

THE WELDING OF SPECIAL AND ALLOY STEELS

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Introduction

FOR applications in which the properties of mild steel are inadequate there are other steels which meet a wide range of specific requirements. These special and alloy steels are many and varied. Some are closely similar in composition to mild steel, but are made by special processes to meet the needs of a special application; others contain considerable percentages of alloy additions, but still qualify to be called steels, as having an iron content of not less than 50 per cent.

In this paper we are concerned only with steels which find applications involving fabrication by welding, but here the number of individual steels concerned is still very large. In this review, steels have been grouped according to their intended applications, and where a steel used for some applications is rather outside the usual grouping it is considered as a 'special' steel.

It has been said that if a steel cannot be welded, its commercial value is very much reduced. Except, perhaps, in heavy sections, mild steel can be welded without much trouble by all the available processes, and the weldability of this material is the criterion by which the welding response of any other steel is usually assessed. Weldability has been defined as 'the capacity of a metal to be welded under the fabrication conditions imposed, into a specific suitably designed structure and to perform satisfactorily in the intended service'¹. Within the meaning of that definition, all the steels we shall discuss can be welded, although in some cases a special technique may be necessary. At this stage, we should also define a weld as 'a union between pieces of metal at faces ren-

dered plastic or liquid by heat or pressure or both. Filler metal may be used to effect the union'². The methods of producing a weld are best illustrated by an adaptation of a sketch from the Welding Handbook of the American Welding Society. Obviously, in this review we cannot discuss in detail each welding method for every steel, so that processes and/or some methods will, therefore, be dealt with very briefly or omitted entirely.

All the steels to be considered will be characterized, as compared with mild steel, by the following attributes:

- (1) Improved corrosion resistance.
- (2) Higher tensile properties which may, or may not, be associated with (1).
- (3) Better low-temperature ductility.
- (4) Improved resistance to creep at elevated temperatures.

Corrosion Resistance

Consideration will be given to resistance to atmospheric corrosion and to the more severe attack likely to arise in chemical plant. The rusting or corrosion of mild steel under atmospheric conditions may be prevented by surface protection such as painting, galvanizing, or plating, or by phosphate or similar treatments. Much welded mild steel plant is finished by these methods and such treatments do not give rise to any particular problem. If, however, it becomes necessary to weld pre-treated units, there may be some obvious difficulties, such as the effect which zinc from a galvanized surface may have on fusion welding or the effect of a phosphate film on resistance welding. These are aspects rather outside present considerations.

As the copper content of mild steel increases, so does its resistance to atmospheric corrosion, and steel containing about 0.3 per cent of copper but otherwise generally similar in properties to mild steel is now being used in large quantities. The weldability of such a steel is also very similar to that of mild steel, and copper-bearing electrodes are available to give a metallic-arc weld deposit having similar rust-resisting characteristics.

Mild steel is quite suitable for use in contact with chemicals such as dry chlorine or cold concentrated sulphuric acid. Such applications of the material are, however, limited, and it is the stainless steels that are usually considered in relation to the field of chemical engineering. These steels do, of course, resist atmospheric corrosion, but it is generally uneconomic to use them for such applications. It is, nevertheless, interesting to note that they are being used for the bodies of certain railway carriages and for the curtain walls³ of skyscrapers; in these applications their complete immunity from atmospheric corrosion enables the use of light gauge material thereby reducing weight.

Stainless steels may be divided into three broad groups, ferritic, martensitic, and austenitic. The martensitic group is difficult to weld but is used mainly for cutlery and for engineering applications which do not involve welding. The ferritic steels contain about 12-30 per cent of chromium with carbon usually less than 0.1 per cent, but such steels present some difficulty in welding on account of brittleness in the heat-affected zone⁴. This brittleness is not necessarily accompanied by high hardness, but may be associated with local grain growth. Addition of small amounts of titanium and aluminium renders these steels much less susceptible to embrittlement, provided the carbon content is kept at a low level. Post-weld treatment at 750°C. also has a beneficial effect, and there is some advantage in preheating. Metallic-arc electrodes of equivalent composition are

available, but it is necessary to compensate for the chromium loss across the arc; the more usual practice is to use an austenitic nickel-chromium steel electrode, to give a much more ductile deposit.

