INDIAN ALLOY STEELS FOR ENGINEERING INDUSTRIES

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Abstract

The evolution of alloy steels during the last two decades has been characterized by serious efforts to make use of alloying elements as economically as possible and commonly to rely upon indigenous alloying elements as far as possible. Nickel, cobalt, chromium, molybdenum, manganese, vanadium, tungsten, etc., are amongst the chief elements used for conveying high strength at room and elevated temperatures, toughness and corrosion resistance to alloy steels. If extensive production of alloy steels is to be undertaken in India, (a) the main alloying elements must be essentially those which occur in India and (b) the composition of alloy steels must be so adjusted that these new Indian steels will not be merely replicas of standard grades evolved in other countries, but should adequately replace them without impairment of properties such as hardenability and toughness together with any special characteristics called for by the service conditions. The subject has been discussed on this basis for alloy constructional steels, low-alloy high-strength steels, corrosion-resistant steels, etc. The beneficial effects of rare earth and other minor additions have also been discussed. Some data in respect of alloy steels for the Indian automobile industries are presented.

Introduction

IN modern engineering industries, there is practically no field of production in which alloy steels are not used in one form or the other, such as the following industries:

(a) Machine tool industry
(b) Loco industries
(c) Automobile industry
(d) Aircraft industry
(e) Cycles and light engineering
(f) Post and telegraph industry
(g) Electrical machines
(h) Textile
(i) Scientific equipment
(j) Agriculture
(k) Shipbuilding, etc.
(l) Defence and ordnance industry

The following general categories of alloy and special steels are commonly used to feed the industries as shown above:

1. Carbon tool steels for making cutting tools, coinage dies, precision tools, razor-blades, taps and punches, etc.

2. Nickel steels for constructional purposes, such as automobile and machine construction of all kinds.

3. Chromium steels for special purposes involving resistance to wear and abrasion, such as roller-bearings, crusher plates, balls and stamp shoes, rustless steel parts, such as pump rods and cutlery; and also for decorative purposes.

4. Silicon steels for low hysteresis steels and springs and for acid-resistant parts.

5. Manganese steels for points, crossings, rails, crushers and dredger parts.

6. Tungsten steels for magnets and high-speed cutting tools.

7. Nickel-chrome steels for highly stressed constructional parts, oil-hardening and case-hardening gears, armour plates and projectiles.

8. Austenitic nickel-chromium steels for corrosion and heat-resistant parts.

9. Chrome-vanadium steels for springs, constructional work, hooks, forgings and superheated tubes.

10. Molybdenum steels for superheated steam parts such as tubes, bolts, etc.

It is said that ' a steel for any particular use is properly selected when the result is a part that will satisfy the engineering use at the lowest final cost. Many factors enter into such a selection, principally the mechanical and physical properties required to satisfy the engineering use, the cost of processing, the processing equipment required and its availability, and the cost and availability of the steel. Since these factors vary widely, the correct choice of steel for any set of conditions is the one that provides the best balance among all the factors. Thus, a categorical selection of steel for a certain type of part is impractical. The successful use throughout industry of different steels for similar parts is ample evidence of the complexity of the problem.'

The Automobile Field

When, in 1907, Henry Ford launched his 'Model T' on to the motoring world, one of its attractions was that its weight was only half that of other contemporary American cars, largely because of the use made in it of highly stressed alloy and special steels. Since that date, the automobile industry has retained the characteristic of making large relative demands on such alloy steels, despite the policy of individual makers who have prided themselves on economies in alloying elements secured by developing private specifications which were closely 'tailored' to minimum requirements and by applying special engineering techniques to make the best of lower grade materials. As examples of the latter, we have the extensive use made by some makers of cold-drawn bars and the practice of shot-peening machined parts subject to alternating stresses in order to suppress the damaging effects of notches. It is unfortunately not yet the position in India that such measures can commonly be taken.

It is stated that in U.S.A. the automobile industry consumes 50 per cent of the total iron and 25 per cent of the steel production, and 80 per cent of the weight of the average car is iron and steel.

Compared to many advanced countries, India is backward in the development of the automobile industry. The latest automobile world census (1954) shows that there are on the roads:

50 million	vehicles	in	U.S.A.
3·3	,,	,,	U.K.
2·6	,,	,,	France
1·7	,,	,,	U.S.S.R.
0·3	,,	,,	India

Total number of vehicles in India has increased from 1·45 lakhs in 1946 to 3·00 lakhs in 1954.

India's road development is far behind most other countries as the following shows:

Country	*Road miles per* 1000 *sq. miles*
Belgium	2441
U.K.	1949
Netherlands	1919
France	1852
Switzerland	1800
U.S.A.	996
Italy	835
Sweden	612
India	205
Australia	178
Canada	153

Source: International Road Federation.

The motor transport development is even far behind road development as the following figures show:

Country	*Number of motor vehicles on* 1000 *miles of road*
U.K.	14874
U.S.A.	12416
Belgium	8385
Netherlands	4884
Switzerland	3995
France	3717
Italy	3698
Canada	3236
Sweden	2246
Australia	1753
India	829

Source: International Road Federation.

This suggests that the existing road system could carry a higher motor transport volume. Nevertheless, India has about 90,000 trucks, vans, etc., 40,000 buses, etc. — the largest number in any country except U.S. and U.K.

National Income and Motor Vehicle Population — National income and motor vehicle population are interconnected as experience and statistics show. How far high national income is the cause and big automobile fleet the effect or vice versa is open to discussion.

Country	*National income per capita in Rs.*	*Motor vehicle population (without motor-cycles), motor vehicles per 100,000 inhabitants*
U.S.A.	6919	25801
Canada	4143	14176
Switzerland	4048	2531
Belgium	3476	2875
Sweden	2952	3501
U.K.	2762	5590
France	2238	3593
Netherlands	1771	1318
Italy	1119	887
India	255	62

Source: O.E.E.C., International Road Federation.

Regarding the off-take of alloy steels for the Indian automobile industry, precise figures may be difficult to determine in view of the formative conditions of this industry today.

In private specifications, emphasis is naturally put on locally available resources, for instance, General Motors Corporation makes great use of the Amola steels which rely on molybdenum as the main alloying element and on additions of aluminium and vanadium to give controlled fine-grain size. Such private specifications lose many of their merits when transferred to countries other than those of their origin, since the special steels can then be made only by recourse to non-indigenous alloying elements. Moreover, where several overseas designs of cars are being made, as in India, in relatively small numbers, insistence by the producers on steels to the private specifications of each of the designing firms would place unreasonable demands on steel producers to supply a multiplicity of steels in small quantity, or alternatively would lead to unnecessary importations. The same overall picture holds good for other engineering industries in India.

It has been a characteristic of the last two decades that, under stress of the shortages directly and indirectly induced by the Second World War and the Korean conflict, engineering industries in general have been compelled to approach their steel requirements in the spirit of substitution and conservation. The almost insatiable demands made on resources by expanding industries the world over, and especially in North America, make it difficult to foresee a date at which this attitude can be relaxed. It is fortunate, therefore, that researches have shown the way, and engineering practice during these critical years has proved the validity of suggested measures, for efficient substitutions and rationalizations of alloy steels, without lowering their serviceability.

The total Indian alloy steel demand is extremely small from the point of view of the steelmaker; if it is to be divided up between a multiplicity of steels, according to the existing practices of the engineering industry, consumption of no single steel would be adequate to sustain production. Also in this country there is very limited exprience in the production, heat treatment and fabrication of alloy steels, and while the techniques are being learned and developed, it would be unwise to spread the effort too widely, as every alloy steel presents to some extent its individual problems in manufacture and use. The establishment in India of an alloy steel industry of any magnitude which employed indigenous alloying elements would demand as a prerequisite establishment of the production of ferro-alloys for the alloying elements to be used. Clearly the extent of this complication would be a minimum the fewer the different alloy steel types under production.

To illustrate the above point, it is stated that it should be possible by following lines developed in detail below to make in the Indian automobile industry with not more than six or seven types of alloy constructional steel, excluding special steels for electrical and magnetic purposes, stainless steels and so on. However, the demands from the automobile industry would clearly not be sufficient for them to be made efficiently and economically; it, therefore, seems necessary for the special steels needed by the automobile industry to be accepted, so far as possible, by all engineering firms in India for widespread use whenever alloy steel is called for. That is to say, for an acceptable solution to be reached, the problem must be extended beyond the immediate field of the automobile industry and steel compositions must be defined which are widely acceptable and could meet a high proportion of the total Indian needs for special and alloy steels.

In what follows, the problem has been tackled on a wide front to develop lean alloy steels making use of indigenous source materials and forming an essentially Indian range of constructional steels which should meet the alloy and special steel requirements of industry outside the fields of tool steels, steels for electrical and magnetic purposes, and steels for resisting specially corrosive conditions or standing up to creep under high or low temperatures.

The chief alloying elements in use in alloy constructional steels in the world at large are nickel, chromium and molybdenum, although considerable use is also made of constructional steels alloyed with manganese and silicon. Other elements, such as tungsten, cobalt, vanadium and titanium, occupy very minor roles in alloy constructional steels. It will be noted that of the three major alloying elements listed above, only chromium occurs in India on any significant scale. Manganese and silicon are also indigenous. The metallurgist has, therefore, a limited range of indigenous ingredients at his command. Taking the matter literally, he has virtually only one, silicon, since the other elements though occurring in India and in several cases being mined for export are smelted here to a very limited extent, where at all, to give ferro-alloy suitable for application in alloy steel making. As already remarked, a prerequisite to an effective alloy steel industry in India is thus the establishment of a ferro-alloy industry. This subject is discussed elsewhere in this symposium.

Any answer to the question whether there is need for further research in India on steels for engineering industries is necessarily a personal and partly subjective answer. Some metallurgists might give a downright negative as an answer, on the score that each of the Indian manufacturers in the case of automobile industry is associated with interests abroad which know the business thoroughly and have been particularly active in defining material specifications which ensure satisfactory performance of the cars produced. It is, however, the case that the overseas associates of the Indian automobile firms use between them a great diversity of steels, very few of which are produced in India today and many of which could never be produced in India because they would not be required in economic quantities. The idea of rationalizing the demand to a comparatively few types is, therefore, one which soon emerges from consideration of the problem, since it seems likely that a wide variety of steels is not technically necessary and a rationalized series should be possible to manufacture in India. Even, however, if this point is conceded, some metallurgists might still query the need for research, in naming the rationalized series of steels, claiming that this subject of equivalent or alternate steels has been thoroughly worked over, during the war years and the Korean shortages, in Europe, America, Germany, France, etc., and all the best solutions as regards economical compositions are now well known. This still is not a fair statement of the case so far as India is concerned. It may be presumed that no steels would be regarded as a long-term solution of the Indian industry's needs which placed heavy demands on ' non-indigenous ' resources, but this would be the position if India were to conform to the economy steels developed in other countries, where the shortages have been different. So far as India is concerned, the main alloying elements in any steels produced in quantity must be manganese, chromium and silicon, with all possible use also being made of aluminium, titanium and the rare-earth group of metals, and tungsten, vanadium and possibly zirconium being available in the background for use in small amounts; of the two main alloy steel ingredients of other countries, molybdenum is virtually totally unknown indigenously in India so far, while nickel occurs to a very minor extent in the copper worked at Ghatsila — totalling, say, 80 tons per annum, if extractable.

On the presumption made above, there is thus established clear room for research on steels for the automobile and other engineering industries to provide essentially Indian rationalized series of steels which shall have been proved to be equivalent to the steels presently used elsewhere in all material respects. This theme, incidentally, though important is not one on whose solution the industry must necessarily wait before indigenous steel production is attempted, since an interim series of steels which should serve most of the purposes required and which would not place very large demands as non-indigenous resources can already be named with confidence. This is not, however, the only field warranting research in connection with steels for the Indian automobile industry. There is, for example, the vexed question of corrosion of body-work and the undersides of cars under tropical conditions. It is by no means to be assumed that the protective measures taken in other countries are adequate for India where months of driving sand may precede the rains and expose vulnerable points to severe attack. The fact that almost half the motor vehicles on the roads of India are buses or trucks, usually with country-built bodies, raises the question of finding really satisfactory materials of construction for these, and especially of providing a foundation for Indian production of light-weight body members.

