AN EXPOSITION OF ALLOY STEELS FOR THE ENGINEER

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Abstract

Necessity of using alloy steels. Effects of alloying elements on the properties of steels, by alterations in hardenability characteristics or the changes induced in the ferrite and carbide phases. Grouping of alloy steels according to ultimate tensile strength. Special properties of each group. Temper-brittleness. General properties of alloy steels.

Introduction

WHILST plain-carbon steels have been found to be satisfactory in the lower ranges of tensile properties for structural and engineering purposes, they suffer from certain deficiencies in the higher ranges of tensile properties (50 tons/sq. in. and above), especially with regard to their notched-bar impact values. It is also true that, at ordinary levels of tensile properties, high notched-bar values can be obtained in plain-carbon steels with comparative difficulty, and, then, one cannot be always certain of repeating them regularly at all times. Plain-carbon steels also suffer greatly from mass effect in hardening, which does not permit thorough hardening from surface to centre of massive sections.

Alloy steels of today have been gradually developed over a period of years to overcome these deficiencies of plain-carbon steels and to offer to the engineer of today such steels as will serve him well in highly stressed components of machines and under varying and exacting conditions of service. Alloy steels can now be produced within a tensile range of between 40 and 100 tons/sq. in. approximately, with satisfactory notched-bar impact values which may range from, say, about 60 ft.-lb. in steel with 40 tons/sq. in. tensile strength to about 12 ft.-lb. in steel with 100 tons/sq. in. tensile strength. These wide ranges of mechanical properties can be obtained by appropriate heat treatment with comparative ease and regularity. By suitably selecting the composition of the steel, many of the difficulties that arise through mass effect can also be circumvented.

One or more of the following elements generally constitute the alloying elements present in alloy steels: manganese, nickel, chromium, molybdenum, vanadium, copper, tungsten, cobalt, silicon, aluminium, titanium, zirconinm.

The physical properties of any steel, which may range widely by appropriate heat treatment, are generally controlled by the resulting microstructures of the steel.

In the make-up of the steel, as generally heat-treated commercially today, there are generally four possible micro-constituents to be found:

1. Micro-ferrite grains, some carrying alloying elements in solution.	Relatively slow-cooled or well-tempered steel
2. Carbide (Fe_3C) with other elements in solution, or complex carbides if sufficient amount of strongly carbide forming elements is present.	
3. Martensite — very hard, and formed only by low-temperature transformation resulting from rapid cooling.	Relatively rapid-cooled steel
4. Austenite — soft and tough residual high-temperature solid solution. Unstable and usually destroyed by tempering.	

The alloying elements have been known to improve the physical properties of steel in one or more of three ways:

1. By changing the state of dispersion of the carbide in the ferrite matrix.
2. By changing the properties of the ferrite.
3. By changing the properties of the carbide.

Hardenability

Hardenability[1,2,3] is the basis for much of the demand for alloy steel today. It is also the property which is largely lacking in plain-carbon steels, for which reason they fail to develop appropriate microstructures which induce high strength in the interior of large sections.

Plain-carbon steel may be made moderately deep-hardening by coarsening the austenitic grain size. Such a practice is not generally desirable, because the transformation products of coarse-grained austenite possess low ductility and low impact strength. It is, therefore, desirable to retain fine grain structure and develop the necessary hardenability by the introduction of alloying elements. Steels, generally, produce a finer dispersion — lamellar or acicular — of the carbide with increasingly lower transformation temperatures, thus resulting in hardness and strength increase (FIG. 1).

If now the reaction rate is further retarded by the introduction of any alloying element into solid solution in the austenite, the transformation temperature is further lowered which causes an increasingly finer dispersion of ferrite and carbide, resulting in an increasingly harder product. If a still more rapid cooling is applied so that the transformation temperature is reduced below about 115°C. (250°F.), the transformation constituent produced is martensite which is characterized by great hardness and little ductility. The rate of cooling which will just result in complete transformation of austenite to martensite is known as the 'critical cooling rate'. Therefore, steel cooling faster than the critical cooling rate will escape the austenite pearlite transformation and reach the temperature range of martensite formation still unchanged. Fig. 2 shows the hardness distribution of three different steels quenched in an identical manner. It will be seen that the alloy contents of the

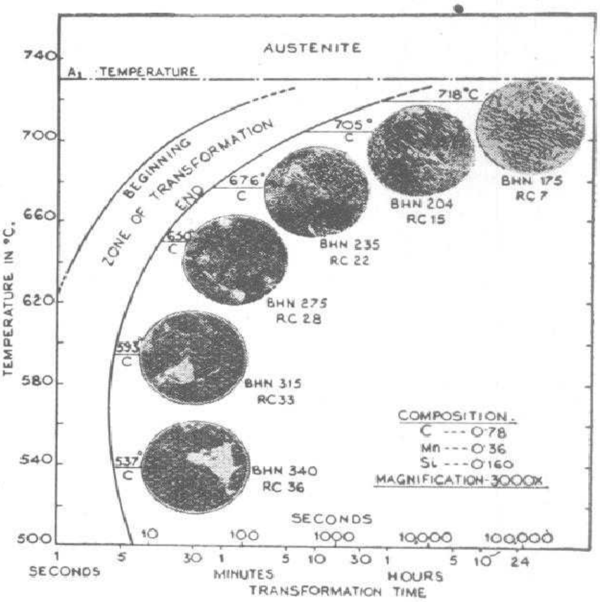

FIG. 1 — INFLUENCE OF TRANSFORMATION TEMPERATURE ON FINENESS OF PEARLITE

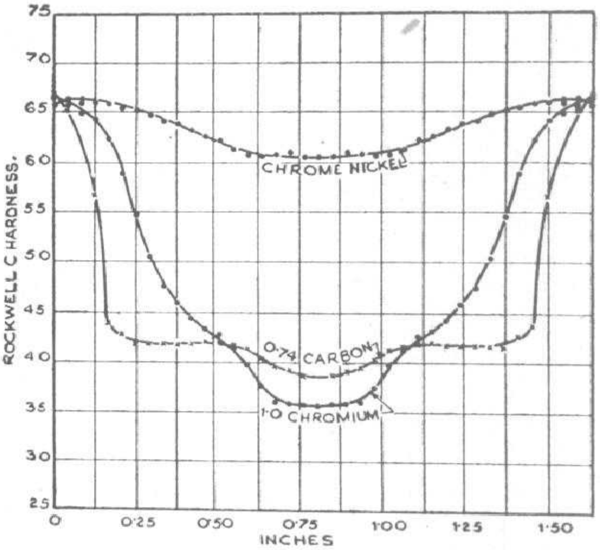

FIG. 2 — HARDNESS TRAVERSE IN SOME PLAIN-CARBON AND ALLOY STEEL ROUNDS OF $1\frac{5}{8}$ IN. DIAMETER

nickel-chrome steel have accomplished the necessary lowering of the critical cooling rate to the extent that the metal in the centre of the section, which normally cools most slowly, is also enabled to harden effectively.