The austenitic group of stainless steels, most of which have been developed from the original 18 per cent chromium - 8 per cent nickel type, is a most important one. Much has been written on these steels, their composition, applications and welding characteristics⁵⁻⁷. The British Welding Research Association has issued a useful book on this subject⁸. As a group, the austenitic chromium-nickel stainless steels are more amenable to welding than the ferritic types, and in the chemical, dairy, brewery and food industries wide use is made of austenitic steel plant fabricated by welding. For light-gauge equipment argon-arc welding has tended to replace oxy-acetylene welding; for heavier equipment metallic-arc welding is the process mainly used, but there have been some developments of submerged arc and inert-gas metal-arc methods⁹. The variety in composition of austenitic stainless steels makes it necessary to have a wide range of electrodes available. Generally speaking, electrodes matching the respective parent materials in composition are suitable. Electrodes with coatings containing rutile may be used on A.C., but the basic coated electrodes require D.C. for their operation. D.C. is essential for welding material less than $\frac{1}{8}$ in. in thickness. The more important types of stainless steels are listed in Table 1.

Whenever austenitic stainless steels are mentioned, the question of 'weld decay' always arises. This is the name given to a vicious type of corrosion which may occur in the heat-affected zone adjacent to a weld in some of the austenitic stainless steels. This 'weld decay' is a metallurgical effect, and, in the true sense, not an actual welding fault. Much has been written and said about this problem and it is not proposed to add now to the discussion, but for those interested

TABLE 1 — WELDABILITY OF CORROSION-RESISTING STEELS

TYPE OF STEEL	MAJOR FIELDS OF APPLICATION	WELDABILITY	NOTES ON ELECTRODES AND WELDING TECHNIQUES
Copper-bearing mild steel	Structural — for improved resistance to atmospheric corrosion	Good	Mild steel practice but copper-bearing steel electrodes available.
Ferritic stainless steels	11-14% chromium	Difficult	Better with austenitic chromium-nickel electrodes wherever possible. Some pre-heat and post-heat necessary. (Steels with aluminium content give better welding response.)
	14-18% chromium	Slightly better than above	Generally as above.
	20-30% chromium	Difficult	Generally as above. Poor mechanical properties in heat-affected zone.
Austenitic stainless steels	18% chromium, 8% nickel grades	Good	Appropriate electrodes available. Use stabilized or low-carbon grade of steel for welding to avoid weld decay.
	18% chromium, 8% nickel, 3% molybdenum grades	Good	As above.
	25% chromium, 20% nickel grades	Good	Fully austenitic electrodes introduce danger of hot-cracking in heavy section welds. Controlled ferrite type of electrode usually recommended.

in studying the subject more closely there is much to be found in the literature which has been ably summarized by Keating¹⁰. Either by the addition of titanium or niobium ('stabilization') or by the control of carbon content, as in the recently developed extra-low-carbon steels, this 'weld decay' effect may be eliminated or greatly reduced.

For chemical plant the quality of the weld must be of a high standard and the deposit of a composition which will ensure, in the joint, an overall corrosion resistance equivalent to that of the parent material. In the dairy, brewery and food industries severe corrosion attack is not likely to be encountered, but the austenitic stainless steels

are, nevertheless, often chosen for such applications, because their use precludes any danger of the flavour or colour of the product being affected by traces of metallic contamination. The ease with which the surface can be polished is a further advantage for hygienic reasons and in facilitating maintenance. The weld deposit in such plant must be sound, so that after grinding or polishing there are no crevices or defects which will be difficult to clean.