Recent Developments in Materials

Recent developments in materials may be classified mainly into two groups: the first group concerns mainly materials developed with the object of conserving scarce alloying elements, to replace materials having a greater proportion of these elements. Materials in the second group are fruits of research aimed at better quality. Most of the recent developments in countries like U.S.A. and U.K. arose out of the need to conserve scarce metals like cobalt, tungsten, chromium, molybdenum and particularly nickel. The Anglo-American Council on Productivity recently prepared a report on the material supply situation in U.K. and U.S.A. and have suggested in it methods for conserving scarce materials.

Low-alloy Steels

In order to economize on the use of scarce elements like nickel, several B.S. emergency specifications covering case-hardening steels have been issued. These are: En 351, 352, 353, 354, 355, 361, 362 and 363, and are meant to replace the case-hardening steels En 33, 34, 35, 36, 37, 38, 39 and 325 respectively. The use of these new steels effects a large saving in nickel and hence is of great importance to India, since in India also, as in U.K., a great shortage of nickel is felt. For example, En 36, 3 per cent Ni-Cr case-hardening steel, has 3-3·75 per cent Ni, 0·6-1·0 per cent chromium and 0·3-0·6 per cent manganese; whereas En 354, 1·75 per cent Ni-Cr-Mo steel suggested as alternative to En 36, has only 1·5-2·0 per cent Ni, about 1·5 per cent less nickel, 0·75-1·25 per cent chromium, 0·5-1·0 per cent manganese and, in addition, 0·10-0·20 per cent molybdenum.

While it might be possible after research to formulate compositions for most or all of these types which would rely entirely on indigenous sources of alloying elements, an interim recommendation is made of the following compositions which correspond to well-tried specifications and make only very moderate demands on alloying elements of which there are no indigenous resources:

Spring Steels — (1) En 47: 1 per cent Cr-V; (2) $1\frac{1}{2}$ per cent Si-Cr.

High-tensile Weldable Steel — Fortiweld (United Steel Co.): 0·5 per cent Mo-B.

Heat-treatable Alloy Steels — Case-hardening: En 325, low Ni-Cr. Through-hardening: En 18, 1 per cent Cr for O.H. $1\frac{1}{8}$ in. bars; En 19, 1 per cent Cr-Mo, or En 24, $1\frac{1}{2}$ per cent Ni-Cr-Mo for O.H. $2\frac{1}{2}$ in. bars; En 29, 3 per cent Cr-Mo for A.H. $2\frac{1}{2}$ in. bars; En 31, 1 per cent C-Cr-bearing steel.

Stainless Steel — En 56D: 0·3 per cent C, 13 per cent Cr cutlery stainless.

High-temperature Steels — En 20, 1 per cent Cr-Mo for steam bolts; En 52, $3\frac{1}{2}$ per cent Si-8 per cent Cr for I.C. engine valve springs.

In passing, it is pointed out that an Indian industry for producing the alloying materials which could be derived from indigenous resources has essentially yet to be developed. The main elements concerned are manganese, of which the standard quality ferro-manganese would be required, and chromium, to be supplied as a medium to low-carbon ferrochrome. Until local arrangements are made to produce these in suitable amounts, they would need to be imported together with the nickel and ferro-molybdenum (or alternatively molybdic oxide) requirements.

The main classes of Indian alloy constructional steels would be the following:

(a) An alloy case-hardening alloy steel with good core strength.
(b) Medium-carbon content steel that will oil-harden in section up to $1\frac{1}{8}$ in. dia. allowing use at 70 tons per sq. in.
(c) Medium-carbon content alloy steel of air-hardening type in small sections and oil-harden fairly fully up to $2\frac{1}{2}$ in. dia. allowing use at 70 tons per sq. in.
(d) An alloy steel of similar carbon content which will air-harden up to $2\frac{1}{2}$ in. dia. and oil-harden in larger sizes allowing the use of 80 tons per sq. in. tensile strength.
(e) A high-carbon alloy steel suitable for ball and roller-bearings.

To these may be added a variety of other steels such as grain-refined steels, machinable leaded steels, nitriding steels, etc.

The U.K. practice of the use of given steels in a tensile range is available only in sections of predefined cross-section or 'limiting ruling section'. The practice may be followed in India. India cannot wait for the fruits of research into the development of indigenous alloy steels solely based on alloying elements available in India. A compromise may be necessary during the interim period utilizing the experience of other countries throwing up emergency steel compositions with as lean alloy content as possible without at the same time throwing away depth of hardening properties etc. These steels may be selected from lean alloy compositions developed abroad and could follow the following:

(1) *En* 325 (low Ni-Cr case-hardening steel):

C	0·17-0·22 per cent
Ni	1·50-2·00 per cent
Cr	0·40-0·60 per cent
Mo	0·20-0·30 per cent

Tensile strength, 55 tons per sq. in. in $1\frac{1}{8}$ in. section

Elongation, 15 per cent min.

Reduction of area, 35 per cent

(2) *En* 18 (oil or water-hardening type):
C 0·35-0·45 per cent
Cr 0·80-1·10 per cent
Tensile strength, 55 tons per sq. in. in $1\frac{1}{8}$ in. section
Elongation, 18 per cent
Reduction of area, 40 per cent

(3) *En* 19 (1 per cent Cr-Mo steel) or *En* 24 ($1\frac{1}{2}$ per cent Ni-Cr-Mo steel):

En 19: C 0·35-0·45 per cent
Cr 0·90-1·50 per cent
Mo 0·20-0·40 per cent
Tensile strength, 70 tons per sq. in. in $1\frac{1}{8}$ in. section
Elongation, 15 per cent
Reduction of area, 30 per cent

En 24: C 0·35-0·45 per cent
Ni 1·30-1·80 per cent
Cr 0·90-1·10 per cent
Mo 0·20-0·35 per cent
Tensile strength, 80 tons per sq. in. at $1\frac{1}{8}$ in. section
Elongation, 14 per cent
Reduction of area, 25 per cent

(4) *En* 29 (3 per cent Cr-Mo steel):
C 0·15-0·35 per cent
Cr 2·50-3·50 per cent
Mo 0·30-0·70 per cent
Ni 0·4 per cent max.
Tensile strength, 80 tons per sq. in. at $2\frac{1}{2}$ in. cross-section
Elongation, 15 per cent

Tensile strength, 100 tons per sq. in.
Elongation, 10 per cent
Reduction of area, 10 per cent min.

This steel may supply the Indian requirements of armour plates, etc.

En 31 (1 per cent C-Cr steel):
C 0·9-1·2 per cent
Cr 1·0-1·6 per cent

This steel is excellent for use in ball and roller-bearing field, develops great resistance to wear and high hardness.

Specific Recommendations

It is now proposed to outline specific recommendations for development to be individually dealt with, as far as possible, within these pages. The development of the following Indian alloy steels requires serious study and research:

1. 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.

2. Steels based on maximum use of chromium and manganese for stainless and corrosion-resistant categories with optimum additions of nitrogen, copper, silicon and micro additions of mischmetal or cerium to counteract hot-shortness.

3. Plain carbon and alloy steels based on boron additions for maximum hardenability with or without molybdenum additions.

4. Steels based on rare earth additions to mild, boron-treated and low-alloy steels for improved properties.

5. Austenitic grain-refined steels to replace low-alloy steels and grain-refined low-alloy steels to replace high-alloy steels for optimum applications.

6. Assessment of substitute steels in comparison with existing standardized steels and the problem of drawing up of suitable Indian specifications for Indian alloy steels required for automobile and other engineering industries.

The above lines of study represent in a nut-shell the general mode of examination of this vastly important subject. The ideas outlined may need modification and adjustment as the experimental research results are applied to production conditions and methods. Different modes of solution may present themselves. These points can only be resolved solely by experience gained as the work progresses.

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

These have been discussed by the author in another paper entitled ' Tailor-made Alloy Constructional Steels ' in the symposium and hence will not be touched upon here.

Tables 1 and 2, however, give the details of German alloy steels of carburizing and constructional categories based on chromium and manganese with or without molybdenum[1].

Manganese Case-hardening Steels

Thus, 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 and manganese.

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

(c) Creating a chromium - manganese - molybdenum steel. Later one without molybdenum.

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

Some typical compositions of manganese case-hardening steels are given in Table 3. It should be possible, particularly with the alloying combination of the chromium-molybdenum-manganese steels 5 and 6, with a carbon content down to 0·16 per cent max., 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 the nickel carburizing steels.

Likewise, the Japanese during World War II developed substitute steels with silicon, manganese and chromium as the chief alloying elements.

Table 4 gives the particulars of Japanese substitute steels which may reasonably form the basis of Indian alloy steels in these categories (Shiji Nishikiori, ' Japanese Substitutional Steels in the Last War ', *Proceedings, World Metallurgical Congress, Sept.* 1951, 483-489).

The following through or semi-through-hardening steels can be extensively developed in India. These follow the American designations as given in Tables 5, 6, 7 and 8.

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

The steels of this series (Table 5) are most frequently used in the through-hardening and semi-through-hardening grades. 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 engines, 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 belt, 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.

TABLE 1—STANDARD ANALYSES OF GERMAN ALLOY STEELS

DESIGNATION	CHEMICAL COMPOSITION, PER CENT						TENSILE STRENGTH	
	C	Mn	Si	Ni	Cr	Mo	Water-hardened	Oil-hardened
	Carburizing Steels: First German Standards (*circa* 1925)							
EN 15	0·10-0·17	0·50 max.	0·35 max.	1·50±0·25	2·20 max.	—	85000-115000	—
ECN 25	0·10-0·17	0·50 max.	0·35 max.	2·50±0·25	0·75±0·20	—	127500-155000	115000-140000
ECN 35	0·10-0·17	0·50 max.	0·35 max.	3·50±0·25	0·75±0·20	—	—	127500-170000
ECN 45	0·10-0·17	0·50 max.	0·35 max.	4·50±0·25	1·10±0·20	—	—	170000-200000
—	0·12-0·16	0·40-0·60	0·35 max.	2·00±2·30	2·00±2·20	0·20-0·30	—	170000-200000
	Nickel-free Carburizing Steels (1935-1940)							
EC 30	0·10-0·16	0·40-0·60	0·35 max.	—	0·30-0·50	—	78000-100000	—
EC 60	0·12-0·18	0·40-0·60	0·35 max.	—	0·60-0·90	—	100000-127000	—
EC Mo 80	0·13-0·17	0·80-1·10	0·35 max.	—	1·00-1·30	0·20-0·30	—	120000-155000
EC Mo 100	0·18-0·23	0·90-1·20	0·35 max.	—	1·10-1·40	0·20-0·30	—	155000-205000
	Molybdenum-free Carburizing Steels (1950)							
15 Cr 3	0·12-0·18	0·40-0·60	0·15-0·35	—	0·50-0·80	—	—	85000-120000
16 N Cr 5	0·14-0·19	1·00-1·30	0·15-0·35	—	0·80-1·10	—	—	115000-155000
20 Mn Cr 5	0·17-0·22	1·10-1·40	0·15-0·35	—	1·00-1·30	—	—	127500-170000
15 Cr Ni 6	0·12-0·17	0·40-0·70	0·15-0·35	1·40-1·70	1·40-1·70	—	—	140000-185000
18 Cr Ni 8	0·15-0·20	0·40-0·60	0·15-0·35	1·80-2·10	1·80-2·10	—	—	170000-205000