This property of deep-hardening is by far the most important effect of the alloying elements. Thus, large sections may be rendered fully hard throughout, ready for tempering to develop the spheroidized carbide distribution which gives to the steel the maximum toughness at a given strength.

The improvement in hardenability due to the presence of alloying elements is an instance of the improvement in physical properties of an alloy steel as a result of the change in the state of dispersion of the carbide in the ferrite matrix.

Property Changes by Alteration in the Properties of the Ferrite or Carbide

Property changes due to changing of properties of the ferrite are well indicated by Bain[4] in a series of steels with essentially similar carbon contents (0·55 per cent), but with varying manganese contents, respectively at 0·88, 2·21, 3·72 and 6·45 per cent, and each steel treated to develop substantially the same microstructure showing very fine lamellar pearlite. Fig. 3 shows the change in properties caused in the same structures by increase in manganese content. The effect is admittedly moderate and can be attributed to the increased hardness and strength of the ferrite phase because the amount of the carbide in this instance is regulated by the constant carbon content of the steels.

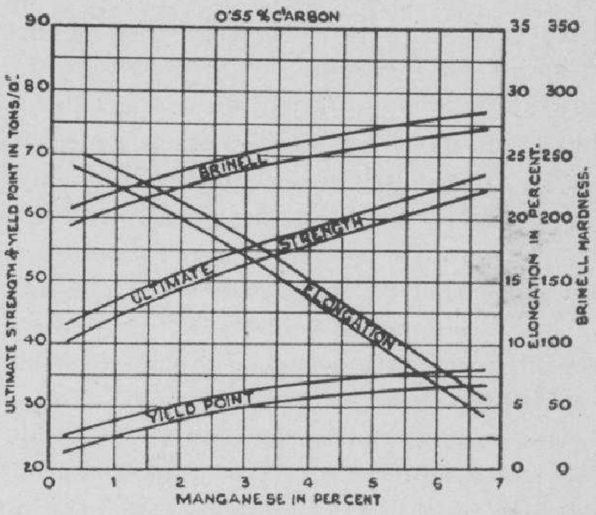

FIG. 3 — INFLUENCE OF MANGANESE CONTENT ON THE PROPERTIES OF STEEL

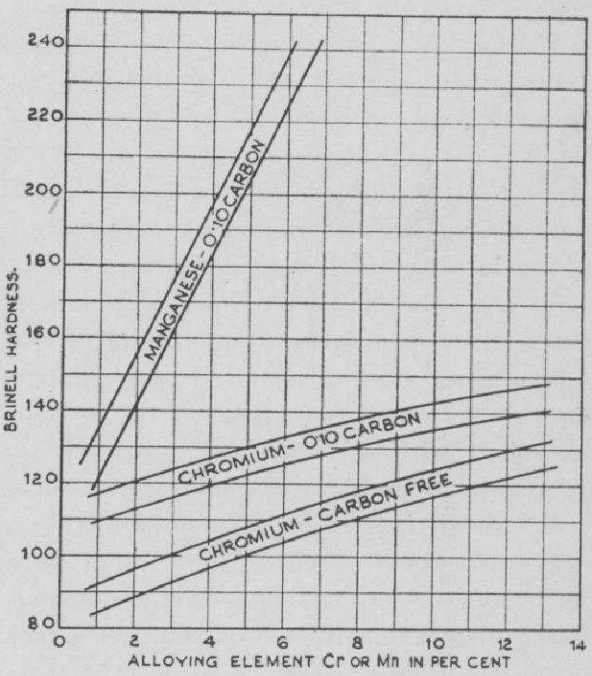

FIG. 4 — EFFECT OF CHROMIUM AND MANGANESE ON THE HARDNESS

The influence of the presence of the alloy content dissolved only in the ferrite is brought out clearly by the hardness curves of Fig. 4. It will be seen that chromium hardens iron very little by its presence in solid solution, but manganese has a greater effect. In these curves, the carbon content is very low and the microstructures are similar, so that the difference in hardness can be attributed only to the solid solution effect.

It is known that some of the hardened alloy steels, particularly those containing more than minor proportions of strongly carbide-forming elements like chromium, molybdenum, vanadium, tungsten and titanium, required to be tempered at higher tempering temperatures to reduce their hardness or strength to a predetermined value. The softening rate is controlled by the rate at which carbon diffuses through the ferrite matrix. Since alloy steels generally soften to a much lesser extent than plain-carbon steels with similar tempering treatment, it is to be concluded that the diffusion rate of carbon is decreased by the presence of such alloying elements. In this respect, nickel[5] exerts little influence on the tempering of steel. Nickel is almost wholly present in the ferrite, and up to about 3·5 per cent hardens the ferrite very slightly. Silicon[6] is fairly effective in hardening the ferrite. Chromium[7] and tungsten[8], however, essentially incorporate themselves in the carbide phase, and are found to strongly resist softening by tempering at temperatures of up to about 450°-480°C. (850°-900°F.). Molybdenum[9], in moderate amounts, is also as effective as tungsten in this respect. The fundamental properties of such carbide-forming elements to reduce the rate of diffusion in alloy steels also permit the use of comparatively higher tempering temperatures, thereby allowing better relief of residual internal stresses and producing a greater measure of toughness in the steel at comparable hardness level.