The stabilizing effect of the elements introduced to combat 'weld decay' leads to the formation of some ferrite in the austenitic steels, and the fast cooling rates associated with welding favour ferrite formation in the weld deposits. The corrosion-resistance of these weld deposits is not markedly changed by the presence of the ferrite, but there are other effects to be considered, one of which concerns subzero properties which will be mentioned later. The other is the formation of sigma phase, a complex structure associated with the decomposition of ferrite. Rate of decomposition is a function of time, temperature and composition of the steel. Titanium, niobium, molybdenum and silicon all tend to favour the formation of sigma, whereas nickel and carbon exert a retarding effect. Much has been written on this subject^{10,11}, but we need only consider here its practical significance. Sigma formation is again a metallurgical effect, rather than a true welding fault. Sigma is a brittle constituent, and its presence in a steel is reflected in the loss of ductility which occurs when steels containing ferrite have been heated at about 650°-900°C., the range within which sigma forms. The effect of normal welding on the heat-affected zone of ferrite-containing steels is not likely to be serious because of the short time involved, but both parent materials and welding deposits containing ferrite may eventually become embrittled after prolonged operation in this temperature range¹⁰. It will be noted that stress-relief temperatures may also fall within the range causing sigma

formation. Compositional changes are a way out of this problem of sigma formation, but it is not possible to discuss these aspects in detail here.

Attempts to produce fully austenitic weld deposits, for service at temperatures at which the presence of ferrite introduces the danger of sigma formation, have always been foiled by a susceptibility to hot-cracking or fissuring, especially in heavy multi-run deposits. This tendency is associated with the characteristically cored columnar austenitic structure of the weld deposit, which seems to give rise to interdendritic cracking. This hot-cracking can be eliminated by the introduction of a strictly controlled amount of ferrite into the deposit. The percentage is critical: the ferrite must be sufficient to prevent cracking, but not so much as to introduce danger of subsequent sigma-phase formation on a scale which could cause loss of ductility.

Brief mention must be made of two new austenitic stainless steels which have recently been introduced into the U.S.A. under the AISI classifications 201 and 202, the type compositions of which are, respectively, chromium 17, nickel 4, manganese 6 per cent, and chromium 18, nickel 5, manganese 8 per cent. Both steels contain appreciable amounts of nitrogen. It will be noted, when comparing these compositions with the usual austenitic chromium-nickel types, that some of the nickel has been replaced by manganese. This development is not so much a technical change as one designed to reduce the nickel content during a period of short supply of that metal. So far, these steels have been mainly used under mildly corrosive conditions and there is not yet any accumulated experience of their behaviour in chemical plant. The welding procedure for these steels has been reported as being very similar to that required for the AISI 301 type¹².

As a group, the austenitic stainless steels cannot be hardened by heat treatment, but

recently there has been development of some precipitation-hardenable types which can be heat-treated to give specially high tensile strength. These include the 17 per cent chromium - 7 per cent nickel steels containing 1 per cent of aluminium, which require a double heat treatment at 760° and 510°C. to develop optimum properties; the 17 per cent chromium - 4 per cent nickel type containing 4 per cent copper, which will develop similar properties with a single treatment at about 470°C., and another type, based on 17 per cent chromium - 4 per cent nickel but containing about 3 per cent molybdenum which develops high tensile properties after a subzero treatment at - 73°C. and subsequent heating at 400°C. The immediate interest in such steels is mainly in aircraft applications, and most of the welding experience has been on light-gauge material, using argon-arc welding. Welding speeds must be rather quicker than is usual for the austenitic steels, and the current must be kept as low as possible¹³.

For chemical plant requiring material of heavy section considerable use is made of clad steels which comprise a mild steel backing onto which has been rolled a cladding of nickel, monel, inconel, austenitic stainless steel, or ferritic stainless steel. Copper-clad steel is also available. The minimum thickness of these composite materials is usually $\frac{3}{16}$ in., and the minimum cladding thickness about 0.035 in. generally, the cladding thickness ranges from 10 to 20 per cent of the overall thickness, although on the very thick material it is kept to a maximum of about $\frac{1}{4}$ in. The cladding is integral with the steel backing and will withstand the normal operations associated with the fabrication of chemical plant.

