

# LOW-ALLOY HIGH-STRENGTH STEELS \*

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## Introduction

**I**T is significant that this symposium on alloy steels is being held in the year 1956 which marks the centenary of the birth of tonnage steel. It was exactly a hundred years ago that Henry Bessemer heralded a new era by making it possible to produce steel for the first time in commercial tonnages. The largest proportion of steel made and rolled today finds its way into structural applications such as the building of bridges, transport cars, etc. Therefore structural steel occupies a prominent place in the eyes of the metallurgist and the engineer. Although the manufacture of Bessemer steel was well established within a few years of its discovery, the general use of steel in building bridges and other structural uses had to wait for several years. As late as 1877, a Board of Trade Regulation in England prohibited the use of mild steel in bridges. The Firth of Forth Bridge built during 1880-1890 used for the first time steel in large quantities. The earliest use of mild steel for bridges in U.S.A. was in the Eads Bridge over the Mississippi river. Since then the use of mild steel for bridges has become almost universal.

Even by the turn of the 19th century, some progress was made in the use of higher strength steel for structural purposes. The need that led to the use of higher strength steel was the use of higher unit stresses which demanded the development of stronger steels. The use of higher working stresses involved a substantial reduction in the section modulus of structural members. In other words, it involved the use of lighter sections. The use of lighter sections in its

turn raised the problem of corrosion resistance of the steel in order that the onset of corrosion may not reduce the section below the limits required for safety and stiffness. A number of sporadic attempts were made both in Europe and America at the development of high-strength steel for structural purposes, but it was not until the thirties of the present century that the advantages of saving in weight gained recognition and led to the development of a class of high-strength low-alloy steel for structural purposes. Before discussing the production and properties of these steels, it is worthwhile to consider the general requirements of a structural steel.

## The General Requirements of a Structural Steel

Engineering design is largely empirical and is based on considerations of strength of materials and stress analysis. Steel like other materials of construction has certain well-defined characteristics and design is based on a knowledge of these characteristics and directed at the effective and economic utilization of the material. The dimensions of structural members are evaluated on the basis of some arbitrary working stress derived by dividing a strength property of the steel by a suitable factor of safety. According to the British Standard Code of practice for the structural use of steel in buildings, the maximum permissible axial tension in a member is  $0.59 f_y$  where  $f_y$  is the guaranteed yield point of the steel. Similarly the extreme fibre stress permissible in compression (bending) is  $0.65 f_y$ . It is noteworthy that the British Standard Specification No. 15 for structural steel prior to 1948 did not

specify the yield point. It would, therefore, appear that British designers had till very recently employed the maximum tensile strength as the basis of their design. This shift in the basis of design has largely been responsible for the development of high-strength structural steels. Even today, there is a certain school of thought amongst engineers that the maximum tensile strength rather than the yield point should form the basis of design. The reason usually advanced is that the endurance limit of the material is related more closely to the maximum strength than the yield point. However, the former factor determined in the laboratory has little bearing on the actual strength of a completed structure and the yield point has been more or less universally accepted as a basis of design, at least for static structures. The use of high-strength structural steel has permitted a considerable increase in working stresses. The use of fibre stresses of 12-14 tons per sq. in. is quite common when using this category of steel.

Considerations of elastic stability also govern design. With the use of higher strength materials, it is not possible to reduce the thickness of members below a certain optimum value. The elastic modulus of steels is a fairly constant figure and the elastic deflections produced by a given load will increase with the reduction in dimensions of the member. Undue reduction in thickness may thus lead to buckling of certain members and so render them ineffective. Consequently other members would be called upon to bear increasing loads and may be damaged. Elastic stability of a structure is very important and unless guarded against may lead to serious consequences. Considerations of elastic stability thus limit the maximum strength of steels that can be employed for structural purposes.

Another important consideration that also lays down a ceiling on strength properties of structural steel is ductility. The ductility demanded in standard grades is adjudged

on the basis of ductility factors obtained in a tensile or bend test. Ductility is demanded for the purpose of satisfying service requirements such as bending and flanging before fabrication. Ductility is also important as it permits redistribution of stresses in a structure when one of the members is overstressed. The requirements of ductility for effecting such redistribution is, however, very small.

One of the most important requirements of structural steel is that it should be capable of easy fabrication. Today the use of welding for general fabrication work is almost universal. The use of high-strength structural steel for welding generally involves the employment of chemical compositions that lead to weld-hardening and consequent danger of weld failure, particularly under conditions of welding that impose restraint on the joint. It is imperative that, when welding is employed, weld-hardening does not proceed to such an extent as to lead to eventual failure. It is because of the general susceptibility to weld-cracking that two distinct grades of high-strength steels are recognized, namely, those suitable for riveting only and those that may be welded. The use of welding has resulted in low-temperature ductility as being an additional requirement for structural steel.

In conclusion, it may be stated that the requirements of a structural steel may be stated in terms of strength, ductility and weldability. In view of the fact that structural steel is required in large quantities, it is also imperative that its enhanced properties are obtainable in the as-rolled condition as delivered by the mills or after a simple normalizing treatment. Otherwise, the cost factor may prove rather decisive against their use.