TABLE 2—STANDARD ANALYSES OF GERMAN ALLOY STEELS

DESIGNATION	CHEMICAL COMPOSITION, PER CENT						TENSILE STRENGTH	
	C	Mn	Si	Ni	Cr	Mo	Water-hardened	Oil-hardened
				Heat-treating Constructional Steels: First German Standards (*circa* 1925)				
VCN 15w	0·25-0·32	0·40-0·80	0·35 max.	1·50±0·25	0·50±0·20	—	—	92500-107500
VCN 15h	0·32-0·40	0·40-0·80	0·35 max.	1·50±0·25	0·50±0·20	—	—	107500-120000
VCN 25w	0·25-0·32	0·40-0·80	0·35 max.	2·50±0·25	0·75±0·20	—	—	100000-120000
VCN 25h	0·32-0·40	0·40-0·80	0·35 max.	2·50±0·25	0·75±0·20	—	—	115000-135000
VCN 35w	0·20-0·27	0·40-0·80	0·35 max.	3·50±0·25	0·75±0·20	—	—	107500-127500
VCN 35h	0·27-0·35	0·40-0·80	0·35 max.	3·50±0·25	0·75±0·20	—	—	127500-150000
VCN 45	0·30-0·40	0·40-0·80	0·35 max.	4·50±0·25	1·30±0·20	—	—	142500-165000
				Nickel-free Constructional Steels (1935-1940)				
VC 135	0·30-0·37	0·50-0·80	0·35 max.	—	0·90-1·20	—	—	107500-127500
VC Mo 125	0·22-0·29	0·50-0·80	0·35 max.	—	0·90-1·20	0·15-0·25	—	92500-115000
VC Mo 135	0·30-0·37	0·50-0·80	0·35 max.	—	0·90-1·20	0·15-0·25	—	115000-142500
VC Mo 140	0·38-0·45	0·50-0·80	0·35 max.	—	0·90-1·20	0·15-0·25	—	135000-155000
VC Mo 240	0·38-0·43	0·50-0·80	0·35 max.	—	1·60-1·90	0·30-0·40	—	155000-185000
				Low-alloy Constructional Steels (1950)				
40 Mn 4	0·36-0·44	0·80-1·10	0·25-0·50	—	—	—	—	115000-135000
30 Mn 5	0·27-0·34	1·20-1·50	0·15-0·35	—	—	—	—	115000-135000
37 Mn Si 5	0·33-0·41	1·10-1·40	1·10-1·40	—	—	—	—	127500-150000
42 Mn V 7	0·38-0·45	1·60-1·90	0·15-0·35	—	—	—	Note: 0·07-0·12 V	142500-170000
34 Cr 4	0·30-0·37	0·50-0·80	0·15-0·35	—	0·90-1·20	—	—	127500-150000
41 Cr 4	0·38-0·44	0·50-0·80	0·15-0·35	—	0·91-1·20	—	—	127500-150000
25 Cr Mo 4	0·22-0·29	0·50-0·80	0·15-0·35	—	0·90-1·20	0·15-0·25	—	115000-135000
34 Cr Mo 4	0·30-0·37	0·50-0·80	0·15-0·35	—	0·90-1·20	0·15-0·25	—	127500-150000
42 Cr Mo 4	0·38-0·45	0·50-0·80	0·15-0·35	—	0·90-1·20	0·15-0·25	—	142500-170000
50 Cr Mo 4	0·46-0·54	0·50-0·80	0·15-0·35	—	0·90-1·20	0·15-0·25	—	157500-185000
30 Cr Mo V 9	0·26-0·34	0·40-0·70	0·15-0·35	—	2·30-2·70	0·15-0·25	Note: 0·10-0·20 V	180000-207500
36 Cr Ni Mo 4	0·32-0·40	0·50-0·80	0·15-0·35	0·90-1·20	0·90-1·20	0·15-0·25	—	142500-170000
34 Cr Ni Mo 6	0·30-0·38	0·40-0·70	0·15-0·35	1·40-1·70	1·40-1·70	0·15-0·25	—	157600-185000
30 Cr Ni Mo 8	0·26-0·34	0·30-0·60	0·15-0·35	1·80-2·10	1·80-2·10	0·25-0·35	—	177500-207500

TABLE 3 — MANGANESE CASE-HARDENING STEELS

No.	C, %	Si, %	Mn, %	P, %	S, %	Cr, %	Mo, %	REMARKS			
1	0·10-0·20	0·15-0·35	1·10-1·30	0·05 max.	0·08-0·15	—	—	Case-hardening machining steel			
2	0·10-0·15	0·15-0·35	1·25-1·55	0·05 max.	0·08-0·15	—	—	Case-hardening machining steel			
3	0·14-0·18	0·20-0·40	1·40-1·70	0·04 max.	0·09-0·12	0·40-0·60	—	Case-hardening machining steel			
4	0·13-0·17	0·15-0·40	0·80-1·10	—	—	1·00-1·20	0·15-0·25	Standardized case-hardening steel ECMO 80			
5	0·18-0·23	0·15-0·30	1·00-1·20	—	—	1·00-1·20	0·15-0·25	Standardized case-hardening steel ECMO 100			
6	0·17-0·23	0·35 max.	1·20-1·50	—	—	1·70-2·00	0·15-0·25	Standardized case-hardening steel ECMO 200			
								Standardized case-hardening steel	Core strengths in ½ in.	1¼ in.	2¾ in.
7	0·14-0·19	0·40 max.	1·00-1·30	0·04 max.	0·035 max.	0·80-1·10	—	16 MC 5	60-79	50-70	41-60
8	0·17-0·22	0·40 max.	1·10-1·40	0·04 max.	0·035 max.	1·00-1·30	—	20 MC 5	70-92	63-82	54-76
9	0·20-0·25	0·40 max.	1·30-1·60	0·05 max.	0·040 max.	1·20-1·50	—	22 MC 5	—	73-95	79-89

Chromium Steels

The steels of this series (Table 6) 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 the steels in this series are in the manufacture of clutch shafts, transmission main shaft, 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 (Table 7) are used principally for balls, ball races, rollers and roller-bearings. They are characterized by high hardness and excellent wear resistance. They 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. Because of their susceptibility to quench cracks these steels must be handled very carefully.

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 (Table 8) are characterized by fine grain structure, high strength and excellent ductility. In the lower carbon grades 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

TABLE 4 — PROPERTIES OF JAPANESE SILICON-MANGANESE-CHROMIUM HIGH-STRENGTH ALLOY STEEL

PURPOSE	TITLE OF SPECN.	CLASSI-FICATION	CHEMICAL COMPOSITION, PER CENT						HEAT TREATMENT, °C.			
			C	Si	Mn	P max.	S max.	Cr	Normalize	Anneal	Quench	Temper
High Strength Alloy Steel for Aircraft	I-232	A	0·25-0·35	0·7-1·0	0·7-1·0	0·030	0·030	0·7-1·0	850-900	About 850 F.C.	850-900 O.(W.)Q.	550-650 R.C.
		B	0·25-0·35	0·7-1·0*	0·7-1·0*	0·030	0·030	0·7-1·0	850-900	About 850 F.C.	850-900 O.(W.)Q.	450-550 R.C.
		C	0·25-0·35	0·7-1·0	0·7-1·0	0·030	0·030	0·7-1·0	850-900	About 850 F.C.	850-900 O.(W.)Q.	350-450 R.C.
	I-234	A	0·33-0·43	0·8-1·0	0·8-1·2	0·030	0·030	0·8-1·2	850-900	About 850 F.C.	850-900 O.(W.)Q.	600-630 R.C.
		B	0·33-0·43	0·8-1·0	0·8-1·2	0·030	0·030	0·8-1·2	850-900	About 850 F.C.	850-900 O.(W.)Q.	570-650 R.C.
		C	0·33-0·43†	0·8-1·0*	0·8-1·2*	0·030	0·030	0·8-1·2	850-900	About 850 F.C.	850-900 O.(W.)Q.	450-600 R.C.
		D	0·33-0·43	0·8-1·0	0·8-1·2	0·030	0·030	0·8-1·2	—	About 850 F.C.	850-900 O.(W.)Q.	350-500 R.C.
High-strength Alloy Steel for Ordnance	Si-Mn-Cr Steel-1	A	0·27-0·35	0·8-1·2	0·8-1·2	0·030	0·030	0·8-1·2	—	—	850-900 O.(W.)Q.	550-600 O.Q.
		B	0·27-0·35	0·8-1·2*	0·8-1·2	0·030	0·030	0·8-1·2	—	—	850-900 O.(W.)Q.	180-200 550-600
	Si-Mn-Cr Steel-2		0·35-0·40	0·8-1·2	0·8-1·2	0·030	0·030	0·8-1·2	—	—	850-900 O.(W.)Q.	630-700 O.Q.
Steel for Armour Plate	—	A	0·35-0·43	0·8-1·2	0·8-1·2	0·030	0·030	0·8-1·2	—	—	850-900 O.Q.	120-200
		B	0·30-0·40	0·8-1·2	0·8-1·2	0·030	0·030	0·8-1·2	—	—	850-900 O.Q.	180-220
		C	0·38-0·48	0·8-1·2	0·8-1·2	0·030	0·030	0·8-1·2	—	—	850-900 O.Q.	100-180
Steel Plate for Aircraft	II-232	A	0·25-0·35	0·7-1·0	0·7-1·0	0·030	0·030	0·7-1·0	—	About 700 A.C.	About 880 A.C.	About 650 A.C.
		B	0·25-0·35	0·7-1·0	0·7-1·0	0·030	0·030	—	—	—	—	—
		C	0·25-0·35	0·7-1·0*	0·7-1·0	0·030	0·030	—	—	About 700 A.C.	About 880 O.Q.	About 600 A.C.
		D	0·25-0·35	0·7-1·0	0·7-1·0	0·030	0·030	—	—	About 700 A.C.	About 880 O.Q.	About 500 A.C.
		E	0·25-0·35	0·7-1·0*	0·7-1·0	0·030	0·030	—	—	About 700 A.C.	About 880 O.Q.	About 400 A.C.
Steel Tubing for Aircraft	III-232	A	0·25-0·35	0·7-1·0	0·7-1·0	0·030	0·030	0·7-1·0	—	About 700 A.C.	About 880 A.C.	About 600 A.C.
		B	0·25-0·35	0·7-1·0	0·7-1·0	0·030	0·030	0·7-1·0	—	About 700 A.C.	About 880 A.C.	About 600 A.C.
		C	0·25-0·35	0·7-1·0	0·7-1·0	0·030	0·030	0·7-1·0	—	About 700 A.C.	About 880 A.C.	About 600 A.C.
		D	0·25-0·35	0·7-1·0*	0·7-1·0	0·030	0·030	0·7-1·0	—	About 700 A.C.	About 880 O.Q.	About 600 A.C.
		E	0·25-0·35	0·7-1·0	0·7-1·0	0·030	0·030	0·7-1·0	—	About 700 A.C.	About 880 O.Q.	About 500 A.C.
		F	0·25-0·35	0·7-1·0	0·7-1·0	0·030	0·030	0·7-1·0	—	About 700 A.C.	About 880 O.Q.	About 400 A.C.

*Subsequently revised to 0·30-0·80 per cent.

†Subsequently revised to 0·33-0·40 per cent.

R.C., Rapid Cooling; O.Q., Oil Quenching; A.C., Air Cooling; W.Q., Water Quenching; F.C., Furnace Cooling.

TABLE 5

DESIGNATION	C %	Mn %	P %	S %	Si %
1330	0·28-0·33	1·60-1·90	0·040	0·040	0·20-0·35
1335	0·33-0·38	1·60-1·90	0·040	0·040	0·20-0·35
1340	0·38-0·43	1·60-1·90	0·040	0·040	0·20-0·35
1345	0·43-0·48	1·60-1·90	0·040	0·040	0·20-0·35
1350	0·48-0·53	1·60-1·90	0·040	0·040	0·20-0·35

TABLE 6 — THE STEELS OF THE 5100 SERIES

DESIGNATION	C %	Mn %	P %	S %	Si %	Cr %
5120	0·17-0·22	0·70-0·90	0·040	0·040	0·20-0·35	0·70-0·90
5130	0·28-0·33	0·70-0·90	0·040	0·040	0·20-0·35	0·80-1·10
5140	0·38-0·43	0·70-0·90	0·040	0·040	0·20-0·35	0·70-0·90
5145	0·43-0·48	0·70-0·90	0·040	0·040	0·20-0·35	0·70-0·90
5150	0·48-0·55	0·70-0·90	0·040	0·040	0·20-0·35	0·70-0·90
5152	0·45-0·55	0·70-0·90	0·040	0·040	0·20-0·35	0·90-1·20

TABLE 7 — HIGH-CARBON CHROMIUM STEELS

DESIGNATION	C %	Mn %	P %	S %	Si %	Cr %
52095	0·95-1·10	0·25-0·45	0·025	0·025	0·20-0·35	0·40-0·60
52098	0·95-1·10	0·25-0·45	0·025	0·025	0·20-0·35	0·90-1·15
52100	0·95-1·10	0·25-0·45	0·025	0·025	0·20-0·35	1·20-1·50
52101	0·95-1·10	0·25-0·45	0·025	0·025	0·20-0·35	1·30-1·60

TABLE 8 — THE STEELS OF THE 6100 SERIES

DESIGNATION	C %	Mn %	P %	S %	Si %	Cr %	V %
6120	0·17-0·22	0·70-0·90	0·040	0·040	0·20-0·35	0·70-0·90	0·10 min.
6145	0·43-0·48	0·70-0·90	0·040	0·040	0·20-0·35	0·80-1·10	0·15 min.
6150	0·48-0·55	0·65-0·90	0·040	0·040	0·20-0·35	0·80-1·10	0·15 min.
6150	0·47-0·53	0·70-0·90	0·025	0·025	0·20-0·35	0·80-1·10	0·15 min.
6152	0·48-0·55	0·70-0·90	0·040	0·040	0·20-0·35	0·80-1·10	0·10 min.