The welding of such steels requires special consideration. It is usual to complete the welding on the steel side first, using steel electrodes, and then to finish on the clad side by welding or by using an overlay technique, employing the material appro-

priate to the cladding. The important objective is to preserve the continuity of the cladding, and in some circumstances the weld will be made entirely with a composition similar to that of the cladding. It is impossible here to describe fully the various procedures, but they have been described in greater detail elsewhere¹⁴.

Higher-tensile Steels

There are so many steels in this classification that they can be dealt with only in a general way. It is proposed to omit entirely any reference to the high-tensile constructional steels used in automobile and aero-engines and also steels used for armour plate. Table 2 shows a grouping of the steels to be reviewed. These types are used mainly for structural purposes, on static assemblies such as bridges and girders, or for the mobile units employed in road, rail and sea transport. Such work is mostly fabricated by metallic-arc welding.

Early development was on steels having a carbon content of 0.3 per cent, with manganese at 1.5 per cent: the metallic-arc welding of that type of steel gave some trouble, which was minimized by reducing the carbon content to 0.26 per cent maximum. These lower-carbon steels gave a tensile strength of about 40 tons per sq. in., with a yield point of about 22 tons per sq. in., in sections up to $\frac{1}{2}$ in. in thickness. With thicker sections, however, these properties could not be obtained with the lower carbon content and other low-alloy high yield point steels were, therefore, developed, e.g. those based on manganese-molybdenum, chromium-molybdenum, nickel or nickel-copper, etc. Another type of steel is a copper-bearing grade with about 0.5-1.25 per cent chromium and a high phosphorus content, about 0.1 per cent. Many of these low-alloy steels, particularly those containing nickel and copper, are resistant to atmospheric corrosion, and reduction in thickness, to take

TABLE 2 — WELDABILITY OF LOW-ALLOY HIGH-TENSILE STEELS

TYPE AND COMPOSITION RANGE OF STEEL	PRE-HEAT	POST-HEAT	SPECIAL ELECTRODES OR TECHNIQUE REQUIRED
Manganese (C, 0.26% max., Mn, 0.9-1.5%)	None	None	Generally none but low-hydrogen types or pre-heat to 200°C. may be necessary on heavy sections.
Manganese-molybdenum (C, 0.26% max.; Mn, 0.9-1.3%; Mo, 0.4-0.6%)			
Nickel (C, 0.26% max.; Ni, 2.3-7.5%)	200°C. min.	Not essential but may be required for the higher carbon alloys	Low-hydrogen type, preferably of equivalent composition, maintain interpass temperatures around 200°C. (stress-relief at about 625°C. improves low-temperature impact properties).
Nickel-copper (C, 0.22% max.; Ni, 2% max.; Cu, 1.25% max.)	Not normally required	Not normally required	Use ordinary steel or 'high-tensile steel' electrodes of good quality.
Nickel-copper-chromium (C, 0.15% max.; Ni, 0.5-1%; Cu, 0.3-0.7%; Cr, 0.3-1%; P, 0.12% max.)			For heavy or severely restrained sections pre-heat slightly, use low-hydrogen electrodes and maintain interpass temperature.
Nickel-copper-molybdenum (C, 0.12% max.; Ni, 0.5-1%; Cu, 0.5-1.3%; Mo, 0.1-0.2%; P, 0.12% max.)			

advantage of their high tensile strength, does not introduce a serious corrosion risk. It is also considered that a better 'paint' life is obtained on these low-alloy steels as compared with that of mild steel.

Some development work on weldable high-tensile steels was started about 1937 by the British Institute of Welding, and since the war has been continued by the F.M.8 Committee of the British Welding Research Association. The objective was a steel which should have a yield point of 25-30 tons per sq. in. and be characterized by good weldability: particular emphasis was placed on freedom from hard-zone cracking in the heat-affected area, or underbead cracking as it is often called¹⁵. The introduction of alloy elements to improve mechanical properties does, in general, increase hardenability, so that when welding these steels there is always a risk of crack formation in the heat-affected zone of the welded joint.