Such property changes due to the changing of the properties of the carbide have also an important bearing upon creep strength. Molybdenum, in particular, in combination with other elements, is specially beneficial in imparting excellent creep-resisting qualities to alloy steels.

With all the foregoing advantages, structural and engineering alloy steels are more expensive than plain-carbon steels and, because of their greater strength, are less amenable to hot-working and drop-forging. Therefore, they should be used only for the manufacture of such components as demand steel possessing much higher mechanical properties than can be obtained with plain-carbon steels. Alloy steels should always be used in the hardened and tempered condition in which state they possess their optimum mechanical properties.

To engineers the mechanical properties of a steel are of principal importance — a steel is required which is sufficiently strong to stand up to the work it is expected to perform and at the same time possess other desirable properties of ductility and high notched-bar impact value. Chemical compositions of steels should remain but a means to an end, because they are of subsidiary interest to engineers. This fact, however, is not always fully appreciated, and a very unfortunate tendency often exists to regard chemical composition as the end, and not as the means.

Choice of Appropriate Steels for a Particular Job

The wise choice of a steel for an engineering component possessing an appropriate strength value is a matter of great importance to the engineer, since the number of alloy steels in use at present is legion. Some steels possess the requisite properties after cooling in air, others after cooling in oil or water, all being tempered subsequently at appropriate temperatures. For example, let it be said that a steel having a tensile strength of about 80 tons/sq. in. is required in a particular component. If tensile strength were the only factor in the selection of a suitable steel, the choice would be very wide. But the different steels, although at approximately similar levels of tensile strength, vary quite widely in respect of their ductility and toughness values. For this reason the engineer's selection of steel will be governed by a careful assessment of its ductility and toughness value at the appropriate level of tensile strength. Of two steels which are available for a particular purpose, and both capable of possessing similar levels of tensile strength, all other things being equal, the steel to be selected should be the one possessing the best impact value and which requires to be tempered at the higher temperature.

Groupings of the Common Engineering Alloy Steels

The common engineering alloy steels have been conveniently grouped as follows:

Group I. Ultimate tensile strength of 100 tons/sq. in. and over.

Group II. Ultimate tensile strength of 75-100 tons/sq. in.

Group III. Ultimate tensile strength of 60-75 tons/sq. in.

Group IV. Ultimate tensile strength of 50-60 tons/sq. in.

Group V. Ultimate tensile strength of 40-50 tons/sq. in.

A similar classification has been adopted by the British Standards Institution, as per B.S. 970: 1947 which covers the known 'En' series of wrought alloy steels, hardened and tempered (*see* Table 1). For such individual steels it is essential to take into account the effect of mass. If any of the ranges of mechanical properties were to be desired only in thin sections of steel, say 1 in. in diameter, it would not be necessary at all to use any type of alloy steel, because a well heat-treated plain-carbon steel of a sufficient carbon content would be able to satisfy the desired strength properties. When components of mixed sizes have to be considered, it becomes necessary to examine and evaluate this effect of mass. The ruling sections considered in the above groupings range up to a maximum of 6 in.

It is now proper to examine the appropriate heat treatment to produce the desired properties of the typical steels in each group and also indicate any peculiarities which these steels may possess.

Group I (*over* 100 *tons tensile strength*) — Very few steels can attain an ultimate tensile strength of 100 tons/sq. in. or more in both large and small sections, and yet be easy to produce. Only air-hardening types of steels (Ni-Cr or Ni-Cr-Mo) with a moderate amount of carbon possess the capacity to harden completely with ease and attain the high strength of 100 tons/sq. in. in the centre of large sections. In smaller sections this strength value may be attained by other alloy steels capable of being hardened by cooling in oil or water, but experience has indicated that the latter do not possess the same good ductility and toughness values as would be obtained from air-hardening steels.

The air-hardening properties of Ni-Cr steels can be attributed more to the chromium than to the nickel. The presence of chromium causes the phenomenon of 'undercooling' to occur and the presence of nickel causes the lowering of the critical point during the cooling of the steel in the hardening operation. These combined effects of nickel and chromium produce the conditions necessary for 'air-hardening'. The presence of manganese in these steels acts similarly to nickel in this respect and, therefore, contributes further to the efficiency of the air-hardening process.

A typical chemical composition range of this group of steel can lie within the following range:

	Per cent
Carbon	0·25-0·35
Manganese	0·45-0·65
Nickel	4·00-4·40
Chromium	1·10-1·40
Molybdenum	0·20-0·40

This class of steel can be hardened generally by heating to 830°-850°C., followed by cooling in still air. Cooling in an air blast will yield no better properties, nor will oil or water-quenching produce any increase in tensile strength. Actually, if air-hardening steels are cooled very rapidly, some austenite may remain untransformed to martensite, in which case the tensile strength and hardness will be lower than if the steel had been cooled in air. Also, the use of these other methods of cooling may be comparatively dangerous because of the severe stresses that may be induced in the steel by contraction and expansion during quenching. Generally, a steel should always be cooled at

TABLE 1 — ALLOY STEELS FOR HARDENING AND TEMPERING, 40-100 TONS/SQ. IN. ULTIMATE TENSILE STRESS BARS, BILLETS, LIGHT FORGINGS AND STAMPINGS UP TO 6 IN. RULING SECTION

The mechanical properties specified are obtainable within the limits of ruling section given below