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, pistons and plungers and parts for pressure vessels. In the machine tool industry this series of steel is used for gears, chuck jaws, precision lead screws spindles and tool holders and collets.

High-tensile Low-alloy Steels

These have been discussed by the author in another paper in the symposium entitled 'Tailor-made Alloy Constructional Steels' and hence will not be touched here.

Steels Based on Maximum Use of Chromium and Manganese for Stainless and Corrosion-resistant Categories with Additions of Nitrogen, Copper, Silicon and with Micro Additions of Mischmetal or Cerium to Counteract Hot-shortness

These have been discussed in papers 'Investigation into the Development of Prospective Indian Austenitic Stainless Steels' and 'Micro-metallurgy of Alloy Steels' by the author and will not be discussed here.

Plain-carbon and Alloy Steels Based on Boron Additions for Maximum Hardenability with or without Molybdenum Additions

In India cobalt, columbium, tungsten, nickel and molybdenum are practically non-existent. Some of these elements find extensive alloying applications in different grades of alloy steels, such as heat-treatable constructional grades, for the purpose of imparting hardenability.

In most applications of constructional alloy steels, boron can replace a sizeable quantity of nickel, chromium, molybdenum and other critical elements. In addition to conserving alloy elements, however, boron has other advantages. It improves the hot and cold working properties of the steel, gives a shorter annealing cycle, and imparts better machinability. When boron is used as an alloy replacement in carburizing steels, the treatment is simplified by the shorter annealing cycle, and the retained austenite and undissolved carbides in the carburized case are minimized.

In some applications which require medium or high-carbon steels, too, a boron steel can replace a richer alloy with considerable savings, not only in steel cost, but also in fabrication. In the last part of World War II, thousands of tons of boron steels were used in foreign countries for military equipment. Since 1945, large production applications for boron steels have been found in diesel locomotive crankshafts, heavy-duty tractor axles, cold-headed parts, etc.

Effects of Boron in Steel — The *Metals Handbook* of the American Society for Metals describes the role of boron in steel as follows: 'Boron is used in steel for one purpose only — to increase the hardenability; that is, to increase the depth to which the steel will harden when quenched. Only a few thousandths of a percent is ordinarily added.'

The effect of boron on hardenability is very potent. It can replace several hundred times its own weight of manganese, chromium, molybdenum and nickel. It has been shown, for example, that 0·001 per cent boron gives the same hardening effect as 1·33 nickel, plus 0·31 chromium, plus 0·04 per cent molybdenum — a total of 1·68 per cent alloy. This effect of boron on hardenability, however, decreases with increasing carbon content, and boron is most effective in conserving critical alloys in the low-carbon steels. The carburizing grades of alloy steel, with less than 0·30 per cent carbon, are more fertile fields for boron substitution than spring steels with 0·60 per cent carbon.

Isothermal transformation diagrams aid in understanding the behaviour of boron steels during conventional quenching, normalizing and annealing heat treatments. The transformation completion time for a boron steel is only slightly longer than it is for the same steel minus the boron. In this respect boron is unique. It delays the start of transformation appreciably, but delays completion only slightly. The boron steel is much softer in the as-rolled or normalized state, provided that the piece is large enough to prevent air-quenching.

In spite of the fact that boron has such a powerful effect on hardenability, it makes almost no change in the Ae_1, Ae_2 or Ms temperatures of the base composition. Boron tends to lower the austenitic coarsening temperature of a steel. This effect can be counteracted by a judicious use of aluminium additions used for grain size control.

The exact effect of boron on notch toughness is not clear. Comparison of a given composition with and without boron indicates that the addition increases notch toughness at high hardness levels (Rc 50 and above) and reduces it at lower hardness. When a low-alloy boron composition is compared with a higher alloy steel, however, the effect of the boron on the notch toughness may be masked by the effects of the other elements. In any event, the notch toughness in all cases is adequate for most engineering applications.

The endurance limit and the endurance ratio of a boron steel are the same for a given hardness as values shown by other alloy steels heat-treated to the same hardness.

In the amounts normally used, boron does not increase the resistance to softening on tempering as other alloying elements like vanadium, molybdenum and tungsten do. When boron is used to replace these elements partially or completely to obtain equivalent hardenability, it is usually necessary to use a lower temperature to get a given hardness and strength. The tensile strength will be the same at the same tempered hardness, even though a different tempering temperature is used.

Since boron apprently does not retard softening appreciably during the tempering, these steels will not be adequate replacements for the higher alloy steels containing molybdenum, vanadium and tungsten that are designed for high-temperature service. When the steel is annealed to a microsctructure of pearlite, or of ferrite and pearlite, such as might be encountered in the centre of large pieces of moderate or low hardenability grades, boron lowers the tensile strength and the notch toughness. For this reason the hardenability of a boron steel must be sufficient to obtain martensite prior to tempering, so that optimum properties can be developed at the point in the part where the highest stresses are encountered.

There has been little mention of the desirable processing characteristics of the boron steels. The forging, cold-heading, descaling, annealing and machining qualities of these steels are better than those of the steels they replace.

Boron steels are easier to anneal than the higher alloys they replace because the boron steel has about the same annealing characteristics as the base composition to which boron is added. Changing to a boron steel may cut annealing time and costs in half. Machinability can also be improved by obtaining a more desirable structure in the boron steel.

Carburizing Boron Steels — During the past few years, development work on carburizing steels containing boron has been undertaken to find a steel with hardenability comparable to American 3310 and 9310 steels which would minimize certain undesirable characteristics of these higher alloys such as retained austenite and undissolved carbides after carburizing and hardening which made expensive treatments necessary with 3310 and 9310. The United States Steel Co. developed USS Super-Kore A, which is essentially 4312 with boron and 0·03-0·07 per cent vanadium added. This boron alloy has been thoroughly tested by the Pratt and Whitney Div., United Aircraft Corporation, for heavy-duty gears, shafts and pinions and is approved for aircraft use under AMS Specification 6266. Pratt and Whitney reported improved carburizing characteristics— much less retained austenite and undissolved carbides on direct quenching. This development has been extended by the United States Steel to lower alloy contents such as Super-Kore E (C 4615-plus-boron) and Super-Kore C (8615-plus-boron), with comparable results. Two problems associated with boron in the carburizing steels, however, deserve special attention. The first problem is that of the hardenability of the case. The hardenability effect of boron decreases with increasing carbon content. This means that although the core hardenability of a boron steel is similar to that of a higher alloy, the case in a piece of boron steel that is carburized to a carbon content of 1 per cent or more has only got the hardenability of plain base composition. Soft spots may be induced in heavy sections and even in small sections where fixture quenching is used to control distortion.

The second problem presented by boron in carburizing steels is the partial or complete loss of the hardenability effect of the boron when the steel is heated to high temperatures. This apparent loss in hardenability is also found after long time heating at carburizing temperatures followed by direct quenching. The exact mechanism of this change is still a matter of conjecture. Thus, the carburizing behaviour of the boron steels has not been found to be affected by the presence of boron, but considerably more attention must be paid to heat treatment than when using the high nickel-chromium and nickel-molybdenum types of steel in order to obtain equivalent impact strengths. Owing to the inability of boron to increase hardenability to the same degree in the presence of high carbon as for low, the balance in properties between case and core in case-hardening boron steels is disturbed. To minimize this the carbon and manganese contents of the base analysis are usually lowered a point or two as compared with the standard steel and efforts made to control the carbon content of the case to about the eutectoid composition; the latter can be achieved by gas carburizing.

New Boron Alloy Steels — Because of the necessity for conserving nickel, chromium and molybdenum, the American Iron & Steel Institute has announced two new series of steels designed to accomplish this purpose. These steels, 80Bxx and 81Bxx, are low nickel, chromium and molybdenum compositions in which boron has replaced about half of the critical alloy content of the 8600-8700 steels, which were the basic national emergency steels of World War II and have since taken their place in the mass production industries.

The 80Bxx steels will match the hardenability of the 86xx-87xx types and the 81Bxx will match the 41xx types. The new alloys should be able to replace 70-80 per cent of the present constructional alloy steels on an equivalent hardenability basis. The hardenability of the production heats seems to be exceeding the limits predicted from laboratory data.

Table 9 illustrates the substitution of standard AISI steels with boron-treated AISI substitute steels.

Applications of Boron Steels in U.S.A.[9] — The bulk of the tonnage of boron steel production has in the past been consumed by a few manufacturers, the main ones being the Caterpillar Tractor Co. (bolts and screws); International Harvester Co. (bolts, axles, shafts, gears, etc.); Plomb Tool Co. (engineers' hand tools); Timken (Detroit) Axle Co. (gears and shafts).

While these companies are still absorbing a substantial proportion of the production, the use of boron steels is spreading to other

TABLE 9*— COMPOSITION OF STANDARD AISI STEELS WITH B-TREATED AISI SUBSTITUTE STEELS

AISI DESIGNATION	ALLOY CONTENT, %				BORON DESIGNATION AISI	TYPE OF STEEL	ALLOY CONTENT OF BORON STEEL AS AGAINST STANDARD								ALLOY SAVING, %
							Decrease, %				Increase, %				
	Cr	Mn	Mo	Ni			Cr	Mn	Mo	Ni	Cr	Mn	Mo	Ni	
1300	—	1·75	—	—	80B00		—	1·00	—	—	0·25	—	0·10	0·3	0·35
2300	—	—	—	3·50	86B00	Direct hardening	—	—	—	3·00	0·50	—	0·20	—	2·30
2500	—	—	—	5·00	80B00		—	—	—	4·70	0·25	—	0·10	—	4·35
3100	0·7	—	—	1·25	80B00	Carburizing	0·50	—	—	1·10	—	—	0·10	—	1·40
					80B00	Direct hardening	0·40	—	—	1·00	—	0·3	0·10	—	1·00
					14B00	Direct hardening	0·70	—	—	1·25	—	—	—	—	1·95
3300	1·5	—	—	3·50	43B00		1·00	—	—	2·00	—	0·2	0·25	—	2·55
4000	—	0·80	0·25	—	80B00		—	—	0·20	—	0·25	—	—	0·3	−0·35 Mo saved
4100	1·0	0·80	0·20	—	80B00	Carburizing	0·75	—	0·10	—	—	—	—	0·3	0·55
					81B00	Direct hardening	0·60	—	0·10	—	—	—	—	0·3	0·40
					14B00	Direct hardening	1·00	—	0·20	—	—	—	—	—	1·20
4300	0·7	—	0·25	1·80	94B00	Carburizing	0·30	—	0·15	1·30	—	—	—	—	1·75
					86B00	Direct hardening	0·70	—	0·15	1·30	—	0·2	—	—	1·95
					81B00	Direct hardening	0·30	—	0·15	1·50	—	—	—	—	1·95
4600	—	—	0·25	1·80	80B00		—	—	0·15	1·50	0·25	—	—	—	1·40
					94B00	Carburizing	—	—	0·15	1·30	0·40	0·4	—	—	0·65
4300	—	—	0·25	3·50	94B00		—	—	0·15	2·00	0·40	—	—	—	1·75
					43B00	Carburizing	—	—	—	1·70	0·50	—	—	—	1·20
					46B00	Carburizing	—	—	—	1·70	—	—	—	—	1·70
5000	0·5	0·80	—	—	40B00		0·50	—	—	—	—	—	0·25	—	0·25
5100	1·0	0·80	—	—	80B00		0·75	—	—	—	—	—	0·10	0·3	0·35
6100	1·0	0·80	0·10	—	80B00		0·75	—	0·10	—	—	—	0·10	0·3	0·45
8600	0·5	0·80	0·20	0·50	80B00		0·25	—	0·10	0·20	—	—	—	—	0·55
					94B00	Carburizing	0·10	—	0·10	0·20	—	—	—	—	0·40
					50B00		—	—	0·20	0·50	—	—	—	—	0·70
					14B00	Carburizing	0·50	—	0·20	0·50	—	—	—	—	1·20
8700	0·5	0·80	0·25	0·50	80B00		0·25	—	0·15	0·20	—	—	—	—	0·60
9200	1·2	—	0·10	3·20	43B00	Carburizing	0·50	—	—	1·40	—	—	0·15	—	1·75
9400	0·4	1·10	0·10	0·50	80B00	Direct hardening	0·15	0·40	0·10	0·20	—	—	—	—	0·85