Various tests may be used for the assessment of weldability: several of these are based on the Reeve test. The B.W.R.A. 'controlled thermal severity' tests represent one of the later developments which have served to show that there is a critical rate of cooling below which no cracking is likely to take place, but above which there is a direct relation between the degree of cracking and the rate of cooling¹⁶. Cottrell has demonstrated that if the rate of cooling at 300°C., using a given electrode, exceeds a certain critical figure, cracking will result. The selection of this figure of 300°C. was somewhat arbitrary; but for many of the steels involved it represents the middle of the temperature range in which the austenite-to-martensite transformation takes place. During this transformation there is a sudden decrease in the solubility of hydrogen, and the gas is forced out of solution, causing stresses in the

martensite which may be a contributory cause of hard-zone cracking.

Considerable attention has been given to the significance of hydrogen in relation to hard-zone cracking¹⁷, and this has led to the development of low-hydrogen electrodes which are also referred to as basic or lime-ferritic electrodes. Such electrodes contain only about 2 cc. hydrogen per 100 g. of weld deposit, as compared with a figure of about 12 cc. for the rutile types. Many carbon steel electrodes will give mechanical properties suitable for welding these low-alloy high-tensile steels, but special electrodes are available which will deposit steels of the chromium-molybdenum, manganese-molybdenum, or nickel types.

With the low-alloy steels, in addition to the hard-zone cracking in the parent material, the weld metal itself may be involved in cracking troubles. Many of these weld-metal cracks are associated with shrinkage stresses at the solidification stage and are

akin to the hot tears that may occur in castings under restraint.

Table 3 summarizes some of the results and remedies for various welding faults in steels of the types under review¹⁸.

A publication¹⁸ of the Welding Research Council, U.S.A., contains a detailed review of many of the factors that have been briefly discussed in this paper. In that publication the steels have been conveniently grouped into three ranges, in relation to composition and thickness:

- (1) Those requiring no pre-heating, post-heating or special electrodes.
- (2) Those requiring some control of heat input and the use of low-hydrogen electrodes.
- (3) Those requiring pre-heating, post-heating and special welding techniques.

One special steel, somewhat outside this grouping, which has been developed in England, has a low carbon content and contains 0.5 per cent of molybdenum with a small

TABLE 3 — LOW-ALLOY HIGH-TENSILE STEELS — WELDING DEFECTS AND THEIR REMEDIES

DEFECT	CAUSE	POSSIBLE REMEDIES
Weld metal cracks (hot cracks)	<ul style="list-style-type: none"> Restraint in joint Unsuitable or damp electrodes Poor alignment Small weld beads 	<ul style="list-style-type: none"> Pre-heat. Vary welding sequence. Change electrodes. Dry electrodes. Correct assembly to reduce root gap. Increase size of bead. Change type of electrode.
Base metal cracks (underbead cracks; cold cracks)	<ul style="list-style-type: none"> Hydrogen in welding atmosphere High hardenability 	<ul style="list-style-type: none"> Pre-heat. Use low-hydrogen electrodes. Pre-heat. Increase welding heat input. Post-heat.
Porosity in weld deposit	<ul style="list-style-type: none"> Surface contaminations (oil, paint, etc.) Improper manipulation or poor arc control Rapid rate of weld metal freezing Damp electrodes 	<ul style="list-style-type: none"> Clean joint area. Attention to welder's technique. Pre-heat. Increase heat input. Dry electrodes.
Inclusions in weld deposit	<ul style="list-style-type: none"> Surface scale Trapped slag Improper electrode manipulation 	<ul style="list-style-type: none"> Clean joint area. Improve joint design. Completely remove slag between passes. Attention to welder's technique.

amount of boron. Such a steel has a yield strength of about 34 tons per sq. in., with maximum stress at 40 tons per sq. in. and the weldability is very satisfactory¹⁹.

In the lighter gauges these low-alloy steels are often spot-welded, and the very rapid cooling associated with this method will produce weld embrittlement. Weld ductility may be greatly improved by 'programme control' of the welding cycle, i.e. controlling the current so as to pre-heat and also post-heat the weld area. This subject has been admirably dealt with by Dixon²⁰.