### **Historical Development of High-strength Low-alloy Steels**

The composition and properties of some of the earliest types are listed in Table 1.

TABLE 1 — HIGH-STRENGTH STEELS FOR RIVETING AND WELDING

(Reproduced from *Encyclopaedia Britannica* 1953, Steels, p. 369A)

TYPE	PERCENTAGE CHEMICAL COMPOSITION				MECHANICAL PROPERTIES		
	C	Si	Mn	Others	Tensile strength 1000 lb./sq. in.	Yield point 1000 lb./sq. in.	% El. on 8 in.
Good structurals	0.20	0.15	0.50	—	60-68	40-47.5	30-25
Nickel	0.33	0.06	0.60	3.25 Ni	105	63	20
Structural silicon	0.30	0.25	0.80	—	85-90	50	20
Mauretania	0.25	1.10	0.75	—	92-105	65	30-25
'D' Steel	0.33	0.12	1.25	—	83-96	56	17
Corten	<0.10	0.75	0.40	0.15 P 1.00 Cr 0.40 Cu	65-75	50-60	25 on 2 in. g.
Manten	<0.30	<0.30	1.50	—	80-90	55-60	30-20 on 2 in.
Double strength	<0.12	<0.30	0.75	1.00 Cu 0.60 Ni 0.20 Mo	75	65	30

The earliest high-tensile steel employed for structural purposes is undoubtedly the 3½ per cent nickel steel. Early in 1902, this steel was employed in the construction of the Queensboro Bridge and later the same steel was employed in the Manhattan Bridge. Although this steel satisfied the demands of higher strength for riveting purposes, it proved to be an expensive steel. In spite of this fact, it is reported that it was used as late as 1923 in the construction of the Delaware Bridge. In view of the high cost of nickel, attempts were made to obtain equivalent properties by using other alloy additions. As a matter of fact, it has been stated by Aston that the whole group of other steels in this class may be described as the result of an attempt to produce these properties more cheaply than nickel. The use of the so-called silicon structural steel followed. This steel was employed in the building of the San Francisco-Oakland Bay Bridge.

The use of high-silicon structural steel was reported in England as early as 1907. The

great ocean liners *Lusitania* and *Mauretania* were both built of silicon steel plate. In the early thirties of the present century this steel was widely used in Germany and was called ST 52. In 1933, the famous 'Flying Dutchman', the first light-weight stream-lined train, was built in Germany using this steel. Similar steels using a variety of combinations of alloys were developed in other countries, 'AC 54' in France, 'Corten' in America, 'Tiscrom' in India and 'D' steel in England.

All these steels, developed to satisfy higher requirements of strength for structural purposes, are known as low-alloy high-strength steels. These are a specific class of steels in which enhanced mechanical properties, and, in most cases, good resistance to atmospheric corrosion are obtained by intentional incorporation of moderate quantities of one or more alloying additions other than carbon. These steels are employed for applications where savings in weight can be effected by reason of their greater strength and atmospheric corrosion resistance.

## The Mechanical Properties of High-strength Steels

In the early days of the use of mild steel for structural purposes, the tensile strength of the steel employed was 23-28 tons per sq. in. without a guaranteed yield strength. Standard mild steel to B.S. 15 has a tensile range of 28-33 tons per sq. in. and an yield point of 15.25 tons for plates and sections up to  $\frac{3}{4}$  in. thick. The British Standard Specifications 548/1934 and 968/1941 relating to high-tensile steel lay down a tensile range of 37-43 tons per sq. in. and a minimum yield strength of 23 tons min. The chemical and mechanical requirements of these specifications are given in Table 2. From the mechanical properties of commercial high-strength steels given in Table 3, it may be seen that most of the American steels have lower tensile strengths than required by B.S. 548 but satisfy the yield requirements. The difference is caused by the lower carbon contents of the American steels, which render them easily weldable. Steels satisfying the requirements of B.S. 548, although termed as fusion-welding quality, generally lead to weld-hardening and cracking unless adequate precautions are taken. However, the recent British development of the molybdenum-boron steel of the 'Fortiweld' type has enabled the production of a really weldable high-tensile steel satisfying the requirements of B.S. 548. However, if yield point alone is taken as the basis of design, the American and British types should be considered as strictly equivalent. On grounds of formability, the tensile strength cannot be usefully increased beyond 42 tons/sq. in.

