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Vanadium in structural steels

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SYNOPSIS

This paper reviews the metallurgical functions of vanadium in high-strength low-alloy steels, and discusses the ways in which vanadium is used in various types of steel supplied as reinforcing bars, plates, sections, and strip. Potential developments to meet new engineering requirements are discussed briefly.

SAMEVATTING

Hierdie referaat gee 'n oorsig oor die metallurgiese funksies van vanadium in hoëtreksterkte-laelegeringstaal en bespreek die maniere waarop vanadium gebruik word in verskillende soorte staal wat as wapeningstawe, plate, profiele en bande voorsien word. Moontlike ontwikkelings om in nuwe ingenieursbehoeftes te voorsien, word kortliks bespreek.

Introduction

High-strength low-alloy (HSLA) steels were developed mainly as alternatives to higher-carbon non-alloyed steels after the introduction of welding for joining steel plates and sections. The low-alloy steels had lower carbon contents, and the excessive cost and practical problems of the welding procedures necessary to avoid cold cracking in the heat-affected zones of welded structures were thus overcome or reduced. Vanadium steels were almost exclusively used at that time, but, with the development of controlled rolling techniques and the development of niobium supplies in the 1960s, new steels were developed for some applications, particularly for pipelines. These steels had even lower carbon contents and improved weldability, and contained niobium. Vanadium steels continued to be used, however, and steels containing both vanadium and niobium were developed.

The demands of engineers are continuously changing, and new steels are required for new conditions. Today a wide range of steels containing vanadium alone and in combination with niobium, molybdenum, and titanium are available.

The Metallurgical Functions of Vanadium

Vanadium has been used in HSLA structural steels for at least forty years, and indeed it was the first of the so-called micro-alloying elements (excluding aluminium) to be used. Vanadium alone, and together with the other micro-alloying elements aluminium, niobium, and titanium, contributes extra strength to carbon–manganese structural steels through the formation of carbides and nitrides, acting directly to strengthen the steel by precipitation, or indirectly by mechanisms leading to refinement of the ferrite grain size. Grain refinement also increases the low-temperature toughness of steels.

In some cases, as when added with aluminium, the vanadium precipitates and precipitates of other micro-alloying elements reinforce each other in their effects on the steel. In other cases, such as control-rolled vanadium–niobium plates, the precipitates of the two micro-alloys are used to produce different effects on the structure and properties. For example, the niobium carbide enables a fine grain size to be obtained, and the vanadium carbonitride contributes precipitation strengthening.

The specific roles of the various carbides and nitrides in any steel are controlled primarily by the relation of the temperature range over which they form to the Ar_3 temperature. When more than one alloy is present, the alloy forming a carbide or nitride at the highest temperature dominates the structure and its effect on properties because (a) the compounds present at the high temperatures have a prior effect on grain structure over those forming at lower temperatures, and (b) it has first choice of the carbon and nitrogen in the steel. An alloy forming a compound at a high temperature frequently inhibits or completely suppresses the formation of compounds of alloys that form at lower temperatures and also lowers the temperature at which these compounds form. This can affect the size of the precipitates.

In some cases, the lowering of the temperature at which compounds form means that they form in ferrite instead of austenite, which can completely change their effect on the properties of the steel. It makes sense therefore, in an interpretation of the structure and properties of steels containing more than one micro-alloying element, that consideration should be given to the effect of the alloy-forming compounds at the highest temperature, before the effect of other alloys whose compounds form at lower temperatures is assessed. In the case of a steel containing vanadium with titanium or niobium, the effect of the vanadium on the titanium or niobium steel is discussed, and not the effect of the other elements on the vanadium steel.

The maximum temperatures at which the carbides and nitrides of micro-alloys form under equilibrium conditions are given in Table I. Although for convenience reference is made separately to carbides and nitrides, it should be realized that the compounds invariably contain both carbon and nitrogen, and they should be regarded as carbon- or nitrogen-rich carbonitrides. Further, it was recently shown[1,2] that carbides and nitrides of a micro-alloy that forms compounds at high temperatures can contain atoms of a micro-alloying element that would normally form compounds at a lower temperature. Vanadium has, for example, been found in titanium nitride

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and in niobium carbide. Moreover, the presence of the second micro-alloying element in these compounds can affect the size of the precipitates, and hence their effect on the structure and properties of steels. This can also mean that the amount of the second alloy to precipitate at a lower temperature is reduced, and that its precipitate forms at a lower temperature.