B.S. No.	Type of steel	C	Si	Mn	Ni	Cr	Mo	40-50 tons tensile Q	45-55 tons tensile R	50-60 tons tensile S	55-65 tons tensile T	60-70 tons tensile U	65-75 tons tensile V	70-80 tons tensile W	75-85 and 80-90 tons tensile X & Y	100 tons min. tensile Z
En 12	1 per cent nickel	0·30-0·45	0·10-0·35	1·50 max.	0·60-1·00	—	—	All sizes	—	—	—	—	—	—	—	—
En 13	Manganese-nickel-molybdenum	0·15-0·25	0·10-0·35	1·40-1·80	0·40-0·70	—	0·15-0·35	All sizes	—	—	—	—	—	—	—	—
En 14A and	Carbon-manganese	0·15-0·25	0·10-0·35	1·30-1·70	0·40 max.	0·25 max.	—	Up to 4 in.	Up to 1⅛ in.	—	—	—	—	—	—	—
En 14B		0·20-0·30	0·10-0·35	1·30-1·70	0·40 max.	—	—	Up to 4 in.	Up to 2½ in.	—	—	—	—	—	—	—
En 15	Carbon-manganese (higher tensile)	0·30-0·40	0·10-0·35	1·30-1·70	—	—	—	All sizes	Up to 2½ in.	Up to ⅞ in.	—	—	—	—	—	—
En 16	Manganese-molybdenum	0·25-0·40	0·10-0·35	1·30-1·80	—	—	0·20-0·35	—	All sizes	Up to 4 in.	Up to 2½ in.	Up to 1⅛ in.	Up to ⅞ in.	—	—	—
En 17	Manganese-molybdenum (higher molybdenum)	0·30-0·40	0·10-0·35	1·30-1·80	—	—	0·35-0·55	—	All sizes	All sizes	Up to 4 in.	Up to 2½ in.	Up to 1⅛ in.	—	—	—
En 18	1 per cent chromium	0·35-0·45	0·10-0·35	0·60-0·95	—	0·80-1·10	—	—	Up to 4 in.	Up to 2½ in.	Up to 1⅛ in.	—	—	—	—	—
En 19	1 per cent chromium-molybdenum	0·35-0·45	0·10-0·35	0·50-0·80	—	0·90-1·50	0·20-0·40	—	All sizes	Up to 4 in.	Up to 2½ in.	Up to 2½ in.	Up to 1⅛ in.	Up to 1⅛ in.	—	—
En 19A	1 per cent chromium-molybdenum	0·35-0·45	0·10-0·35	0·50-0·80	—	0·90-1·20	0·20-0·35	—	All sizes	Up to 4 in.	Up to 2½ in.	Up to 1⅛ in.	Up to ⅞ in.	—	—	—
En 21	3 per cent nickel	0·25-0·35	0·10-0·35	0·35-0·75	2·75-3·50	0·30 max.	—	—	Up to 4 in.	Up to 2½ in.	—	—	—	—	—	—
En 22	3½ per cent nickel	0·35-0·45	0·10-0·35	0·50-0·80	3·25-3·75	0·30 max.	—	—	—	Up to 4 in.	Up to 2½ in.	—	—	—	—	—
En 23	3 per cent nickel-chromium	0·25-0·35	0·10-0·35	0·45-0·70	2·75-3·75	0·50-1·00	0·65 max. (opt.)	—	—	All sizes	All sizes	All sizes	Up to 2½ in.	—	—	—
En 24	1½ per cent nickel-chromium-molybdenum	0·35-0·45	0·10-0·35	0·45-0·70	1·30-1·80	0·90-1·40	0·20-0·35	—	—	All sizes	All sizes	Up to 4 in.	Up to 2½ in.	Up to 1⅛ in.	Up to 1⅛ in.	Up to 1⅛ in. if oil-hardened
En 25	2½ per cent nickel-chromium-molybdenum (medium carbon)	0·27-0·35	0·10-0·35	0·50-0·70	2·30-2·80	0·50-0·80	0·40-0·70	—	—	—	All sizes	All sizes	All sizes	Up to 4 in.	Up to 2½ in.	Up to 2½ in. if oil-hardened
En 26	2½ per cent nickel-chromium-molybdenum (high carbon)	0·36-0·44	0·10-0·35	0·50-0·70	2·30-2·80	0·50-0·80	0·40-0·70	—	—	—	—	All sizes	All sizes	All sizes	All sizes	Up to 4 in. if oil-hardened
En 27	3 per cent nickel-chromium-molybdenum	0·25-0·35	0·10-0·35	0·70 max.	3·00-3·75	0·50-1·30	0·20-0·65	—	—	—	All sizes	All sizes	All sizes	Up to 4 in.	—	—
En 28	3½ per cent nickel-chromium-molybdenum	0·25-0·40	0·10-0·35	0·70 max.	3·00-4·50	0·75-1·50	0·20-0·65	—	—	—	—	All sizes	All sizes	Up to 4 in.	Up to 2½ in.	—
En 29	3 per cent chromium-molybdenum	0·15-0·35	0·10-0·35	0·65 max.	0·40 max.	2·50-3·50	0·30-0·70	—	All sizes	All sizes	All sizes	All sizes	Up to 4 in.	Up to 4 in.	—	Up to 2½ in. if oil-hardened
En 30A and	4¼ per cent nickel-chromium and	0·26-0·34	0·10-0·35	0·40-0·60	3·90-4·30	1·10-1·40	—	—	—	—	—	—	—	—	—	Up to 2½ in. if air-hardend
En 30B	4¼ per cent nickel-chromium-molybdenum	0·26-0·34	0·10-0·35	0·40-0·60	3·90-4·30	1·10-1·40	0·20-0·40	—	—	—	—	—	—	—	—	Up to 6 in. if oil-hardened
En 100	Low alloy	0·35-0·45	0·50 max.	1·20-1·50	0·50-1·00	0·30-0·60	0·15-0·25	—	All sizes	Up to 4 in.	Up to 2½ in.	Up to 1⅛ in.	Up to 1⅛ in.	—	—	—
En 110	Low nickel-chromium-molybdenum	0·35-0·45	0·10-0·35	0·40-0·80	1·20-1·60	0·90-1·40	0·10-0·20	—	All sizes	All sizes	Up to 4 in.	Up to 2½ in.	Up to 1⅛ in.	Up to 1⅛ in.	—	—
En 111	Low nickel-chromium	0·30-0·40	0·10-0·35	0·60-0·90	1·00-1·50	0·45-0·75	—	—	All sizes	Up to 4 in.	Up to 2½ in.	Up to 1⅛ in.	— —	—	—	—
En 160	2 per cent nickel-molybdenum	0·35-0·45	0·10-0·35	0·30-0·60	1·50-2·00	—	0·20-0·35	—	All sizes	Up to 4 in.	Up to 2½ in.	Up to 1⅛ in.	—	—	—	—

the slowest rate which is necessary for the development of the desired tensile strength. Because Ni-Cr air-hardening steel can acquire the required tensile strength by cooling in air, it is unnecessary and undesirable to harden it by quenching at a more rapid rate. The mechanical properties of two typical air-hardening Ni-Cr steels, within the range of chemical composition indicated above, are shown in Table 2.