## The Chemical Composition of Low-alloy High-strength Steels

The chemical composition of high-strength steels is so balanced as to obtain the requirements of strength properties and welding

characteristics. The influence of alloying elements on the strength properties of steel is now well known. The effects of the common alloying elements on the mechanical properties of iron are shown in Fig. 1. Of all the alloying elements carbon is by far the most effective in raising the strength. This increase is accompanied by a marked increase in hardenability and a decrease in ductility, weldability and notch toughness. It becomes, therefore, necessary to keep the carbon content below a maximum value because of the hardening accompanying high rates of cooling obtained adjacent to the weld when carrying out heavy weldments. The high carbon content has a twofold effect. Because of the effect on hardenability there is an increased tendency to form a brittle martensitic layer near the weld. The high carbon content further causes the martensite when formed to be more brittle than when formed from a low-carbon steel. The maximum permissible limit of carbon content in welding quality structural steel has been suggested by several investigators<sup>2,3,4</sup>. Most of them agree that, with carbon contents over 0.15 per cent, difficulties are encountered in welding.

The other alloying elements normally present in low-alloy high-strength steels are Si, Cu, Mn, Cr, P, V, Ti, Mo and B. The use of manganese and silicon offers the cheapest method of obtaining the required strength characteristics. It has been recognized that small amounts of copper increase the resistance to atmospheric corrosion<sup>5</sup> and this has been definitely proved by the A.S.T.M. tests. These tests also proved the beneficial effects of nickel and chromium when present in small quantities. The advantages bestowed by alloying additions on corrosion resistance have now been proved by long-term exposure tests<sup>6</sup>.

The influence of the carbon content of a plain-carbon steel on the weld hardness is

TABLE 2 — SHOWING CHEMICAL AND PHYSICAL PROPERTIES OF TYPICAL LOW-ALLOY STRUCTURAL STEELS

	CHEMICAL COMPOSITION IN PER CENT										T.S. tons/sq.in.	Y.P. tons/sq.in.	ELONG. % (on 2 in.)	REDUC. % AREA	REFERENCE AND REMARKS
	C	Mn	Si	P	Cr	Cu	Ni	Mo	V						
1. Corten*	0-10 max.	0-10-0-30	0-50-1-00	0-10-0-20	0-50-1-50	0-30-0-50	—	—	—	—	29-33	22-26	22-27	40-45	Iron Age (Dec. 31, 1936), 33.
2. Cromansil*	0-12-0-20	1-10-1-40	0-70-0-80	—	0-40-0-60	0-50 (opt.)	—	—	—	—	35-40	24-26	20-28	50-62	Iron Age (Dec. 31, 1936), 32.
3. Yoloy*	0-08	0-60	0-260	0-020	—	1-02	1-99	—	—	—	29	23	28	52	Iron Age (Dec. 31, 1936), 34.
4. Hi-steel*	0-24	0-67	0-260	0-050	—	1-00	2-00	—	—	—	39	26	27 on 8 in.	—	Iron Age (Feb. 27, 1936), 42.
5. U.S. Navy*	0-10	0-50	0-150	0-100	—	1-00	0-50	—	—	—	33-37	24-29	22 on 8 in.	—	Iron Age (Feb. 27, 1936), 42.
6. R.D.S. Grade 1*	0-18	1-45	0-250	—	—	0-20	—	—	0-18	—	35	22	20 on 8 in.	—	Iron Age (Feb. 27, 1936), 42.
7. Man-ten*	0-12 max.	0-50-1-00	—	—	—	0-50-1-50	0-40-0-80	0-20 max.	—	—	33	26	25	—	Eng'ng-Alloys, by Woldman & Dorn- blatt, 1936, p. 122.
8. Allan Wood*	0-25-0-35	1-25-1-70	0-150 max.	0-040	—	—	—	—	—	—	35-40	24-29	25-30	40-50	Welding Handbook, 1938, A.M.
9. Cromador (British)	0-27	0-45	0-010	0-100	—	0-45	—	—	—	—	40	33	14-20 on 8 in.	—	Iron Age (Feb. 27, 1936), 42.
10. ST 52, Krupp†	0-26	0-74	0-110	—	0-93	0-31	—	—	—	—	41	25	22 on 8 in.	—	Iron Age (Feb. 27, 1936), 42.
11. ST 52, Dortmund Heerder Huttenve- rein A.G.†	0-18	1-43	0-500	0-026	—	0-48	—	—	—	—	38	24	25	—	Trans. Institute of Welding (Jan. 1939), 5.
12. ST 52, Gutehoff- nungsh. A.G. Ober- hausen†	0-17	0-87	0-450	0-037	0-17	0-49	—	—	—	—	33	22	20	—	Trans. Institute of Welding (Jan. 1939), 5.
13. Typical Brit. High Tensile	0-15	0-98	0-520	0-031	—	0-25	—	0-11	—	—	33	21	21-3	—	Trans. Institute of Welding (Jan. 1939), 5.
14. Tata's Tisor	0-25	1-50	0-130	0-034	—	0-25 (opt.)	—	—	—	—	40	24	22 on 8 in.	—	Iron & Coal Trades Review (July 14, 1939), 41.
15. Tata's Tiscrom	0-08	0-16	0-752	0-136	1-16	0-35	—	—	—	—	33	22	32	50	½ in. thick plate in as- rolled condition.
16. Fortiweld	0-23	1-25	0-096	0-033	0-62	0-35	—	—	—	—	40	23	19	—	½ in. thick plate in as- rolled condition.
17. Pearlite-free Low Carbon Steel	0-12	0-50	0-300	0-040	—	0-003- 0-005 B	—	—	—	—	40	29	25	—	J. Iron & Steel Inst., 163 (1949), 277-294.
	0-015 max.	0-20	0-050	0-100	0-015 Nitrogen	—	—	—	—	—	28	22	25	70	J. Iron & Steel Inst., 177 (1954), 118-128.