Another interesting study on lighter gauge material has involved the argon-arc welding of a chromium-molybdenum steel of the A.S.T.M. 4130 type²¹.

Low-temperature Ductility

It was perhaps the spectacular failure of several welded ships^{22,23} that first focussed attention on the relation of welding to 'brittle fracture'. There have also been failures of welded bridges and storage tanks which have been associated with a form of spontaneous cracking occurring at low temperatures. Similar failures have occurred in riveted structures, but the extent of cracking was usually less since the propagation of the crack was halted at a rivet hole or plate junction, whereas in monolithic welded structures there was no such barrier to the progress of the crack.

The association of welding with these failures sometimes led to this method of joining being blamed as the primary cause of brittle fractures. A study of the metallurgy of the subject has shown, however, that such is far from being the truth. The metallurgical aspects cannot now be discussed in detail here, but much has been written about them²⁴, and reference may be made to one important factor. There is a temperature called the transition temperature, at which steels become extremely notch-sensitive, as the fracture changes from ductile to brittle,

but in assessing the transition temperature it is often necessary also to consider the nature of the fracture face, and to note the relative percentages of fibrous (ductile) and crystalline (brittle) material.

At low temperatures ordinary carbon steels including commercial mild steel appear to be characterized by extremely high notch-sensitivity under conditions of static or dynamic loading. High notch-resistance at a temperature below about -50°C . certainly cannot be obtained from an ordinary carbon steel, but down to that temperature it is possible to produce one that can be made to give useful impact properties. Such a steel must be fine-grained, with a carbon content not exceeding 0.15, and the manganese more than four times this value; the steel must be so deoxidized with aluminium that there is a small residual content of this metal²⁵.

In the handling of liquid gases where the operating temperature is so low that even the special carbon steel just mentioned is of no practical value, there are fortunately alloy steels which can be employed. So far as ferritic steels are concerned, the addition of nickel seems to have the greatest effect²⁶, and the austenitic chromium-nickel steels maintain high impact values even below temperatures of -180°C . A useful review of the properties of such steels and many other materials has been prepared by Teed²⁷.

The precise influence of welding upon notch brittleness in steels operating at low temperatures is still not entirely clear. The impact values of mild steel weld-metal deposits are generally better than those of the parent material, but there is some indication that welding causes a loss of ductility in the heat-affected zone. The main feature, however, would seem to be that unsuitable geometry of the welded joint can provide a starting-point for a brittle fracture in notch-sensitive steels. Cracks have been traced to an origin coincident with the spot where

an arc has been carelessly or accidentally struck on a thick plate. In ship failures some cracks appear to have started at defects in welded joints, but these have usually progressed through the plate well away from the weld and have crossed sound welds without deviation. It certainly seems that if the steel used satisfies an arbitrary minimum impact specification of 15 ft.-lb. (Charpy) at $-50^{\circ}\text{C}.$, brittle fractures at temperatures above this are unlikely to occur in welded constructions, whatever the method of welding employed. This does not, of course, in any way excuse poor-quality welding, and some metallic-arc welding electrodes will give better low-temperature impact values than others. Low-hydrogen type electrodes are usually satisfactory for the carbon steels, but in themselves are not any solution to this problem of brittle fracture when welding ordinary mild steel. The effect of residual stresses must also be considered: this aspect will not be discussed here, since it is dealt with in some of the papers to which reference has been made. The cross-section of the steel being used is also a factor that needs consideration: there is some difficulty in obtaining the required properties in heavier plates. The submerged-arc method has been used on such plates with satisfactory results so far as the actual weld has been concerned.

The welding of the nickel steels has been dealt with in some detail by Armstrong²⁶ and others²⁸. In general, the use of low-hydrogen electrodes is advocated to minimize the danger of underbead or weld-cracking and also to maintain good impact properties at low temperatures. Steels containing small amounts of molybdenum, or the low-alloy manganese-molybdenum or chromium-molybdenum steels, can be used as the core of electrodes for welding these nickel steels, but, particularly in the U.S.A., electrodes with nickel-steel core wire are preferred. The steels used contain 2-2½ per cent nickel, sometimes with ½ per cent

molybdenum, or 3-3½ per cent nickel. Such electrodes will again have the low-hydrogen type of coating, to minimize risk of underbead cracking. These deposits have particularly good low-temperature properties.