These results substantiate the earlier remarks that no better physical properties are attained through oil-quenching than are obtained by air-cooling.

After hot-rolling or forging, the air-hardening steels are so hard as to be considered practically unmachinable for general engineering purposes. Such steels are, therefore, tempered after the hot-working operations to facilitate easy machining. Fig. 5 shows that when a 100-ton steel is tempered at about 650°C., its tensile strength is lowered to about 55 tons/sq. in., at which level of hardness the steel may be delivered to the shops for comparatively easy machining. At this stage, the Brinell hardness number of the steel would not exceed 300. All machining operations on an air-hardening steel should be carried out in this softened condition before it is finally hardened, allowing a small margin on the section for final grinding to size after hardening and tempering to the desired strength values.

Further reference to Fig. 5 indicates that a 100-ton air-hardening Ni-Cr steel suffers no appreciable loss of strength when tempered within a temperature range of 180°-220°C., but that its ductility and notched-bar impact values are improved. Therefore, it is recommended that this type of steels be tempered within the range of 180°-220°C. before final grinding.

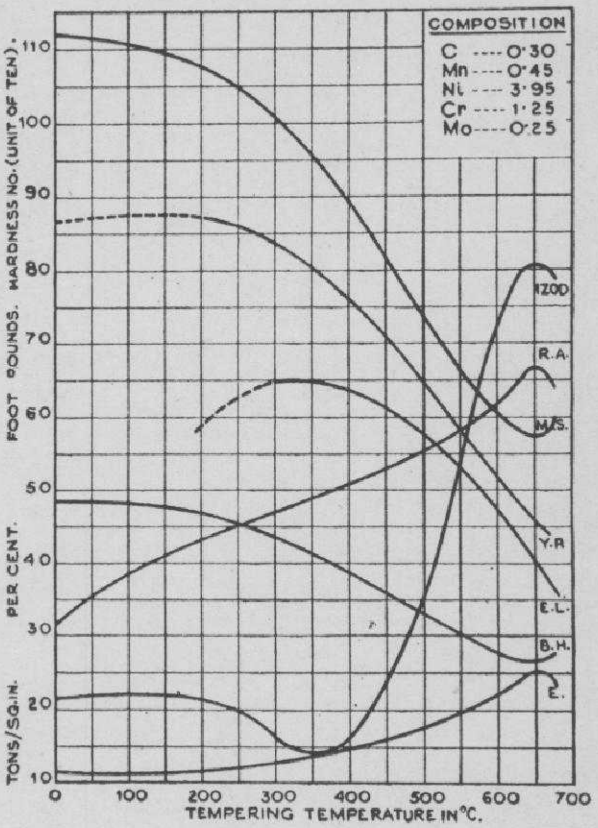

FIG. 5 — TEMPERING CURVES FOR NICKEL-CHROMIUM-MOLYBDENUM AIR-HARDENING STEEL

It should, however, be pointed out here that the Ni-Cr air-hardening steel, unless it contains molybdenum, is gravely susceptible to temper-brittleness, as shown by low impact

TABLE 2 — MECHANICAL PROPERTIES OF Ni-Cr AIR-HARDENING STEELS

STEEL	HEAT TREATMENT		ULTIMATE TENSILE STRENGTH, tons/sq. in.	ELONGATION, %	IMPACT, ft.-lb.
A	Air-cooled	830°C.	112	13	14
	Oil-quenched	830°C.	114	11	13
B	Air-cooled	840°C.	108	12	15
	Oil-quenched	840°C.	111	13	14

values, when tempered between 250° and 400°C. with subsequent air-cooling. This is also clearly indicated in the tempering curves of Fig. 5. Therefore, this range of temperature should be avoided in tempering of this group of steels.

Group II (75-100 *tons tensile strength*) — The selection of steel in this group, with a tensile strength ranging between 75 and 100 tons/sq. in., would depend on the mass of the part to be manufactured. For heavy components, an air-hardening steel of Group I would be called for. If, however, the components are smaller, it is more convenient to employ oil-hardening steels of Ni-Cr or Ni-Cr-Mo types. A typical chemical composition range of this group would be as follows:

	Per cent
Carbon	0·25-0·35
Manganese	0·45-0·65
Nickel	3·00-3·75
Chromium	0·80-1·30
Molybdenum	0·25-0·60

The above steel will acquire good physical properties after oil-quenching from 830°C., provided the mass of the component is not too large. By appropriate heat treatment, it is possible to produce any required tensile strength between 75 and 100 tons/sq. in. with satisfactory values of ductility and toughness, as can be seen from the tempering curves of Fig. 6.

Another steel in this group, suitable for the manufacture of still smaller sized components, has the following range of chemical composition:

	Per cent
Carbon	0·25-0·35
Manganese	0·50-0·70
Nickel	2·50-2·80
Chromium	0·50-0·80
Molybdenum	0·40-0·60

This steel should also be oil-quenched for hardening and tempered at an appropriate temperature (450°-550°C.) to obtain the desired properties.