\*American.

†German.

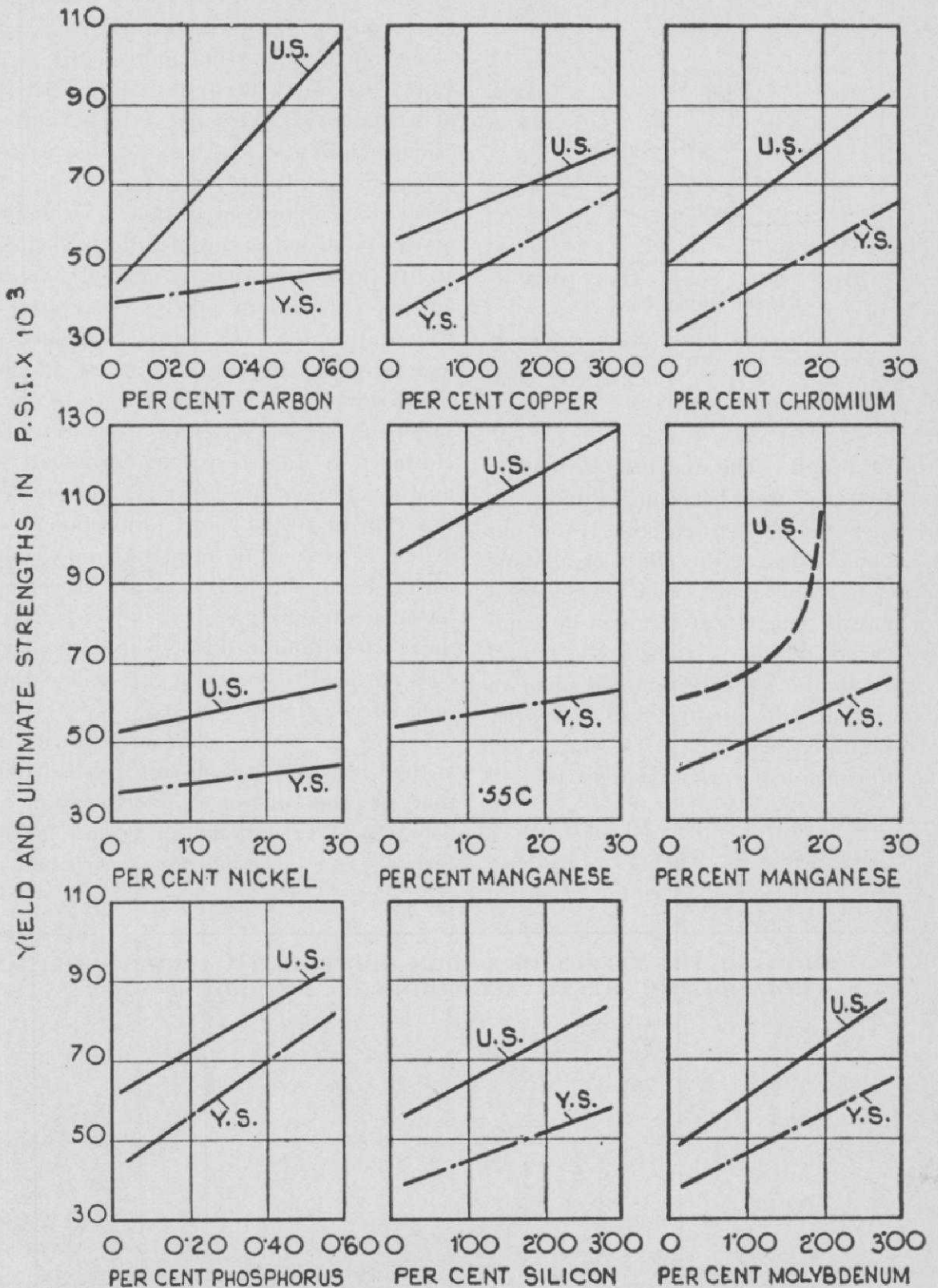


FIG. 1 — EFFECT OF THE ADDITIONS OF VARIOUS ALLOYING ELEMENTS ON THE TENSILE STRENGTH AND YIELD POINT OF IRON

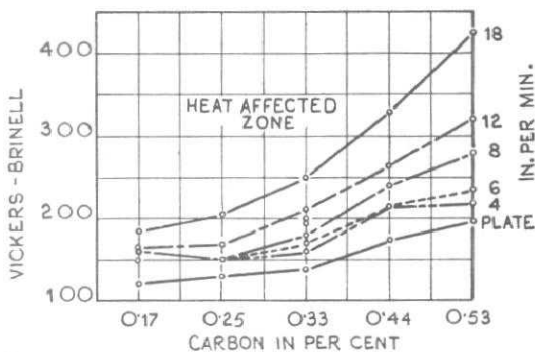


FIG. 2 — DEPENDENCE OF MAXIMUM WELD-HARDENING ON CARBON CONTENT AND SPEED OF WELDING. WELD BEADS MADE ON  $\frac{1}{2}$  IN. THICK PLATES, 9 IN. LONG AND  $\frac{3}{4}$  IN. WIDE