TABLE I

MAXIMUM TEMPERATURES (UNDER EQUILIBRIUM CONDITIONS) UNDER WHICH CARBIDES AND NITRIDES OF MICRO-ALLOYING ELEMENTS FORM IN HSLA STEELS

Compound	Approximate maximum temperature of formation °C
TiN	1200
NbN	1240
NbC	1090
VN	1070
VC	900

Apart from the effects on the microstructure and properties produced by their carbides and nitrides, the micro-alloying elements can have an influence through their effect on the γ–α and α–γ transformations, and in this their effect has to be taken together with the influence of other alloys such as manganese, chromium, molybdenum, nickel that may be present and that also affect the transformation characteristic of steel. These effects of the micro-alloys are important in determining the structure and properties of certain types of steel, and they are becoming increasingly important in determining the properties of welds in some steels, particularly steels welded under high heat-input conditions.

The micro-alloys vary in their effects on the transformations. Vanadium has a particularly strong effect in delaying the formation of bainite, i.e. increasing hardenability, and, providing conditions are such as to avoid the formation of vanadium carbide, it can be more effective than some established alloys such as molybdenum. It is also unique (except for silicon) in not retarding the formation of ferrite. These two functions combine to inhibit bainite or side-plate structures in the heat-affected zones of welds, which it is known can lead to embrittlement of these zones. These structures are more likely to form when welding procedures requiring a high heat input are used. In this respect, the effect of vanadium differs from that of niobium. Vanadium, like molybdenum, also delays the formation of pearlite, a feature that is employed in the design of some pipeline steels.

Copper and nickel are sometimes added to steels to give strength in solid solution, and vanadium and the other micro-alloying elements may be used together with these alloys. Molybdenum[3] and copper[4] have also been added to vanadium steels to refine the V (CN) precipitate, thus enabling the strength to be maintained in thick sections. In some steels, for example in the manufacture of strip, accelerated cooling is employed to control the structure, in particular to refine the grain size. In recent years, accelerated cooling has been applied to other steel products, and vanadium and other alloys can be used in collaboration with these processes to produce certain microstructures and properties in various steel products.

The functions of vanadium and their application to various HSLA products are summarized in Fig. 1. Some or all of the effects are used in all vanadium steels, but those actually employed are determined by the properties required in the steel by the ultimate user, the condition of welding and forming stipulated by the fabricators, and the plant available to the steelmaker to produce steel in the required product form (plate, pipe, strip, or section). The plant available, and hence the metallurgical principles involved, sometimes vary from one manufacturer to another, even for the same product, and in fact there are also significant differences between the steel plant available in one country as compared with another. These have been sufficiently divergent to have a large influence on the development of engineering design codes and national steel specifications. The major practical and theoretical factors controlling the selection of a steel composition are summarized in Fig. 2.

There is no logical way in which the application of the above principles can be discussed in relation to all steel products, and each type of product will therefore be discussed separately.

Reinforcing Bars

The addition of vanadium to reinforcing-bar steels enables the carbon content to be reduced, and hence the weldability to be improved. The strength lost by a reduced pearlite content in lower-carbon steels is restored and enhanced by vanadium carbonitride precipitates. The effect of vanadium can be increased by raising of the nitrogen content. The strength achievable for 30 mm bars in a 0,25 per cent carbon, 1,4 per cent manganese steel are as shown in Fig. 3. It will be seen from this diagram that a bar with a yield strength of 500 N/mm^2 can be achieved with an addition of 0,10 per cent vanadium in a steel with 0,007 per cent nitrogen. Alternatively, bars of this strength can be produced with steels containing 0,06 per cent vanadium and 0,015 per cent nitrogen. However, in the selection of a steel composition, the cost of making a low-carbon steel has to be balanced against the cost of the additional vanadium and nitrogen. The strength attainable is, of course, a function of bar diameter, but 56 mm bars with a minimum yield strength of 450 N/mm^2 have been produced in vanadium steels for the foundations of some offshore structures.

Vanadium-steel reinforcing bars, because they depend for their strength on precipitation, can be rolled on any mill, including modern high-speed mills, and are not subject to the restrictions of niobium steels, which depend for their strength mostly on the fine grain size that is produced by low-temperature rolling. In some old mills, the finishing temperatures are low, but these temperatures are achieved in modern mills only by a reduction of output. Vanadium steels can also be cast without difficulty and, unlike niobium steels, are not subject to corner cracking in continuous casting, nor are they prone to reheat cracking.