*Replacement of alloy by boron in carburizing and direct-hardening grade. Scherer, *Stahl und Eisen*, Nov. 6, 1952; *Metal Treatment*, Feb. 1952.

companies. In Table 10 are listed the different production trial applications of boron steels so far as they are known. From this table it will be seen that the large tonnages of boron steels which have been consumed in the past have been for: (a) high-tensile bolts; (b) heavy vehicle and tractor transmission and back axle gears; (c) heavy vehicle and tractor crankshaft and steering gear forgings; (d) heavy vehicle and tractor axles; (e) engineers' hand tools.

Grades of Alloy Steel Replaced by Boron Qualities — Trials have been made with innumerable qualities of boron steel and much discussion has taken place on the question of preparing and issuing a substitution table of alternative steels. The Iron and Steel Division of the American National Production Authority, in its efforts to encourage conservation of alloys, has drawn up its own tentative list to include boron steels. Even though by this means a boron alternative steel is frequently recommended, it has not so far become compulsory to use it. The list was drawn up on the basis of what would be the most generally accepted alternative for each standard quality in March 1952. The original list with the analyses of the various grades is given in Table 11.

Substitution of a boron-treated 'triple alloy' steel containing about 0·50 per cent Ni, 0·65 per cent Cr and 0·10 per cent Mo for a 3½ per cent nickel steel in tractor axles and steering mechanisms, together with similar substitutions in other heavy parts, has enabled the Caterpillar Tractor Co., for example, to save some 12,000 tons of alloying nickel since 1940 — certainly a notable performance for a single concern.

Physical Properties of Boron Steel — Hardenability: As explained earlier, substitution in the United States is often based largely upon the results of Jominy hardenability tests. Nowadays one major claim only is made for the use of boron in steel — that it increases hardenability and thereby can be used to replace other alloys such as manganese, nickel, chromium and molybdenum. Boron steels are peculiar in that, at approximately the eutectoid composition, boron appears to have little or no effect on hardenability. However, as the carbon decreases below the eutectoid composition, the effectiveness of boron increases linearly.

Though the bulk of the United States data on boron steels concerns hardenability, there are very few identical production steels which are produced with and without boron because grades have been specially designed to have hardenabilities equivalent to those of more highly alloyed steels. Thus information demonstrating the potency of boron with respect to increasing the hardenability, let alone other physical properties, of a given grade is scarce. Effort has been concentrated on securing information which is directly useful in selecting alternate grades. Unfortunately, it has not been found possible with low-alloy boron steel to duplicate the entire hardenability curve of the more conventional types of alloy steel. This is so because there is a fundamental difference in the shape of the hardenability curves, that for the low-alloy boron steel breaking more sharply as a general rule.

Quenching: During the quenching of boron steels it is usually necessary to use a higher temperature to retain ferrite in solution than with a standard steel. This has two possible disadvantages.

It has been reported that boron steels are more sensitive to temper-brittleness than the qualities they replace. In consequence, it has been considered advisable to avoid tempering above 540°C. unless the part is subsequently liquid-quenched. Since in alloy steels sensitivity to temper-brittleness tends to become more frequent as the total alloying content increases or as the chromium-molybdenum balance is displaced, the lowering of molybdenum and raising of the chromium content in the base composition of many of the boron grades may in itself increase the susceptibility to temper-brittleness.

TABLE 11—BORON ALTERNATIVE STEELS

Standard steel	Analysis, per cent					Type	Downgrade	Analysis, per cent					
	Mn	Si	Ni	Cr	Mo			Mn	Si	Ni	Cr	Mo	V
1300	1·60-1·90	0·20-0·35	—	—	—	Both	No downgrade	—	—	—	—	—	—
2300	0·40-0·60	0·20-0·35	3·25-3·75	—	—	Carburizing	TS.8600	0·70-0·90	0·20-0·35	0·30-0·60	0·55-0·75	0·08-0·15	—
2300	0·70-0·90	0·20-0·35	3·25-3·75	—	—	Through	80B00	0·70-1·00	0·20-0·35	0·20-0·40	0·15-0·35	0·08-0·15	—
2500	0·40-0·60	0·20-0·35	4·75-5·25	—	—	Carburizing	TS.8600	0·70-0·90	0·20-0·35	0·30-0·60	0·55-0·75	0·08-0·15	—
3100	0·40-0·60	0·20-0·35	1·10-1·40	0·55-0·75	—	Carburizing	TS.94B00	0·75-1·00	0·20-0·35	0·30-0·60	0·30-0·50	0·08-0·15	—
3100	0·70-0·90	0·20-0·35	1·10-1·40	0·55-0·75	—	Through	80B00	0·70-1·00	0·20-0·35	0·20-0·40	0·15-0·35	0·08-0·15	—
3300	0·45-0·60	0·20-0·35	3·25-3·75	1·40-1·75	—	Carburizing	43BV00	0·45-0·65	0·20-0·35	1·65-2·00	0·40-0·60	0·08-0·15	0·03
4000	0·70-0·90	0·20-0·35	—	—	0·20-0·30	Both	TS.8100.5100	0·70-0·90	0·20-0·35	0·20-0·40	0·30-0·50	0·08-0·15	—
4100	0·75-1·00	0·20-0·35	—	0·80-1·10	0·15-0·25	Through	TS.4100	0·80-1·05	0·20-0·35	—	0·90-1·20	0·08-0·15	—
4300	0·45-0·65	0·20-0·35	1·65-2·00	0·40-0·60	0·20-0·30	Carburizing	TS.94B00	0·75-1·00	0·20-0·35	0·30-0·60	0·30-0·50	0·08-0·15	—
4300	0·60-0·80	0·20-0·35	1·65-2·00	0·70-0·90	0·20-0·30	Through	TS.86B00	0·75-1·00	0·20-0·35	0·40-0·70	0·55-0·75	0·08-0·15	—
4600	0·45-0·65	0·20-0·35	1·65-2·00	—	0·20-0·30	Carburizing	TS.8600	0·70-0·90	0·20-0·35	0·30-0·60	0·55-0·75	0·08-0·15	—
4600	0·60-0·80	0·20-0·35	1·65-2·00	—	0·20-0·30	Through	80B00	0·70-1·00	0·20-0·30	0·20-0·40	0·15-0·35	0·08-0·15	—
4800	0·40-0·60	0·20-0·35	3·25-3·75	—	0·20-0·30	Carburizing	TS.94N00	0·75-1·00	0·20-0·35	0·30-0·60	0·30-0·50	0·08-0·15	—
5000	0·70-0·90	0·20-0·35	—	0·55-0·75	—	Through	No downgrade						
5100	0·70-0·90	0·20-0·35	—	0·70-0·90	—	Both							
6100	0·70-0·90	0·20-0·35	—	0·80-1·00	(V15 min.)	Through							
8600	0·70-0·90	0·20-0·35	0·40-0·70	0·40-0·60	0·15-0·25	Carburizing	TS.8600	0·70-0·90	0·20-0·35	0·30-0·60	0·55-0·75	0·08-0·15	—
8600	0·75-1·00	0·20-0·35	0·40-0·70	0·40-0·60	0·15-0·25	Through	80B00 (0·40 max. Ni)	0·70-1·00	0·20-0·35	0·20-0·40	0·15-0·35	0·08-0·15	—
8700	0·70-0·90	0·20-0·35	0·40-0·70	0·40-0·60	0·20-0·30	Carburizing	TS.8600	0·70-0·90	0·20-0·35	0·30-0·60	0·55-0·75	0·08-0·15	—
8700	0·70-1·00	0·20-0·35	0·40-0·70	0·40-0·60	0·20-0·30	Through	80B00 (6·40 max. Ni)	0·70-1·00	0·20-0·35	0·20-0·40	0·15-0·35	0·08-0·15	—
9200	0·70-1·00	1·80-2·20	—	—	—	Through	No downgrade	—	—	—	—	—	—
9300	0·45-0·65	0·20-0·35	3·00-3·50	1·00-1·40	0·08-0·15	Carburizing	43VB00	0·45-0·65	0·20-0·35	1·60-2·00	0·40-0·60	0·08-0·15	0·03
9400	0·90-1·20	0·20-0·35	0·30-0·60	0·30-0·50	0·08-0·15	Through	TS.4100	0·80-1·05	0·20-0·35	—	0·90-1·20	0·08-0·15	—
9700	0·50-0·80	0·20-0·35	0·40-0·70	0·10-0·25	0·15-0·25	Through	TS.8100	0·70-0·90	0·20-0·35	0·20-0·40	0·30-0·50	0·08-0·15	—
9800	0·70-0·90	0·20-0·35	0·85-1·15	0·70-0·90	0·20-0·30	Through	TS.86B00	0·75-1·00	0·20-0·35	0·40-0·70	0·55-0·75	0·08-0·15	—

Impact resistance: By American standards the notch toughness of boron steels is adequate for most engineering applications. It has been pointed out that very little success has accompanied efforts to correlate impact test data with performance of actual parts in service, and in the absence of such correlation, the inclusion of impact requirements in specifications is of questionable value.

The actual Izod values of 25 boron steels are given in Table 12[9]. Boron steels, when fully quenched and tempered, appear to have excellent Izod impact strength at low temperatures, down at least to −40°C. It is shown that the wide range of analysis of the 25 boron steels listed (Table 12) indicates that alloy content does not affect Izod impact strength of tempered martensite, and that improved impact strength, usually attributed to the alloy, is more likely a resultant effect obtained from increasing hardenability. However, all these remarks are confined to the impact strengths obtainable in sections sufficiently small to be through-hardened. Under conditions of slack quenching, however, either as a result of heat-treating practice or the mass of the quenched part, there are indications that boron tends to lower the impact strength. However, few data are available from which can be determined how significantly boron lowers the impact resistance of incompletely hardened steels.

Position in England

The search for new and improved steels has occupied considerable attention of the British metallurgist, and one objective over the years has been to provide a steel which has high strength and at the same time is readily weldable. The United Steel Companies Limited in U.K., as suppliers of steels covering a wide range of applications, regarded the development of steel of this type as a matter of considerable importance. Consequently, their Research and Development Department have examined many experimental steels only to find that additions of the more commonly used alloys produced steels which were generally difficult to weld in combination with satisfactory mechanical properties.

In an endeavour to improve the steel used in power station steam pipes, experiments were being conducted to determine the effects of boron on the properties of low-carbon molybdenum steel. It was discovered that when molybdenum and boron were present in certain proportions, the yield point of a low-carbon steel was doubled without any necessity for heat treatment. As little as an ounce of boron, when added to a ton of steel containing 0·40 per cent of Mo, was sufficient to produce this pronounced and important improvement in strength.