shown in Fig. 2. The above figure clearly shows that the weld-hardening rapidly increases over 0.3 per cent carbon. From our present knowledge of the effect of alloying elements on hardenability, each alloy composition may be equated in terms of an equivalent carbon content. It has been found<sup>7</sup> that with an alloy composition exceeding an equivalent carbon content of 0.45 difficulties are encountered in welding. A simple formula for equivalent carbon content is

$$\% \text{ CE} = \text{C} + \frac{\text{Mn}}{6} + \frac{\text{Cr}}{5} + \frac{\text{Ni}}{15} + \frac{\text{Mo}}{4} + \frac{\text{Cu}}{13} + \frac{\text{W}}{5}$$

This may sometimes be stated in terms of the maximum hardness of the metal just below the weld. A maximum limit of 250 Brinell has often been stated as a criterion of weldability. With low carbon contents, a higher hardness may be tolerated without any danger of weld-cracking. Thus, the effect of any alloy composition on weldability may be predicted on considerations of hardenability. On this basis, it may be expected and is confirmed in practice that steel to specification B.S. 548 cannot be welded unless preheating or post-heating is adopted. For welding heavy plates it may be necessary to use special austenitic steel electrodes<sup>8</sup>. However, it was shown<sup>9</sup> by Swindent that by the addition of 0.2 per cent titanium to this type of steel, a large proportion of the carbon is used up to form titanium carbide, which, being sluggish, does not dissolve in the austenite during welding. Consequently, the martensite formed is low in hardness and does not lead to weld-cracking under conditions of constraint.

During the course of research carried out at the United Steels Company, it was found<sup>10</sup> that the combination of molybdenum and boron gave exceptional properties in low-carbon steels. The following figures indicate

TABLE 3 — SHOWING THE EFFECT OF BORON ADDITION TO A MILD STEEL AND MOLYBDENUM STEEL ACCORDING TO BARDGETT<sup>10</sup>

STEEL No.	1	2	3	4
	$\frac{1}{2}$ Mo	$\frac{1}{2}$ Mo WITH B	MILD STEEL	MILD STEEL WITH B
Analysis, %				
Carbon	0.09	0.080	0.09	0.080
Mn	0.43	0.400	0.42	0.410
Si	0.25	0.250	0.25	0.260
Mo	0.58	0.580	—	—
B	—	0.003	—	0.003
Mechanical properties, $\frac{5}{8}$ in. normalized 930°C.				
Maximum strength, tons/sq. in.	28.50	41.000	26.50	25.800
Yield point, tons/sq. in.	16.20	34.800	18.70	17.100
% E. on (4√A)	40.00	26.000	44.00	41.100
Red. of area, %	74.00	71.300	72.00	73.600
Izod impact, ft.-lb.	99.00	93.000	94.00	96.000

the combined effects of molybdenum and boron.

The effect of small quantities of boron on a low-carbon molybdenum steel is unique and the steel that is marked under the name 'Fortiweld' is perhaps the only steel commercially produced to satisfy the tensile requirements of B.S. 548 and that can be welded with the same ease as ordinary low-carbon steel.

**The Weldability of High-strength Steels**

The concept of weldability is a difficult one and is generally considered as a combined property of base metal and filler metal or electrode to produce a crack-free and mechanically satisfactory welded joint under service conditions. The most important service condition is the varying degree of mechanical restraint imposed on the components while cooling after welding. Weldability is generally evaluated by a controlled welding procedure which evaluates the ductility of the test joint.