The properties of austenitic chromium-nickel steels for low-temperature applications are reviewed by Krivobok²⁹, and the welding attributes of such steels have already been discussed in this paper. The most significant feature is the presence of ferrite which, at low temperatures, will certainly have the effect of reducing the impact-resistance as indicated in Table 4. It is significant that the impact-resistance of cast austenitic stainless steels tends to be lower than that of the wrought material, and weld deposits show the same tendency. This difference is probably associated with the dendritic aspects of the macrostructure.

Resistance to Creep at Elevated Temperatures

Creep may be defined as the time-dependent part of the deformation which accompanies the application of a stress to a solid³⁰. At room temperatures steels stressed below the limit of proportionality deform elastically to a given amount, but if the temperature rises, this initial deformation is followed by creep, a slow continuous yielding. Creep may cause the part eventually to break, or at least undergo more extension than can be tolerated in the design.

The creep-resisting properties of steels have assumed practical significance during the past 25 years as a result of the use of higher temperatures and pressures in chemical plant, and higher steam temperatures in power plant, and, more recently, in connection with the high stresses and temperatures involved in gas-turbine operation.

Steels may be grouped according to the temperature range in which they have no practical use so far as creep resistance is concerned. In determining creep resistance

TABLE 4—STEELS FOR LOW-TEMPERATURE APPLICATIONS

STEEL GROUP	TYPE OF STEEL	TEMP. °C.* AT WHICH CHARPY IM- PACT VALUE FALLS BELOW 15 FT.-LB.	NOTES ON WELDING TECHNIQUE	COMMENTS ON JOINT PROPERTIES
Carbon	Controlled quality with high Mn/C ratio	-50	Generally as for mild steel	Similar to parent material.
Nickel	3½% nickel	-150	Use low-hydrogen 3½% nickel steel electrodes. Pre-heat to 200°C. Stress-relieve at 620°C.	Similar to parent material.
	8½% nickel	Below -190	Use austenitic steel electrodes of the 25-20 type or 80-20 nickel-chromium electrode. Stress-relieve at 575°C.	Similar to parent material.
Austenitic Chromium Nickel	18-8 18-10-1 Nb 18-8-3 Mo-1 Ti 25-20	Below -190	Use appropriate electrodes but control ferrite in deposit. Fully austenitic weld deposits are subject to fissuring, but about 5% ferrite will prevent this trouble.	Impact values of the weld metal are lower than those of the parent material.

*Intended as a guide only. Actual impact values vary widely according to composition and heat treatment and are affected by welding conditions and post-welding heat treatment.

the times and temperatures chosen obviously depend upon service requirements. In gas-turbine applications for aircraft, temperatures are high but operating times are short; for power plant, where temperatures will be lower, the expected service life is very much longer. Associated with creep resistance may also be the effects of oxidation or of a particular corrosive environment.

Whilst a considerable amount of work has been done on all the creep-resistant steels, actual data on welded testpieces are rather sparse. It is not proposed to consider here all the implications of creep testing and the precise assessment of values for particular applications, but many relevant references

will be found in literature, including the one of which mention has already been made³⁰.

It would seem that molybdenum, vanadium and chromium are most useful in imparting creep resistance to low-alloy steels for the lower temperature range. Chromium, however, is mainly necessary in relation to the demand for corrosion resistance in steels used for chemical and oil plant installations. For power plants, steels containing up to about 1 per cent of chromium are usually adequate, but those with 2¼ per cent chromium are often used, and as much as 5 per cent chromium will be required in steels to be used for some purposes in oil and