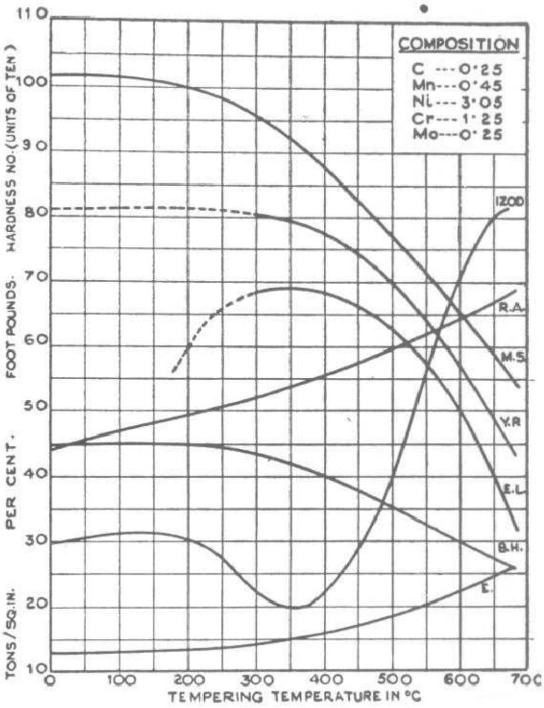

FIG. 6—TEMPERING CURVES FOR NICKEL-CHROMIUM-MOLYBDENUM STEEL

The same precautions for avoiding temper-brittleness should be observed as in the case of steels of Group I.

Softening for machining of this group of steels can be achieved, as in case of Group I steels, by tempering at 650°C. before final hardening and tempering and finish-grinding to size.

Group III (60-75 *tons tensile strength*) — Alloy steels for components demanding an ultimate tensile strength between 60 and 75 tons/sq. in. are more numerous than those of the two groups already discussed. Steels of either Group I or Group II can be used to provide the range of physical properties demanded in this group. An air-hardening steel gives the most satisfactory results for the heavier components, while oil-hardening Ni-Cr steel of the type discussed in Group II can yield equally satisfactory properties after tempering at suitably high temperatures.

A typical chemical composition range of steels in this group would be as follows:

	Per cent
Carbon	0·25-0·35
Manganese	0·40-0·70
Nickel	2·80-3·50
Chromium	0·75-1·00
Molybdenum	0·20-0·60

This steel acquires satisfactory physical properties after oil-quenching from 830°C. and tempering at temperatures around 500°-550°C. if a strength around 70 tons/sq. in. is desired (*see* FIG. 6).

The physical properties of a steel containing 0·32 per cent C, 0·48 per cent Mn, 3·33 per cent Ni, 0·84 per cent Cr and 0·26 per cent Mo in a 1⅛ in. diameter bar after quenching from 830°C. and tempering at different temperatures are indicated in Table 3 below.

TABLE 3 — PHYSICAL PROPERTIES AND TEMPERING

HEAT TREATMENT	ULTIMATE TENSILE STRENGTH, tons/sq. in.	ELONGATION, %	IZOD VALUE, ft.-lb.
Oil-quenched 830°C. (not tempered)	108	11	10
Oil-quenched 830°C., tempered 400°C.	82	14	23
Oil-quenched 830°C., tempered 500°C.	71	17	35
Oil-quenched 830°C., tempered 600°C.	61	21	54
Oil-quenched 830°C., tempered 650°C.	55	24	68

Temper-brittleness

It appears pertinent to devote some attention to temper-brittleness at this stage since the third group of steels is the most susceptible. When an alloy steel is hardened by quenching in air, oil or water and subsequently tempered at progressively increasing temperatures, most of its physical properties, determined at room temperatures, undergo a gradual and smooth alteration, that is to say, the values for elongation and reduction of area rise regularly with increase in tempering temperatures and those for ultimate tensile strength, yield point and hardness decrease. One would expect that the Izod impact value would also show a gradual and continuous increase with increasing tempering temperatures. This is, however, not the case. Actually, the impact value is frequently observed to rise as the tempering temperature rises up to about 200°C. and then to fall abruptly to much lower figures at temperatures in the range of 300°-500°C., and then rise again steeply at temperatures up to 650°C. In specimens tempered within the range of 300°-500°C. and subsequently slow-cooled, it has been found that the impact values are even lower than those obtained originally in the fully hardened condition without tempering. This phenomenon has been recognized as ' temper-brittleness '[10].

Generally, temper-brittleness has been observed to occur in such parts as have been allowed to cool at a relatively slow rate, as in still air, through the critical temperature range of approximately 500° to 300°C. When the steel is tempered at temperatures higher than this range, the onset of temper-brittleness does not occur, but it occurs only if the steel is cooled relatively rapidly by quenching in oil or water from the tempering temperature.

The chemical composition[6,7] of the steel also bears an influence on its susceptibility towards temper-brittleness. Plain-carbon steels, containing normal amounts of manganese and phosphorus, are generally not susceptible to this phenomenon. The presence of carbon, silicon, nickel, vanadium and tungsten in the steel has not been known to exert any effect on the tendency of the material to show temper-brittleness, whereas high proportions of chromium, manganese or phosphorus do increase this tendency.

The presence of molybdenum, in proportions up to about 0·50 per cent, considerably reduces this tendency towards temper-brittleness.

Exhaustive tests have revealed that all the other physical properties of the steel — elastic limit, yield point, ultimate tensile strength, elongation per cent, reduction of area, endurance limit, electric conductivity — are unaffected by an alteration in the method of cooling after tempering, and only the impact value is affected by the rate of cooling after tempering. Microscopic examination of a rapidly cooled and slowly cooled specimen has failed to reveal any appreciable difference in the microstructures when no special methods of etching are adopted. But the use of detergents and special etching reagents has proved that the embrittlement is caused by grain boundary precipitation.

To conclude this short discussion of temper-brittleness, the following facts may be taken to have been established:

(a) After tempering within a definite range of temperature (usually between 300° and 500°C.) most Ni-Cr steels exhibit a low impact value.

(b) Whatever method of cooling is employed after tempering within the above range of temperature, Ni-Cr steels (without molybdenum) may exhibit low impact values.

(c) The low impact values can be avoided by avoiding the above-mentioned brittle range of temperatures for the purpose of tempering followed by rapid cooling after tempering.

(d) The presence of up to about 0·60 per cent molybdenum helps to considerably reduce the susceptibility of these Ni-Cr steels towards temper-brittleness.

After quenching, the steels of Group III are generally tempered at around 550°C. and, therefore, care should always be taken to see that the parts are quickly cooled — by quenching in oil or water depending on the mass of the component — from the tempering temperature.

Steels of Group III can be softened for machining in the same way as steels in Group II.