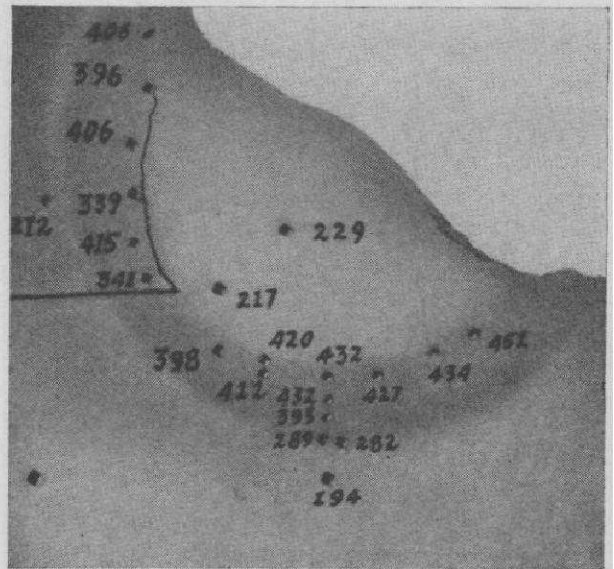


FIG. 4 — SECTION OF REEVE TEST ON TISCROM STEEL SHOWING WELD-CRACKING

A restrained weld test proposed by Reeve has been found useful in appraising the welding qualities of high-strength steels. The testpiece (FIG. 3) AB is clamped to its lower test plate CD and a bed plate by means of bolted cross pieces. The two plates are fixed by fillet anchor welds, laid along the longitudinal edges. Test welds A and B of two different fillet sizes are deposited under standard conditions and after cooling under restraint for 48 hr. are sawn as shown. The degree of cracking round the heat-affected zone is observed and taken as an index of weldability. Tiscrom steel which satisfies the requirements of both B.S. 548 and 968 does not stand this test successfully (FIG. 4). The molybdenum-boron steel of the Fortiweld type passes this test quite satisfactorily as shown in Fig. 5.

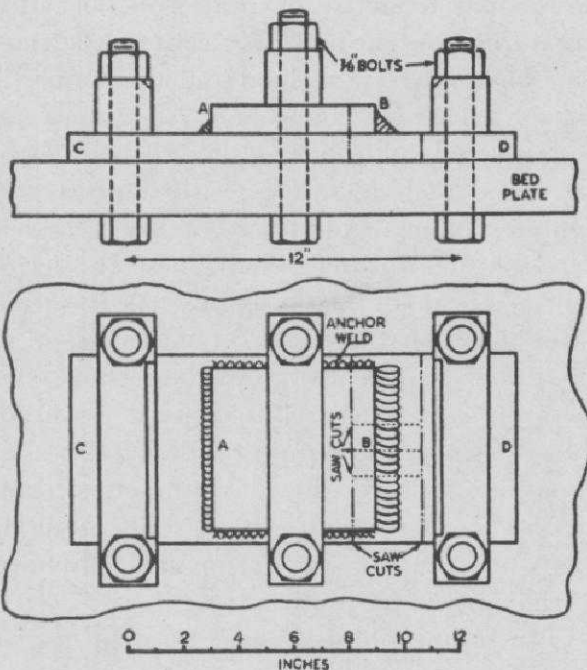


FIG. 3 — THE REEVE WELD-CRACKING TEST

**The Corrosion Resistance of Structural Steels**

Much emphasis has been laid by the early producers of high-strength steels regarding their corrosion resistance. The early claims that these steels were 4 to 6 times as resistant

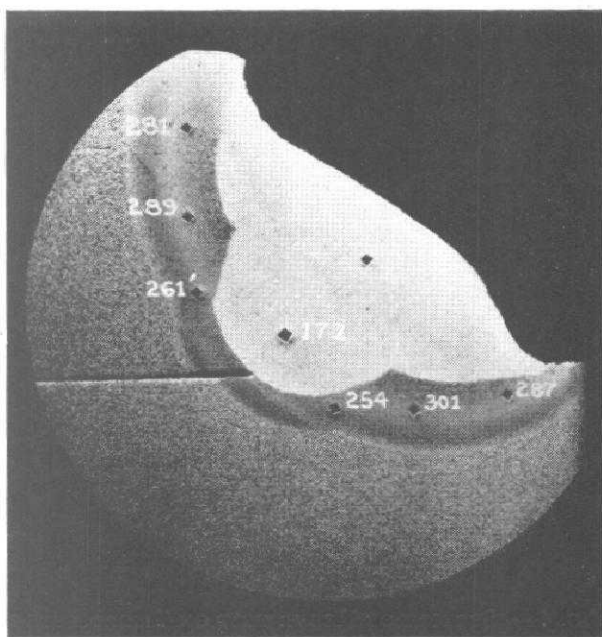


FIG. 5 — SECTION OF REEVE TEST ON FORTIWELD STEEL SHOWING ABSENCE OF WELD-CRACKING

as mild steel were all based on short-time tests. Today, we have the data of long-time tests<sup>6</sup> which indicate positively the superiority of low-alloy steels in this respect. However, the actual utility of increased resistance to corrosion is not perhaps very great as was made out by the early producers. It has been<sup>7</sup> found during the demolition of early buildings in America that the condition of the steel structures was reasonably good wherever adequate precautions had been taken to afford protection. However, for certain specific uses, the employment of high-strength steel offers marked advantages. Fig. 6 shows the condition of two wagons used for handling ash in a boiler plant under identical conditions. It may be seen that the alloy steel (Tiscor) stands up better to the conditions of wear than mild steel.