This new steel has been given the name of ‘ Fortiweld ’, a title derived from the properties of the steel, namely: tensile strength of 40 tons/sq. in. combined with ease of welding, the latter property being attributable to its low carbon content. In addition to its high strength at ordinary temperatures and easy weldability, Fortiweld possesses good properties at 450°-500°C. being capable of withstanding service stresses two to three times those permissible for mild steel.

The unique combination of properties provided by Fortiweld makes it particularly attractive for highly stressed welded structures, either at ordinary or elevated temperatures, and many important applications have already been made, including the casing of aircraft jet engines, special tubing and bridge components.

Bardgett[10] studied the possible advantages of boron additions in improving mechanical properties by the results of tests on a low-carbon 0·50 per cent Mo steel. Yield strength was doubled and tensile strength increased 30 per cent with an addition of 0·003 per cent B. A series of low-carbon steels containing boron and variable molybdenum content was studied. Improvement in the properties of

TABLE 12 — THROUGH-HARDENING STEELS OIL-QUENCHED AND TEMPERED AS 0·535 IN. DIA. ROUNDS

GRADE	ANALYSIS, PER CENT						HARDNESS Rc.	EQUIVALENT TENSILE, tons/sq. in.	IZOD IMPACT, FT.-LB.		
	C	Mn	Si	Ni	Cr	Mo			Room temp.	−30°C.	−40°C.
14B35	0·38	0·82	0·25	0·04	0·04	0·01	45	93	33-35	23-28	—
14B35	—	—	—	—	—	—	37	76	41	—	—
14B35	—	—	—	—	—	—	36	75	58	59	—
14B35	—	—	—	—	—	—	35	73	55-62-68	57-59-63	55
14B35	—	—	—	—	—	—	30	65	75	—	67
14B35	—	—	—	—	—	—	25	58	75	—	—
14B35	—	—	—	—	—	—	13	45	103	—	—
41B50	0·52	0·81	0·26	0·04	0·04	0·01	45	93	15-19	9-12	—
41B50	—	—	—	—	—	—	36	75	46-47	41-42	—
50B60	*	*	*	*	*	*	49	101	15·5	—	13·5
50B60	—	—	—	—	—	—	45	93	15·5	—	13
50B60	—	—	—	—	—	—	43	88	25	—	17·5
50B60	—	—	—	—	—	—	37·5	77	33·5	—	28
50B60	—	—	—	—	—	—	32	68	49·5	—	41
80B30	0·33	0·62	0·24	0·31	0·28	0·17	36	75	—	47	—
80B50	*	*	*	*	*	*	49	101	15	—	11·5
80B50	—	—	—	—	—	—	45	93	—	—	13
80B50	—	—	—	—	—	—	43	88	24	—	17
80B50	—	—	—	—	—	—	37·5	77	31	—	24·5
80B50	—	—	—	—	—	—	32	68	49	—	44
80B60	*	*	*	*	*	*	49	101	6·5	—	3
80B60	—	—	—	—	—	—	45	93	12	—	9
80B60	—	—	—	—	—	—	43	88	16	—	13
80B60	—	—	—	—	—	—	37·5	77	25	—	14·5

*Compositions of these steels were not reported.

TABLE 12 — THROUGH-HARDENING STEELS OIL-QUENCHED AND TEMPERED AS 0·535 IN. DIA. ROUNDS — *Continued*

GRADE	ANALYSIS, PER CENT						HARDNESS Rc.	EQUIVALENT TENSILE, tons/sq. in.	IZOD IMPACT, FT.-LB.		
	C	Mn	Si	Ni	Cr	Mo			Room temp.	−30°C.	−40°C.
81B40	0·41	0·84	0·30	0·33	0·47	0·13	32	68	50	—	26·5
81B40	—	—	—	—	—	—	39	80	35·5	—	—
81B45	0·43	0·80	0·26	0·36	0·45	0·13	34	72	47	—	—
81B45	—	—	—	—	—	—	47	97	19	—	—
81B45	—	—	—	—	—	—	42	86	31·5	—	—
81B45	—	—	—	—	—	—	33	70	58·5	—	—
86B45	0·44	0·80	0·27	0·53	0·75	0·12	26	59	86·5	—	—
86B45	—	—	—	—	—	—	43	88	18	—	—
94B30	0·28	1·06	0·44	0·31	0·39	0·11	36	75	41	—	—
94B30	—	—	—	—	—	—	45	93	36-37	22-25	—
94B30	—	—	—	—	—	—	44	91	30	—	31
94B30	—	—	—	—	—	—	40	82	38	—	—
94B30	—	—	—	—	—	—	36	75	62-55	39-45	—
94B30	—	—	—	—	—	—	35	73	61	—	51
94B30	—	—	—	—	—	—	27	61	89	—	—
94B40	0·42	1·06	0·46	0·34	0·30	0·11	23	56	104	—	—
94B40	—	—	—	—	—	—	44	91	17-17-23	14-15-18	—
94B40	—	—	—	—	—	—	43	88	25	—	—
94B40	—	—	—	—	—	—	36	75	42-45	38-40	—
94B40	—	—	—	—	—	—	35	73	45	42	—
94B40	—	—	—	—	—	—	34	72	51	—	—
94B50	0·50	1·36	0·48	0·30	0·31	0·10	23	56	88	—	—
94B50	—	—	—	—	—	—	45	93	15-18-19	14-14-14-20	—
94B50	—	—	—	—	—	—	36	75	40	23	—
							35	73	43-46-47	29-43-46	—

existing steels by the addition of boron — rather than replacement of alloying elements by boron — may ultimately lead to economic advantages by reductions in the amount of steel used and overall costs. In the lower carbon series, the effect of boron on the mechanical properties, in the presence of 0·15 per cent Mo, was negligible. Tensile strength and yield strength increased progressively with increase in Mo to 0·35 per cent. At 0·44 per cent Mo ultimate tensile stress more than doubled.

Further increase in molybdenum content had no significant effect. Elongation decreased correspondingly to increase in tensile strength. Reduction in area figures decreased only slightly with increase in tensile strength. The high yield stress of the steels containing over 0·35 per cent Mo and with only 0·04-0·05 per cent C was noteworthy. The second series, steels with 0·14 per cent C, had similar characteristics. Remarkably good properties were obtained when the steel contained more than 0·30 per cent Mo. In a series of 0·5 per cent Mo-B steels, increasing the carbon content raised the ultimate tensile stress and yield stress. Poor notch impact toughness was, however, obtained when carbon content reached 0·18 per cent. The effect of increasing boron in the presence of 0·5 per cent Mo was found to be beneficial up to about 0·007 per cent. Beyond this figure ultimate tensile stress and yield stress decreased to low values.

Boron did not improve low-carbon steels containing respectively 0·6 per cent Ni, up to 1·5 per cent Cr, 0·07 per cent and 0·1 per cent Va. Since boron raises yield stress and ultimate tensile stress in the presence of molybdenum but not in the presence of chromium, nickel or vanadium, some interaction of molybdenum and boron is indicated. The maximum effect of boron is obtained only above a certain minimum molybdenum content.

Tests on a 1·0 per cent Mn-Mo-B steel of variable molybdenum content showed a marked change when molybdenum was increased from 0·11 to 0·21 per cent. Ultimate tensile stress increased from 36·4 to 45·9 tons per sq. in. and yield stress from 22·3 to 33·2 tons per sq. in. With further increase in molybdenum to 0·51 per cent ultimate tensile stress and yield stress increased slightly.

Scherer and Bungardt[11] have stated in German investigations on boron steel that in appraising the practical possibilities of American work, it should be remembered that German standards contain but few steels instead of the wealth of varieties available in the United States; also that German carburizing steels contain no molybdenum. Investigations show that about 14 lb. of chromium plus nickel can be saved per ton of steel by treatment with boron, as in the replacement of the present standard 15 Cr-Ni 6 with a steel with the same chromium (1·55 per cent) but with nickel cut almost in half.

Rare Earth Addition to Cast Boron Steel

Cerium rare earths have been found to increase the impact strength of quenched and drawn cast boron basic electric steel of the composition[12]:

C	0·28-3·40 per cent
Mn	1·10-1·70 per cent
Usual Si, S and P	

The beneficial effect appears to decrease with decreasing temperature. Apparently rare earths do not directly increase hardenability. Half of each heat-treated with rare earths has a hardenability greater than the half not treated with rare earths. A 35-45 per cent increase has been obtained in 3-6 heats containing 0·009-0·016 per cent N. It is known that this level of N inhibits the boron effect in improving hardenability.

In case of a normalized high-tensile, low C, low-alloy steel of the composition: C, 0·10-0·18 per cent; Mo, 0·4-0·6 per cent, by adding boron to it, UTS increases from 45,000 to

65,000 p.s.i. with good impact strength except at low temperatures. This drawback can be overcome if further tests substantiate the results of one heat to which 0·10 per cent rare earths were added. The cerium, rare earths, increased the impact from 8 to 18 ft.-lb. at −40°C. Mischmetals have been used in boron steels with interesting results. For example, 3-5 lb. of mischmetal added to a ton of 8640 steel increased the impact strength from about 30 ft.-lb. up to between 40 and 50 ft.-lb.[13]

Bucknall and Mayor[14] have studied some aspects of boron-treated steels with the following results:

The hardenability of boron-free and boron-treated triple-alloy steels containing 0·15-0·53 per cent carbon was investigated by means of Jominy tests on specimens from 4 in. billets. The boron-treated steels showed marked hardenability variations, but were on average much improved in hardenability, whatever their carbon content. The mechanical properties of the boron-treated steels were in general consistent with their hardenability, ruling section and hardening treatment, but two advantages were found in boron-treated steels, namely good impact values at high tensile levels after full hardening and an attractive combination of hardenability and weldability.

Theoretical Aspects of Boron Effects

The effect of boron in steels is based on the retardation of the formation of proteutectoid ferrite and bainite. As a general rule, a nucleation and growth process takes place when the system passes from a disordered state to a more highly ordered state. Shear transformation involves co-operative movement from one ordered state to another ordered state. Fundamentally, carbon, nitrogen and boron cause hardenability by the same mechanism. But boron is considerably more effective than the other two.

There is no general acceptance of the ideas of theories put forth to explain the mechanism of behaviour of these boron alloys. But certain practical aspects of the alloys warrant considerations, such as the following:

(a) The concept that concentration of boron at austenite grain boundaries as an interstitial iron-boron solid solution, the presence of which lowers the rate of grain-boundary nucleation, is the cause of high hardenability.

(b) The boron, or portion thereof in solution at the time of quenching (irrespective of its location), decreases the rate of nucleation of ferrite and carbide in the vicinity of the nose of the S-curve, thereby contributing to martensite formation (that is, increasing hardenability); or

(c) acid-soluble nitride nuclei (principally aluminium nitride) are reacted upon by boron with the formation of relatively inert boron nitride, thus decreasing nucleation, so that in the complete absence of nitrogen (and possibly, aluminium) boron in these small amounts would not display this influence because hardenability would be high initially; or

(d) an expressed but not yet clarified order-disorder phenomenon or an equally incomplete expose of restraint of nucleation by patchy grain boundary films.

Within a relatively short time following the initial discovery, the making and testing of hundreds of alloys demonstrated conclusively the fortuitous composition of the first alloy produced and tried. It was clear that after effective aluminium deoxidation of the steel, a little residual aluminium in the alloy served to keep any subsequently introduced oxygen from reacting with the remaining alloy components; its titanium (or in part zirconium) content was then available for combination with nitrogen, leaving the boron to perform its function by whatever means the future researches may disclose. The key combination is titanium-boron in the added alloy, proved by production developments. In the absence of titanium, the required boron addition is three to fivefold regardless of pre-additions of aluminium and separate pre-additions of titanium or zirconium alloys. Presumably, part of the boron, by combining with oxygen or nitrogen or both, serves to protect the remaining boron so that the latter may be effective in the hardening process.