Group IV (50-60 *tons tensile strength*) — The importance of this group of steels lies in the fact that 60 tons/sq. in. is near about the upper limit in steels which are relatively easy to machine and, therefore, a judicious selection is necessary from numerous types that may be available.

An air-hardening steel of Group I will hardly be suitable, because generally a 100-ton steel can be reduced barely to this limit even after tempering at the highest possible temperature. Air-hardening steels of Group II can be tempered down to only slightly lower strengths. Steels in Group III, however, can be hardened and tempered to meet the tensile range of 50-60 tons/sq. in. of Group IV easily, but it would be extravagant to use such richly alloyed steels for this purpose.

One of the steels that gives satisfactory results after hardening and tempering to produce a tensile strength has the following approximate range of chemical composition:

	Per cent
Carbon	0·25-0·35
Manganese	0·40-0·70
Nickel	1·25-1·75
Chromium	1·00-1·50
Molybdenum	0·20-0·30

This steel possesses only moderate hardenability and, therefore, cannot be recommended for components in heavy sections. For parts of smaller sections, the steel gives satisfactory properties after hardening and tempering between 600° and 650°C. The mechanical properties of such a steel after tempering at different temperatures are indicated in Fig. 7.

A chrome-vanadium steel containing 0·40-0·50 per cent C, 1·10-1·50 per cent Cr and 0·15-0·20 per cent V will also give, after hardening and tempering, good physical

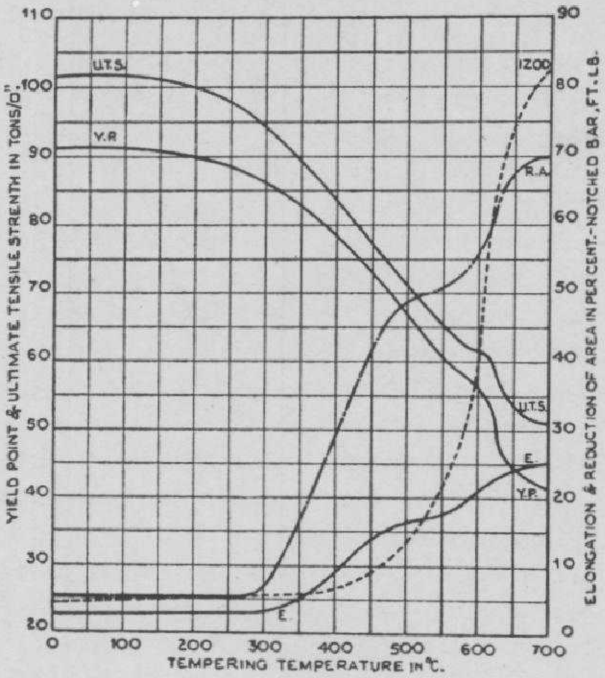

FIG. 7 — TEMPERING CURVES FOR NICKEL-CHROMIUM-MOLYBDENUM (50-60 TONS) STEEL

properties within the range of this group. The exact content of vanadium is not of importance as far as mechanical properties are concerned. Its presence is desirable in that it affects the grain size favourably. The hardenability of this steel is not very high, so that it is necessary to have a reasonably high carbon content if the steel is to be used for components of moderately heavy section.

Group V (*40-50 tons tensile strength*) — The Ni-Cr steels described previously are not generally employed for making components with an ultimate tensile strength of between 50 and 60 tons/sq. in.

When strengths less than 50 tons/sq. in. are required and an alloy steel is to be used to secure more regular toughness properties, either a straight chromium or a chrome-vanadium steel, similar to that described for Group IV, can be used in the hardened and tempered condition, but having slightly lower carbon contents, say 0·22-0·30 per cent. Another steel which can be used with satisfactory results for Group V is a plain nickel steel, containing approximately 0·30-0·40 per cent C, 0·40-0·70 per cent Mn and 1·00-1·50 per cent Ni. If a steel of this type is hardened by oil-quenching and then tempered in the range of 580° to 640°C., a very satisfactory range of strengths can be obtained with excellent toughness values.

The various 'En' steels which meet the strength requirements of Groups I to V for different ruling sections up to 6 in. are listed in Table 4. These 'En' steels have provided good substitutes for many of the prewar alloy steels, and bearing a rationalized character, have given a good account of themselves in engineering service.

General Properties of Alloy Steels

The foregoing discussion has indicated the range of mechanical properties that can be obtained from suitable alloy steels. It is seen that the acceptable toughness and ductility of the steels, as measured by the impact value and the per cent elongation and reduction of area, roughly vary conversely with the ultimate strength. In order to help the engineers in acquiring an idea of what may be regarded as approximately suitable values of toughness and ductility, the curves in Fig. 8 are included.

Although it was mentioned in the earlier part of this paper that the chemical composition of an alloy steel was but a means to an end, it should be mentioned here that a close control on the chemical composition of the steel may be very remunerative to the engineer. A few examples are given below to emphasize this aspect.

It was shown earlier that any of a number of different steels could be used to produce components in a tensile range of 50-60 tons/sq. in. by suitable variations in heat treatment. Therefore, if an engineering work is supplied with two steels differing in composition for the manufacture of the same component, an unnecessary strain would be thrown on the heat treatment department,

TABLE 4 — En STEELS WHICH SATISFY THE VARIOUS PROPERTY REQUIREMENTS IN DIFFERENT RULING SECTIONS

RULING SECTION AT TIME OF HEAT TREATMENT	GROUP I	GROUP II	GROUP III	GROUP IV	GROUP V
$\frac{7}{8}$ in.	En 110 En 111	En 24 En 110	En 100 En 110 En 111	En 15 En 18	En 15 En 18
$1\frac{1}{8}$ in.	En 24 En 25 En 30 En 110 En 111	En 24 En 25 En 26	En 24 En 100 En 110	En 18	En 15 En 18
$2\frac{1}{2}$ in.	En 25 En 26 En 30	En 24 En 25 En 26	En 24 En 110 En 111	En 18 En 100 En 111	En 15 En 18
4 in.	En 26	En 26	En 24 En 25 En 26	En 100 En 111	En 18 En 100
6 in.	En 30	En 26	En 24 En 25 En 26	En 100 En 111	En 100 En 111

which is then compelled to treat each steel separately and with differing heat-treating procedures. This will naturally retard and limit the smooth and efficient production of large numbers of the same component.