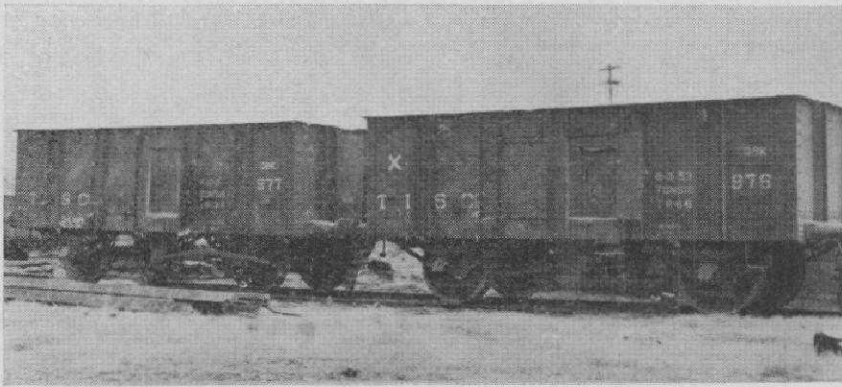
#### High-strength Steels Produced by the Tata Iron & Steel Co. Ltd.

Two high-strength steels are produced at Jamshedpur — Tiscrom and Tiscor. The

former is a chromium-manganese-copper steel satisfying the requirements of B.S. 548 and 968. The physical properties and the chemical composition of the steels are given in Table 2. A large tonnage of Tiscrom (27,000 tons) was used in the construction of the new Howrah Bridge over the river Hooghly. The other steel, Tiscor, is a high-yield steel employing chromium, copper, phosphorus and silicon additions. Tiscor, unlike Tiscrom, is an easily weldable steel as it has no air-hardening tendency. The high phosphorus content, however, leads to pronounced strain-ageing characteristics as shown in a strain-ageing test (Fig. 7). The recent trend in America to work with lower phosphorus contents would reduce this tendency which is of some importance under conditions where fabrication is performed after severe forming.

The manufacture of these steels does not present any serious problems. The steel is made by the basic open hearth using scrap (60 per cent) and hot metal (40 per cent). The melt carbon is 0.50 per cent. The bath is tapered, ore and worked down to a bath carbon of 0.12 per cent. Sufficient lime is worked in to get a 'V' ratio of 3.0 and a total iron content of 15 per cent in the slag. The bath is given a reboil and the copper is added. This is followed by a block of Spiegel and additions of low-carbon ferro-chrome. The furnace is tapped 20 minutes later. Additions of recarburizer, ferro-phosphorus, ferro-manganese and ferro-silicon are made in the ladle. As the total alloy additions are large, it is necessary to maintain a good heat. An immersion temperature of 1600°C. is considered essential. Lower temperatures may lead to poor assimilation of alloys and a layering effect leading to excessive segregation. The steel is cast into narrow-end-up moulds provided with recessed shrink-heads.

The rolling of these steels is done in the same manner as ordinary mild steel. Some care is, however, necessary in the initial



977- MILD STEEL WAGON                      976 TISCOR WAGON  
 USED FOR ASH HANDLING  
 CONDITION OF SIDE PANELS SHOWING THE BETTER  
 RESISTANCE OF TISCOR WAGON AFTER 6 YRS. OF SERVICE.

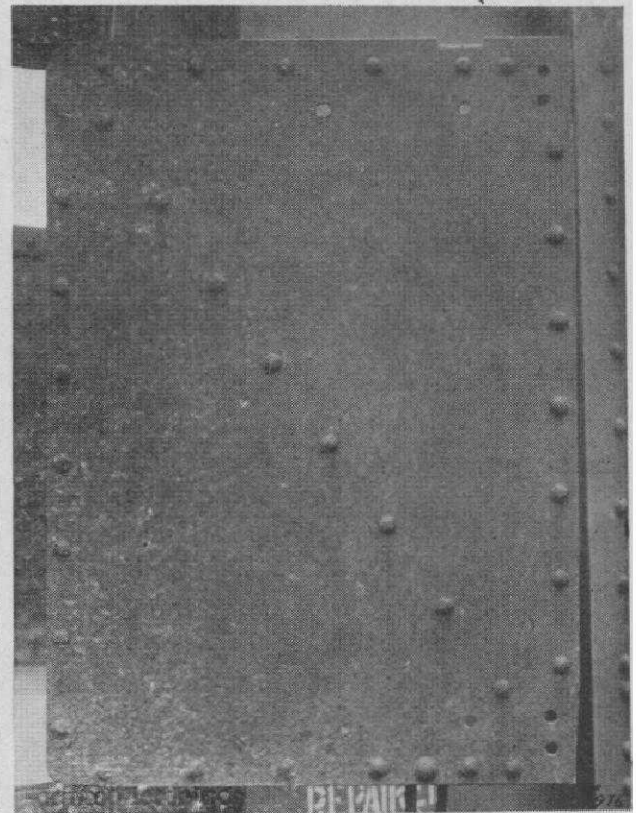
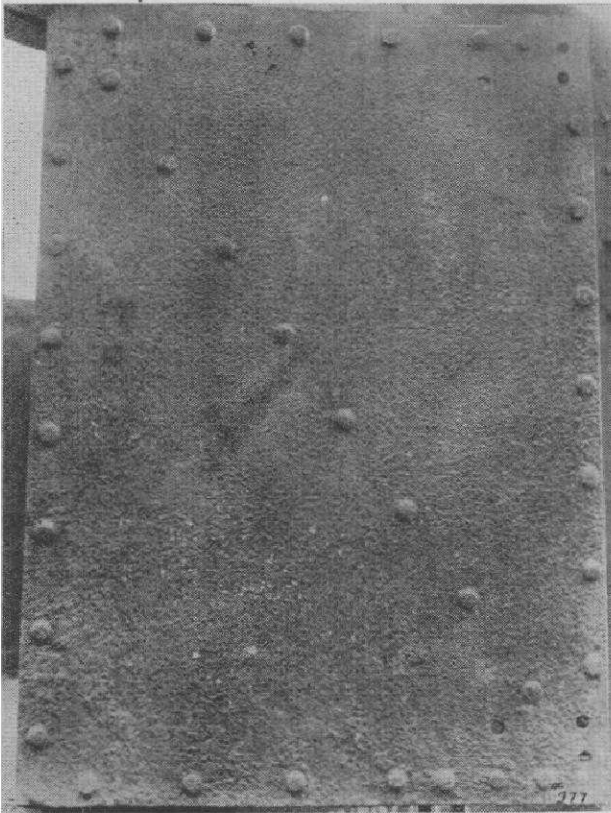