According to American analyses[15] boron combines very actively with either oxygen or nitrogen. In fact, one opinion is that its primary function is to tie up the last traces of nitrogen in the steel. In any case, most of the nitrogen must be removed, but this cannot be accomplished by large additions of boron because of the possibility of recovering more than 0·007 per cent of boron, which produces hot-shortness. The major requirements in producing a steel that will contain at least 0·0005 per cent and not more than 0·007 per cent of boron is to render most of the oxygen and nitrogen inactive by means of aluminium, titanium, or other suitable deoxidizers and nitride-formers. Also, to obtain reasonably consistent recovery of boron, it is essential to avoid practices that will cause wide fluctuations in the oxygen and nitrogen contents of the steel before ladle deoxidation, as for example, an inactive bath during the refining period, over-oxidation resulting from excessive bath temperature, an ineffective furnace block, a slow tap, or the early appearance of slag after tap. If these factors are under reasonable control, the production of satisfactory boron steel depends only on the types, amounts and sequence of the ladle additions.

Another influencing factor is the nitrogen content of the steel, if it exceeds the small amount (0·002-0·006 per cent nitrogen) found normally in open-hearth steels. Working with steels of SAE T-1330 composition, fine-grained (0·3 per cent carbon, 1·7 per cent manganese), Digges and Reinhart[16] found that nitrogen interfered with the boron hardenability effect or nullified it altogether, if the nitrogen content exceeded about 0·007 per cent. Excess nitrogen could be neutralized, however, by adding titanium, whereupon the boron effect was restored. In other words, the full boron influence was obtained when the effective nitrogen was held low by either of two methods: (1) by keeping the total nitrogen content below about 0·007 per cent, or (2) if the total nitrogen exceeded this figure, by adding titanium (presumably to precipitate a nitride), thus reducing the effective nitrogen to a low and harmless amount. Zirconium could also be used[16] instead of (or in addition to) titanium.

The influence of the amount of deoxidizers had been observed often, and is described particularly by Rahrer and Armstrong[17], Udy and Rosenthal[18] and Crafts[19]. It is now well established that steel must be well deoxidized if a boron addition is to exhibit full effectiveness. It is not so well established why this should be so. One body of thought holds that, unless the steel is well deoxidized, a certain proportion of the boron is oxidized out of the steel and lost. Others believe that such data as those of Digges and Reinhart[16] point to a nitrogen effect. They point out that, since aluminium forms a stable nitride as well as a stable oxide, the effect of aluminium 'deoxidation' may be denitrification as well.

Steels Based on Rare Earth Additions to Mild, Boron-treated and Low-alloy Steels for Improved Properties

The use of rare earths as alloying additions has been discussed in previous pages. It has been demonstrated that the addition of cerium plus aluminium to carbon and low-alloy steel castings gives mechanical properties superior to those obtained in corresponding steels in which aluminium or silicon alone is used as deoxidant. Cerium has a twofold effect on sulphide inclusions in cast iron. It not only acts as a desulphurizer, but any remaining sulphide inclusions are small, globular, and randomly distributed, due to the fact that they are precipitated at an early stage in the solidification process. Tests on carbon steel castings indicate that the cerium addition improves ductility at room temperature and raises the sub-zero impact resistance, and it is claimed to improve the properties of steel having sufficient alloying element to ensure a fully martensitic structure on water-quenching. Cerium added in 20 parts to a million parts of steel substantially lowers the impact transition temperature ranges of mild steel.

In nickel-containing steel[20], it has been found that variations in the ratio of the individual rare earth elements, especially of cerium and lanthanum, which are the most widely used, affect the degree of improvement. A rare earth mixture known as lanceramp consisting of not less than 30 per cent lanthanum, 45-50 per cent cerium and 20-24 per cent didymium and yttrium, with iron and residual salts 10 per cent maximum, has been developed and is claimed to give optimum results. It is suggested that the reactions of rare earth elements with hydrogen and nitrogen may be of considerable significance in explaining their beneficial influence.

Among the most important effects attributed to the rare earths is the improvement of the ductility at forging temperatures of nickel-containing steels, including high-alloy steels and the conventional stainless steels, by the addition of lanceramp[21].

The presence of a very small amount of rare earth elements improves the high temperature oxidation resistance of chromium-nickel, chromium-iron, chromium-nickel-iron and chromium-aluminium-iron alloys. The durability, or life, at 1050°C. of a 0·4 mm. diameter wire of chromium-nickel-iron was increased from 75 hr. to 350 hr. by the addition of 0·11 per cent of mischmetal, and to 1100 hr. by 0·39 per cent addition. A comparable effect was produced in a chromium-aluminium-iron alloy. There were also indications that constructional alloy steels treated with rare earth elements scaled more slowly than untreated steels, and formed a thinner, more closely adherent scale[22].

The effect of cerium additions to cast boron steels has been referred to earlier. Work most recently done at the Department of Mines and Technical Surveys, Canada, has shown the effectiveness of cerium rare earths in improving the impact strength of quenched and drawn medium-carbon, medium-manganese, low-molybdenum steel treated with ferro-boron vis-à-vis furnace tapping temperatures of 27 experimental 500-pound basic electric heats. Generally, rare earths were most effective in heats tapped below 1640 °C., fairly effective in heats tapped from 1640° to 1670°C. and ineffective in all seven heats tapped over 1670°C.

Austenitic Grain-refined Steels to Replace Low-alloy Steels and Grain-refined Low-alloy Steels to Replace High-alloy Steels for Optimum Applications

The first result of the recognition of the relations between aluminium additions, inherent austenite grain size and physical characteristics was an important factor that had been established which required due recognition.

When production methods of controlling the grain size were developed, it became possible to produce either fine or coarse-grained steels as required, and variations in physical behaviour were, to a large extent, eliminated. Investigations of the differences between fine and coarse-grained steels then led to the selection of one type for some purposes and the other for other purposes. Coarse-grained steels were recommended for easy machinability, deep hardening and higher strength in a given condition, while fine-grained were favoured because the heating temperature was not so critical, there was less danger of cracking or warping during hardening, a greater toughness was obtained in association with a given strength or hardness, and less austenitic grain growth took place during carburizing. The difference in machinability between fine and coarse-grained steels is not great, and could probably be overcome by altering the normalizing treatment that precedes machining; the shallower hardening of fine-grained steels may be counterbalanced by increasing the manganese content or adding other elements. The view has gained ground that fine-grained and coarse-grained steels are not just different varieties of the same steel, but that the fine-grained are actually materials of better quality to be preferred for all uses involving heat treatment and the composition and treatment altered accordingly. The effects of grain size control are most marked in carbon steels and those containing small amounts of alloying elements. As the content of such elements increases, the influence of strong deoxidation becomes less marked because the alloying elements exert the same kind of effects as it does. The opposite is also true, and the production of fine-grained steels by strong deoxidation leads to many of the advantages hitherto obtained with alloying elements, e.g. wider heating range, higher toughness in association with a given strength, less trouble from warping and cracking, and the elimination of refining treatments after carburizing. Thus fine-grained carbon steels may be used in place of coarse-grained low-alloy steels and fine-grained low-alloy steels in place of coarse-grained high-alloy steels. This is only possible, however, where the greater depth of hardening obtainable with alloying elements is not required. When this is the chief factor, the change from coarse-grained to fine-grained cannot be accompanied by a reduction in the content of alloying elements. However, the capacity of steel to harden at the surface is very well conferred by small additions of aluminium which confers on it the property of a high grade alloy steel as regards toughness.

Work on this important subject has already been done in India on a fairly extensive scale both from theoretical and practical viewpoints[23-29]. Fair amount of data is available on this subject of austenitic grain-refinement vis-à-vis improvement in physical properties of different categories of Indian steels. This work is being continued at the National Metallurgical Laboratory.

Assessment of Substitute Steels in Comparison with Existing Standardized Steels and the Problem of Drawing up of Suitable Indian Specifications for Indian Alloy Steels Required for Automobile and Other Engineering Industries

Apart from the above specific lines of study, development work is also needed on exploring the possibilities of saving W and Mo in high-speed steels by increased use of vanadium. In Germany the elimination of W in high-speed steels was pushed forward to a very advanced state and detailed data on this substitution are available.

Before the war the standard 18/4/1 high-speed steel was replaced by the following alloys in Germany:

C, %	W, %	Cr, %	V, %	Mo, %
0·80	9·50	4·50	1·50	0·50
0·85	11·00	4·50	2·50	0·50
1·40	11·50	4·50	2·50	1·00

In 1944, the following compositions were in use in Germany:

W, %	Cr, %	V, %	Mo, %	Co, %
7·5- 8.0	3·5-4·0	1.8-2·0	0·3	nil
1·2- 1·5	3·5-4.0	2·2-2·5	2·3-2·5	nil
9·0-10·0	3·5-4·0	2·5-2·7	0·3	nil
9·0-10·0	4·0-4·5	1·9-2·2	nil	2·5-3·0

Alternatively the use of tungsten carbide-tipped tool and refractory-metal ceramic combinations for tool applications has to be developed in India.

Full scope should be given to investigations into saving the four elements Ni, Co, Mn and W as they enter the magnetic materials. In this connection, some work on the development of magnetic materials based on Fe, Mn and Al is underway at the National Metallurgical Laboratory.

Work on surface treatments such as stainless cladding of sheet steel and aluminizing of steel can also be of considerable potential for use in heat exchangers, automobile muffles, etc. Work on aluminizing of steel is in progress at the National Metallurgical Laboratory.

It will be observed that as this development work progresses, many side lines will suggest themselves as deserving of special study and pursuit. It will be importune to enter into details about these aspects at this stage. The development of silico-manganese, chrome-vanadium spring steels, sil-chrome valve steel based on En 54, etc., should be considered as substitutional measures for highly alloyed materials in the text of Indian raw materials condition.

The development work may be considered on sheet materials for the low-stress high-temperature parts of gas turbines, essentially on an indigenous basis. This would involve exploration of the Fe, Cr and Mn alloys with strengthening additions such as Ti, Al and the selection of compositions which are suitable from production and performance viewpoints. Long-term work on the development of super-high temperature materials of the cermet type based on titanium carbide, etc., may also have to be undertaken.

The scientific approach and study of alloy steels on the basis of transformation characteristics and hardenability have eliminated quite a few erratic conceptions regarding the application of certain compositions in heat-treated conditions. In constructional alloy steels a composition may be very attractive but yield poor hardenability since some alloying elements favour partly or inconsistent hardenability values. During the last war, it is the writer's experience that Ni-Cr, Mo, Va air-hardening armour plate compositions had to be oil and even water-quenched to develop optimum hardening. Although isothermal transformation characteristic studies have tended to fill the observed gaps and clarify many unexplained points, there are certain factors based on macro-scale crystallization or rather segregation and non-homogeneity that have introduced disturbing anomalies in the hardening response of steels particularly of boron steels. The causes of the hardenability variations are not altogether clear and are due to effects not as yet fully identified. The American tendency has been to over-simplify the subject. It is our view that hardenability is a very complex subject not fully accountable to simple formulation and there are still many gaps in our understanding of its effect. Bucknall and Steven[30] 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.

For some reasons connected with segregation on micro-scale, it appears that the columnar crystals harden well, but the equiaxed do not. One can prove that mean compositions over quite small areas are the same, but the minimum areas for which one can measure composition are big in relation to fluctuation across the dendrites. There is an element of mystery about hardenability variations across the section. More work remains to be done on the subject. It is possible that latest casting techniques such as are introduced in continuous casting of steel may tend to smoothen the difficult path and pave the way for more uniform hardenability response of the same steel of identical casting section.

The subject of framing suitable specifications to meet the new types of Indian alloy steels to be evolved in terms of Indian conditions of requirements, is definitely not going to be easy. In this connection it may be mentioned that British En specifications were drawn up by the Technical Advisory Committee of the Iron and Steel Control, British Ministry of Supply, primarily for the object of rationalizing steel specifications. At the outbreak of World War II, about 2000 specifications covering the manufacture of rolled and forged steels were in use in Britain. Many of these specifications differed from others only in quite unimportant details. Although some efforts had been made during 2-3 years preceding the outbreak of the last war to reduce the number of specifications considerably, it needed the impact of war and consequent critical shortage of essential alloying elements, to relieve the steel industry of this burden of unnecessary and at times whimsical variations in specificational requirements. In India it may be our primary objective not to base our specifications on identical superficial considerations which have now been discarded elsewhere. The British En specifications were based on the basic principle of specifying the mechanical properties to be derived after stated heat treatments. Although compositional requirements were also taken into consideration, these were more in the nature of defining the type of steel to be used rather than setting up narrow compositional limits. The specifications also took proper account of the 'mass effect' — a factor which had earlier been frequently ignored. In steels to be used after hardening and tempering, the properties obtained from a given composition were related to its size. In formulating Indian specifications, we shall have to take these important factors also into serious consideration. This subject will have to be examined in collaboration with the Indian Standards Institution.