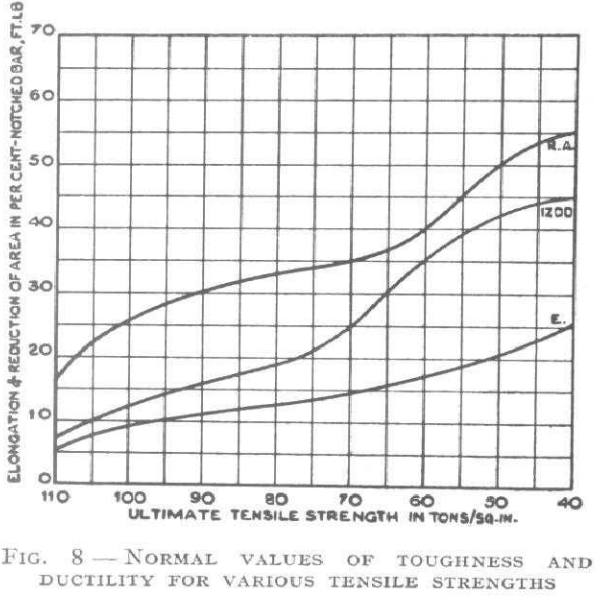

FIG. 8 — NORMAL VALUES OF TOUGHNESS AND DUCTILITY FOR VARIOUS TENSILE STRENGTHS

Then, again, irregularity and variety in chemical composition could adversely affect the production of machined components, because steels of varying chemical composition, although possessing approximately similar mechanical properties, do not appear to machine with the same ease especially where automatic machines are employed.

Yet another reason why regularity of chemical composition is important is that steels of varying composition behave differently under the drop-hammer and the stamping machine.

It, therefore, becomes necessary to specify reasonably close limits of chemical composition for the steel that is required for a particular component, so that standardized heat treatment procedures can be applied and a smooth production ensured.

The mass effect in hardening has already been dealt with in some detail and, therefore, one need only emphasize again that the principal advantage of alloy steels over plain-carbon steels is that the alloying elements considerably improve hardenability, whereby larger sections of metal can be hardened to a greater depth within the limits of the ruling section.

Test results do not reveal any apparent relationship between the fatigue range and any other mechanical property of the steel, except its ultimate strength. The endurance limits of steels are generally between 45 and 50 per cent of their ultimate tensile strength.

Here it is also of interest to review the properties as affected by low temperatures. Nickel steels have been found to be superior to plain-carbon steels in their resistance to the embrittling effects in low-temperature service conditions. Nickel steels have been known to show increasing values for yield point and ultimate tensile strength at temperatures down to —90°C. and still retain fairly good ductility. The hardened and tempered nickel - chromium - molybdenum steels also have been known to show equally good properties at low temperatures. Colbeck and his co-workers[11] studied the properties of a Ni-Cr-Mo steel, containing 0·33 per cent C, 2·54 per cent Ni, 0·67 per cent Cr and 0·64 per cent Mo, hardened from 850°C. and tempered at 640°C. Their results are given in Table 5.

The retention of fair ductility in these hardened and tempered steels at relatively low temperatures is remarkable, particularly when one notes the increase in their strength values. Unalloyed steels begin to show a decline in toughness values at temperatures not far below normal, whereas alloyed steels generally possess an advantage over plain-carbon steels in that they still show adequate toughness values at comparatively lower temperatures. Plain-nickel steels hold their toughness values fairly well down to about —70°C.; the hardened and tempered Ni-Cr steels also behave equally well, and the Ni-Cr-Mo steels in the hardened and tempered condition retain good toughness values at temperatures below —100°C.

The plain-chromium steels, however, are not as good as those containing nickel, and their general behaviour is not much better than plain-carbon steels in this respect.

TABLE 5 — PROPERTIES OF A Ni-Cr-Mo STEEL AT LOW TEMPERATURES

TESTING TEMPERATURE, °C.	YIELD POINT, tons/sq. in.	ULTIMATE TENSILE STRENGTH, tons/sq. in.	ELONGATION, %	REDUCTION OF AREA, %
Room Temp.	61	68	14	65
— 60	64	73	14	63
— 96	67	76	16	61
—180	82	90	17	63

Concluding Remarks

The above review by no means exhausts the list of alloy steels which are used by the engineer, for, as stated earlier, their number is legion. The groups of steels already described, of course, represent the types of engineering alloy steels generally employed in the industries. Besides these, there are also other types of alloy steels, such as stainless steels, heat-resisting steels, high-temperature creep-resisting steels, magnet steels, tool and die steels, and many others, each of which possess their own integral properties — by virtue of the alloying elements employed — required for the specialized purposes for which they are used in engineering service. The interest attached to these steels is vast and each deserves a distinct treatment on its own.

India already uses a fair amount of alloy steels, and her demands are likely to increase as industrialization progresses in the near future. These demands should, as far as practicable, be met by indigenous production, but this is not easy because India does not possess known reserves of many of the alloying elements generally employed. Nickel, in particular, is known to be non-existent at present, and so are molybdenum, vanadium and cobalt. Chromium and manganese are, however, available in the country and these two elements offer the best possibility of intelligent utilization in the indigenous production of alloy steels possessing appropriate physical and mechanical properties as brought out by a recent investigation by our research department. Even so, some nickel and molybdenum will, of necessity, have to be imported. In order to produce the alloying elements from indigenous resources, Indian industry has to be developed and expanded in this direction even to produce the standard grades of ferro-manganese and the low-carbon ferro-chrome.

Suitable rolling will also have to be made available to roll these alloy steels, as also the varied and necessary ancillary equipment required to process them. The production of alloy steels in this country has yet to take its own place as an integral unit and cannot be expected to function effectively and economically if it is to be regarded only as a step-child of a mass-producing plant.

It is hoped that this country will realize and appreciate the complicated implications of an alloy steel industry and its vital importance both to peace-time engineering developments and to the war-time needs of defence.

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