation of austenite on air-cooling and so produce a structure in which the carbide phase is finely dispersed through the ferrite matrix. The properties of these steels depend largely on the rate at which they cool from the austenitic range and thus on the thickness of section. Addition of 0·10-0·15 per cent Mo produces a slight depression in the transformation temperature resulting in an increase in yield stress of the order of 4-5 tons per sq. in., without appreciably affecting the shape of the stress/strain curve. The notch-ductility of these manganese-molybdenum high-tensile steels is much greater than for ordinary mild steel. This steel can be made as a semi-killed or fully-killed and grain-controlled steel in various conditions of heat treatment depending on the degree of notch-ductility required.

It is not proposed in this paper to discuss the extended applications these low-alloy high-tensile steels may find in oil refinery equipment, pressure vessels, etc.

The position, therefore, is that low-alloy high-tensile steels for constructional purposes are available in a range quite adequate to meet the designers' requirements, and it is up to the designers to make full use ot these achievements. In other words, structural practice must be developed to conform with metallurgical progress. This means a departure from the present practice of thinking primarily in terms of mild steel at 8 tons/sq. in. and designing to take full advantage of the materials now available. It is, of course, not practicable politics to expect deliveries of these steels in small quantities involving a large variety of sections. Under present-day condition constructional schemes requiring high-tensile steel should be sufficient to ensure the necessary production.

The value of low-alloy high-tensile steels in the construction of long-span bridges is obvious, and was demonstrated in the Howrah Bridge at Calcutta, where about 6000 tons or 25 per cent of the quantity of mold steel that would have been required was saved by the use of steel to B.S. 548. Similarly savings are possible in wide-span buildings and the Brabazon hanger includes some 3500 tons of B.S. 548, without which the spaciousness required would have been difficult to achieve. Steel to B.S. 968 has been used to good effect in the Callendar-Hamilton Standardized construction bridges, bridges of which example are in use in Assam, Holland and elsewhere demonstrating its value in bridges of comparatively small span. Load capacities are increased by up to 39 per cent over similar bridges in mild steel. Another piece of bold and intelligent design was a 120 ft. jib for a Morgan 20-ton derrick crane where actual test results enabled the designer to base on a yield stress of 30 tons/sq. in. The jib is entirely welded and its weight complete is 4½ tons compared with 9 tons for the normal mild steel construction. Examples could be multiplied, but the above are sufficient to indicate that there are some designing engineers who have made use of the opportunity given to them by the metallurgists.

References

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