TABLE 5 — STEELS FOR RESISTANCE TO CREEP AT ELEVATED TEMPERATURES

STEEL GROUP	TYPE OF STEEL	APPROX.* LIMITING TEMP. °C.	NOTES ON WELDING TECHNIQUE	COMMENTS ON JOINT PROPERTIES
Ferritic	Carbon	450	Generally as for mild steel	Similar to parent material.
	Low alloy, e.g. 0.5% Mo, 1% Cr- 0.5% Mo	525 to 575	Use low-hydrogen electrodes of appropriate composition	Similar to parent material.
	Mo-V 2.25% Cr- 1% Mo			
	High-chromium steels	600	Use appropriate electrodes or austenitic types. Pre-heat to 200°C., control cooling rate after welding. Stress- relieve.	Generally similar to parent material, but may be lacking in ductility.
Austenitic and special†	Chromium- nickel 18-13-1 Nb 25-12 25-20	650	Use appropriate electrode or 25-20 type, but control fer- rite in weld deposit where there is danger from sigma formation.	Weld metal properties are likely to be slightly lower than those of parent material at higher tem- peratures.
	Complex steels con- taining Cr and Ni plus one or more of the follow- ing elements: Co, W, Mo, Nb, Si	700	If available, use appropriate electrode, otherwise 25-20 type or 80-20 nickel-chro- mium types.	May be difficult to match optimum creep-resisting properties of parent materials.

*Intended as a guide only. Precise temperatures will depend upon intended service conditions.

†Beyond the temperature range of these materials it is possible to use nickel or nickel-cobalt base alloys.

chemical plant. In extreme cases even 9 per cent chromium may be required.

The austenitic chromium-nickel stainless steels which are necessarily used in place of the ferritic steels, in the higher temperature ranges do, of course, have an inherent corrosion resistance. Beyond the range of usefulness of even the austenitic steels it is possible to employ complex cobalt-containing steels or nickel-base alloys, but such materials are, however, outside the present survey.

Welding of the chromium-molybdenum steels is usually done by the metallic-arc method, and the technique is governed by the relatively high hardenability of such steels. Special electrodes of the low-hydrogen types now available are capable of dealing with this group of steels: they give weld deposits of composition similar to that of the parent metal. Hardness in the weld area is undesirable, for the reasons already mentioned in connection with higher tensile steels. The low-hydrogen type of electrode has

obvious advantages in welding these creep-resisting steels and the danger of cracking is further reduced by pre-heating them to about 200°C. and using large-diameter electrodes, to maintain the interpass temperature. These precautions against hard-zone cracking are imperative when welding thicker sections of all the steels, but they are especially important as the chromium content increases. When welding heavy sections of steels of the higher chromium contents it may be necessary to control the cooling rate by transferring the component to a furnace at a temperature of about 400°C. In any event a post-weld stress relief at 650°-750°C. should be applied to welded components in these steels; and occasionally a full anneal at 900°C. with furnace-cool is beneficial. A great deal of pipe work is fabricated in these steels and advantage is often taken of local electrical heating, either directly or by induction methods, to control pre-heat and post-heat treatments.

So far as the austenitic steels are concerned, the important aspect to be watched is the development of sigma-phase in the weld deposit: the significance of this has already been discussed. Another interesting problem arises in connection with the need (usually on economic grounds) to join ferritic and austenitic steels. This involves consideration of two main points—the sharp difference in coefficients of expansion in such a joint, and the need to avoid, during service, carbon migration from the ferritic to the austenitic steel, since this may cause corrosion troubles. Again, it is in tubular components that this problem arises, and special composite joints have been manufactured to overcome the difficulties. Special inserts have been developed which are based on an austenitic-ferritic joint in a controlled taper. This controlled taper may be achieved by the extrusion into tube form of superimposed discs of the austenitic and ferritic materials. In this process it is usual to employ nickel foil between the discs to provide a barrier to

any carbon migration at the interface. Another method employs a special drawing technique which starts with an austenitic steel tube inserted into a tube of ferritic material. Both these interface welds are of the pressure type and their quality depends upon careful cleaning and preparation; some machining is required to complete the inserts. The usual fusion welds to austenitic and ferritic tubes respectively may be made at the appropriate ends of the inserts.

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