The foregoing data may serve as a pointer to direct our research and development work along useful lines and to pin-point certain focal aspects of this important subject. It is difficult in research and development work of this kind to predict wisely the exact trends likely to emerge, but with a flexibility of attitude, deviations in the general plan and suitably balanced adjustments sensibly followed will no doubt bring rewards.

One comes across frequent reports in the press about projected developments in the alloy steel industry such as its early establishment at Mysore Iron & Steel Works, Bhadravati, especially of stainless steel categories, inclusion of alloy steel plant at the new steelworks of Hindustan Steel Limited at Rourkela. It will be in the national interest that in setting up these projects proper collaboration be maintained between the National Metallurgical Laboratory and the Government of India authorities, such as the National Development Council, Production and Commerce Ministries, etc., in order that effective co-ordinated plans may be drawn up for the projected alloy steel industry in India. That those in authority are alive to this co-ordination is a healthy sign. This subject has been stressed at many venues including the Board of Scientific & Industrial Research and Indian Tariff Board on the recommendations of which this report has been compiled in the first instance. It needs no emphasis that in pursuit of this research into alloy steels the Indian automobile, alloy steel production units and other engineering industries will have to be taken into active confidence since they will, in the long run, provide the platform for the implementation of research results into production schedules.

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APPENDIX A — INDIAN AUTOMOBILE INDUSTRY

During 1947-48 India imported 35,414 automobiles, of which 23,197 were cars, mainly from the United Kingdom and United States. In 1953, six years later, the imports were running at a yearly average of about 9600 vehicles. In the intervening period assembly plants had been put up in the country, all of them in collaboration with foreign manufacturers, many of whom had provided both technical and financial assistance to indigenous industrialists. The drop has been attributed to the fact that the initial post-war years saw the replenishing of the considerable war-time backlong which by 1950 had been responsible for the import of just under 100,000 vehicles. It is now estimated that the country's annual requirements are about 17,500 vehicles, consisting of 7500 small cars, 2500 big cars and 7500 trucks for both civil and military use. The Government has now formulated a long-range policy for manufacturing the whole number at home; by the end of 1956 it is proposed to reduce the imported components to less than 50 per cent.

Because of this policy, firms which were engaged purely in the assembly of vehicles had to shut down, for they were unable to submit approved programme of manufacture. General Motors of India and Ford Motors of India, the two largest of such firms, have now wound up their operations. The other smaller assembly firms are in the process of doing so, leaving in the field the following four firms with approved manufacture programmes: Hindustan Motors Limited, Premier Automobiles Limited, Standard Motor Products of India Limited, and Automobile Products of India Limited. Of these, the first three had made some progress towards manufacture and the fourth one has so far not succeeded in keeping to its schedule and may be forced to close down. Hindustan Motors will be making Studebaker (big car and medium truck) and a model known as ' Hindustan 14 ', which is the Indian equi-

APPENDIX B — COMPARISON OF En STEEL

A comparison of En steels with other official specifications is provided in the following tab others, it was felt advisable to include these for information purposes since they are st official specifications, based on chemical composition. They include also steels which, thou

En No.	Type of steel	United Kingdom				U.S.A.	
		B.S. Aircraft	D.T.D.	B.S. STA/5	B.S. General	SAE and AISI	A.M.S
12	Direct-hardening 1 per cent Ni	(2S.76)	—	—	(5005/203) (5005/204)	—	—
13	Mn-Ni-Mo	—	510	V.8	—	—	—
21	3 per cent Ni	—	—	—	(5005/401)	2330	—
22	3½ per cent Ni	(S.69)	—	—	(5005/402)	2340	—
23	3 per cent Ni-Cr	(4S.11)	—	—	(5005/501)	(3435)	—
24	1½ per cent Ni-Cr-Mo	S.95	473 480	V.10	(5005/503) (b)	(3240) (b,c) (4340) (c)	6415E (c)
25	2½ per cent Ni-Cr-Mo (medium carbon)	S.96 S.97	473 480	V.11	—	—	—
26	2½ per cent Ni-Cr-Mo (high carbon)	S.98 S.99	473 500	V.12	—	—	—
27	3 per cent Ni-Cr-Mo	(S.65) (2S.81)	—	—	—	(3325) (b)	—
28	3½ per cent Ni-Cr-Mo	—	331	—	—	(3335) (b)	—
30A	4¼ per cent Ni-Cr	—	—	V.13	(5005/502)	—	—

(a) Composition similar but with molybdenum added. (b) Composition similar but without molybdenu chromium range. (g) Has lower nickel range. (h) Not now official specification.

valent of Morris 'Oxford' of Nuffield Motors. Premier Automobiles will be making Dodge, Desoto and Plymouth (big cars) and Dodge, Desoto and Fargo trucks. Standard Motor Products will be manufacturing Standard 'Vanguard' (medium car). Besides this programme for big and medium cars, the Government has also approved a similar planned programme for small cars, of which 'Morris Minor' will be made by Hindustan Motors, 'Fiat 1100' by Premier Automobiles, and 'Standard 8' by Standard Motor Products of India. All these programmes which are now being implemented are for a period of three years.

Recently the Tata Engineering & Locomotive Company Limited announced a programme for the manufacture of Mercedes-Benz Diesel trucks and engines in collaboration with Daimler-Benz of Germany. These trucks can develop a maximum of 108 b.h.p. and have a gross vehicle weight ranging from 14,770 lb. to 18,750 lb. The scheme contemplates the manufacture of all the components of the vehicle within a period of four years, after which no components will be imported. The scheme envisages an initial capital expenditure of Rs. 4 crores (£3,000,000), of which Daimler-Benz will be investing one-fifth. The Tata Company already possesses a modern plant at Jamshedpur, Bihar.

WITH OTHER OFFICIAL SPECIFICATIONS

Although from time to time some specifications have either been withdrawn or replaced by
encountered in technical literature. The table gives the general relationship of all the various
not similar in chemical compositions, are possible alternatives.

EN No.	AUSTRIA	BELGIUM	FRANCE	GERMANY D.I.N.	ITALY U.N.I.	SWEDEN S.I.S.14 SERIES
12	—	—	—	—	—	—
13	—	—	—	—	—	—
21	—	—	—	—	—	—
22	—	—	—	—	—	—
23	VCN25w(g) VCN35w(e) VCN35h	Ni-Cr 322 (c, g)	30NC12	VCN25w(g) VCN35w(e) VCN35h	32NC12	—
24	34 Cr-Ni-Mo 6 (e, f)	Ni-Cr-Mo 415	35NC6 (v, e)	34 Cr-Ni-Mo 6 (e, f)	40NCD7	25-32(c)
25	—	—	30NC11(b)	—	—	—
26	—	—	—	—	—	—
27	—	Ni-Cr-Mo 335	30NCD12	—	30NCD12	25-34
28	—	—	35NCD14	—	35NCD15(f)	—
30A	VCN45(d)	Ni-Cr 342	35NC15(f) 40NC17(d, f)	VCN45(d)	—	25-36

(c) Possible alternative steel. (d) Has higher carbon range. (e) Has lower carbon range. (f) Has higher

APPENDIX B—COMPARISON OF En STEELS

En. No.	Type of steel	United Kingdom				U.S.A.	
		B.S. Aircraft	D.T.D.	B.S. STA/5	B.S. General	SAE and AISI	A.M.S.
30B	4½ per cent Ni-Cr-Mo	3S.28	—	V.13A	—	—	—
100	Low alloy	S.94	600	—	—	8640(c)	—
100A	Low alloy	—	—	—	—	8627(c)	—
100B	Low alloy	—	—	—	—	8632(c) 8735(c)	6280A (c, e) 6320B (c, d)
100C	Low alloy	—	—	—	—	8637(c) 8740 (c, d)	6322B (c, d)
100D	Low alloy	—	—	—	—	8642(c) 8742	—
110	Low Ni-Cr-Mo	—	—	—	—	4340(c)	6415B (c)
111	Low Ni-Cr	—	—	V.9E or V.9E1(a)	—	3135	6330A
111A	Low Ni-Cr	—	—	V.9E or V.9E1(a)	—	3135	6330A
160	2 per cent Ni-Mo	—	—	—	—	4640	6312A
160A	2 per cent Ni-Mo	—	—	—	—	4640	6312A
57	Corrosion-resisting high-tensile Cr-Ni	2S.80	—	V.28	—	51431(c)	—
33	Case-hardening 3 per cent Ni	4S.15	—	V.17	(5005/103)	(2315) 2317(d)	—
34	2 per cent Ni-Mo (lower carbon)	—	—	V.16A	—	4615 4617	6290C 6292C
35	2 per cent Ni-Mo (higher carbon)	—	—	V.16B V.16B/1 V.16B/2	—	4620(e) X4620(e)	—
35A	2 per cent Ni-Mo (higher carbon)	—	—	—	—	4620(e) X4620(e)	6294C (e)
35B	2 per cent Ni-Mo (higher carbon)	—	—	—	—	—	—
36	3 per cent Ni-Cr	S.107(a)	519(a)	V.18 V.18A	682	(3415)	—
37	5 per cent Ni	(S.67)	—	—	(5005/104)	2512 2515	6240C
38	5 per cent Ni	(S.90)	—	—	—	2515 4815(c)	—
39A	4¼ per cent Ni-Cr	—	—	—	—	3316(c)	6254B (c)
39B	4¼ per cent Ni-Cr-Mo	2S.82	—	V.19	—	—	—
320	2 per cent Ni-Cr-Mo	—	—	—	—	—	—
325	Low Ni-Cr-Mo	—	—	—	—	4320	—

(a) Composition similar but with molybdenum added. (b) Composition similar but without molybdenum. chromium range. (g) Has lower nickel range. (h) Not now official specification.

WITH OTHER OFFICIAL SPECIFICATIONS — *Continued*

En No.	Austria	Belgium	France	Germany D.I.N.	Italy U.N.I.	Sweden S.I.S.14 Series
30B	—	Ni-Cr-Mo 342	30NCD16(f) 40NCD18(d, f)	—	35NCD15(d, f)	—
100	—	—	—	—	—	—
100A	—	—	—	—	—	—
100B	—	—	35NCD4(c)	36 Ni-Cr-Mo 3	—	—
100C	—	—	—	36 Ni-Cr-Mo 3	38NCD4	—
100D	—	—	—	—	—	—
110	34 Cr-Ni-Mo 6 (e, f)	—	35NC6 (b, e)	36 Cr-Ni-Mo 4 (g)	40NCD7	25-32(c)
111	VCN15w(e) VCN15h	—	35NCD4(a)	VCN15w(e) VCN15h	35NC5(f)	25-30
111A	—	—	—	—	—	25-30
160	—	—	45ND10(d)	—	—	—
160A	—	—	—	—	—	—
57	—	—	Z10CN17	X22 Cr-Ni 17	X20NC18	23-21
33	—	—	—	—	—	—
34	—	—	—	—	—	25-20-2 25-20-3
35	—	—	20ND6 (e, g)	—	—	—
35A	—	—	—	—	—	—
35B	—	—	—	—	—	—
36	ECN35	Ni-Cr 235	14NC11(g)	ECN35	18NC13	25-14-2 25-14-3 25-15-2 25-15-3
37	—	—	Z12N5	—	—	—
38	—	—	Z20N5(d)	—	—	—
39A	ECN45	Ni-Cr 241	—	ECN45	18NC16	—
39B	—	Ni-Cr-Mo 241	16NCD13 (f, g)	—	—	—
320	ECN Mo 40	—	—	18 Cr-Ni 8(b)	—	—
325	—	—	16NCD4(g)	—	17NCD7	—

(c) Possible alternative steel. (d) Has higher carbon range. (e) Has lower carbon range. (f) Has higher