FIG. 6 — CONDITION OF TISCOR AND MILD STEEL WAGONS USED FOR ASH HANDLING

heating of the ingots, as preferential oxidation leads to the peculiar checking of the surface caused by molten copper so formed on the surface layers. A careful control of the temperature at below 1200°C. suffices to eliminate the trouble. Alternatively, the inclusion of a certain proportion of nickel in the composition also prevents the occurrence

of such trouble. The addition of nickel increases the melting point of the copper alloy formed by preferential oxidation.

#### Future of High-strength Steels

Although Tiscor and Tiscrom have been produced for some time, the demands have

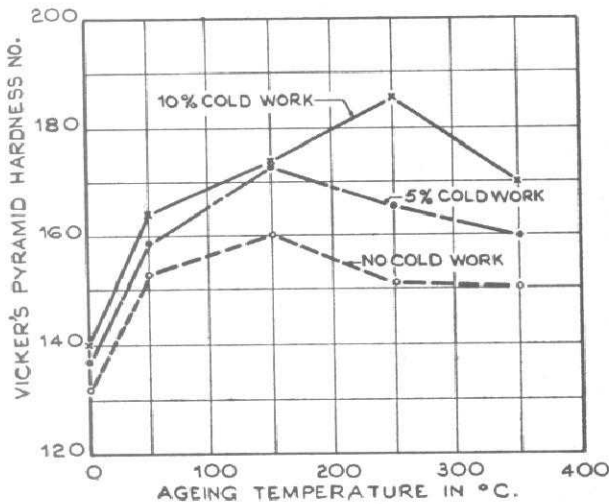


FIG. 7 — STRAIN-AGEING CHARACTERISTICS OF TISCOR

shown a consistent decrease. The reasons for such a decrease are rather obscure. The decline in the demands of the former may be explained as being caused by the fact that many Indian designers continue to attach considerable importance to tensile strength. Decline in the demands for the latter may be attributed to the increased use of welding in this country as a method of fabrication. The development of a steel that is fool-proof as regards welding procedures might pave the way to increased use of high-strength steels and contribute towards steel economy in these critical times.

A considerable amount of work has been done at Jamshedpur to develop steel compositions which can yield the same qualities of weldability as possessed by the patented Fortiweld. The main basis of these experimental compositions was manganese, as it may be considered on grounds of availability alone that for the production of large tonnages, this alloy addition should be used. The availability of electrolytic manganese or the low-carbon alloy is, however, essential. A large number of experimental compositions were investigated<sup>11</sup>. From these investigations, it would appear that although steels

with a suitable balance of mechanical properties can be obtained, they do not have the same welding characteristics as Fortiweld. Further, in order to limit weld-hardening, the carbon content has to be maintained so low that it would be difficult to obtain the low carbon contents in open-hearth steel-making by using standard grades of ferro-manganese. The development of manganese-base steels in this category would have to await the development of low-cost electrolytic manganese or low-carbon ferro-manganese. It has been shown that tungsten-boron<sup>12</sup> steels can be developed having the same properties as that of the patented molybdenum-boron steel. However, the proportions of tungsten required are so large that considerations of cost preclude commercial exploitation. In the present circumstances, it would appear that the manufacture of the patented Fortiweld under licence in this country might prove a real measure to effect steel economy.

There is yet still another line of development that holds promise. This is the production of pearlite-free low-carbon steels<sup>13</sup>. These steels that have been developed in Europe possess very high yield ratios at low values of tensile strength because of their high nitrogen and phosphorus contents. At the same time they have excellent welding qualities because they are pearlite-free. Unless one of these lines of development indicated takes place, the future for high-strength steels in this country appears rather dim.

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