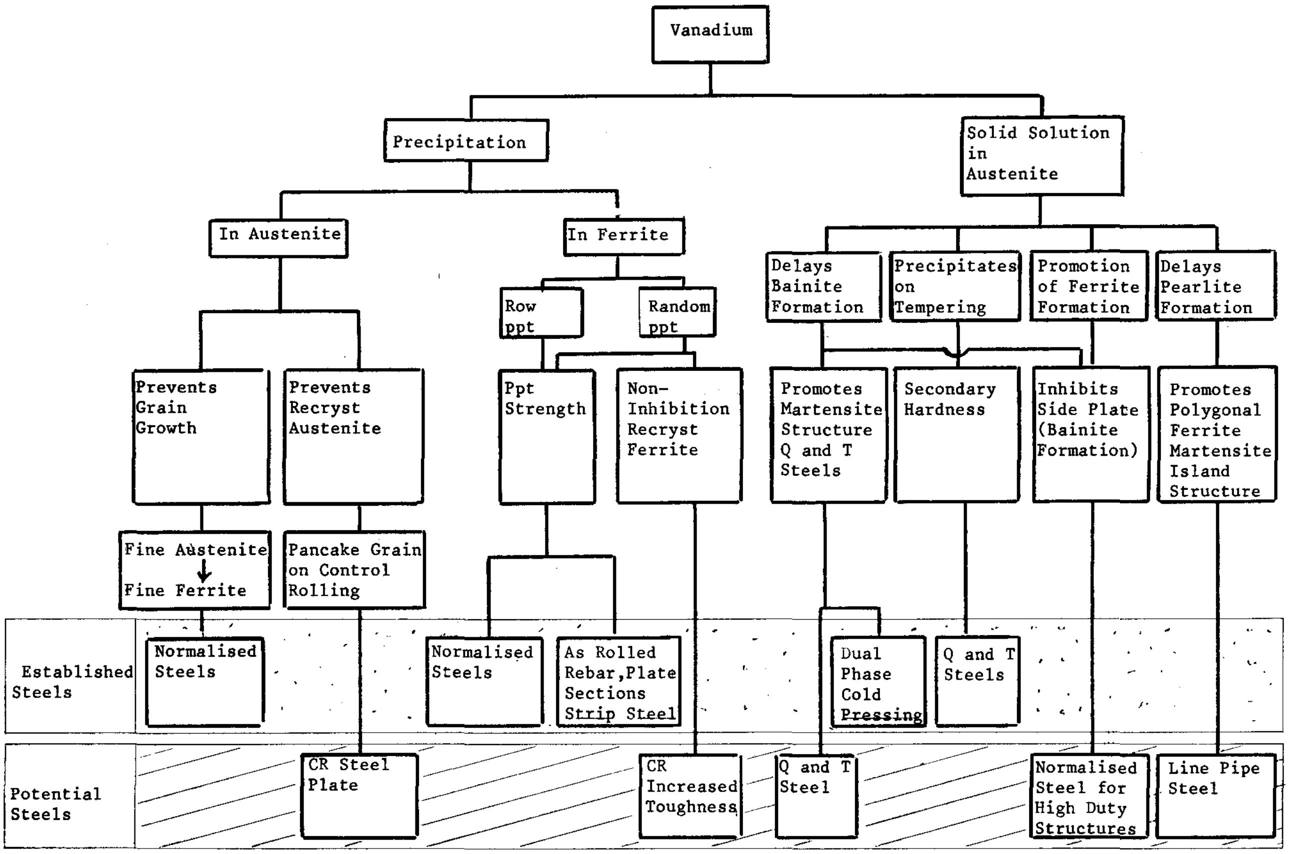

Fig. 1—The metallurgical effects of vanadium in structural steels

Plates

HSLA steel plates are used for a wide range of applications involving differing combinations of steel properties, and are therefore supplied to a large number of specifications stipulating minimum strengths between 350 and 700 N/mm². Many of the specifications also lay down various requirements for low-temperature impact properties, and some incorporate requirements for weldability (resistance to cold cracking), usually in the form of a maximum carbon equivalent value. More recently, some specifications of the ultimate users have required guarantees for the toughness of weld metal and of the heat-affected zones of plates and sections when welded.

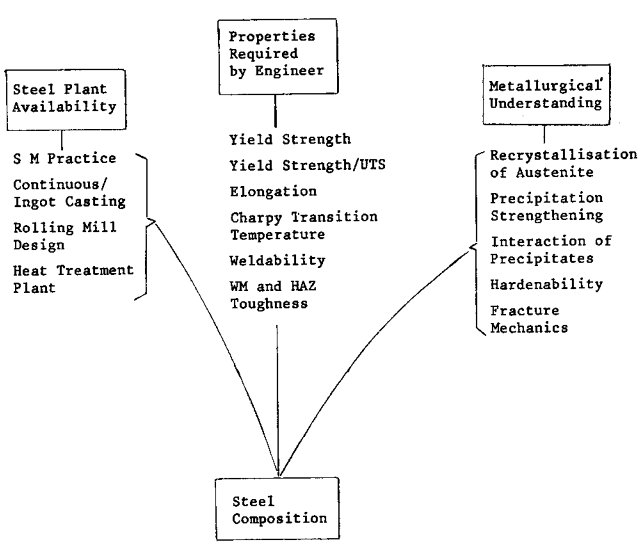

Fig. 2—The parameters controlling the composition of steels

As-rolled Steels (*Yield Strengths up to 350 N/mm²*)

The simplest HSLA steels and those which all steelmakers would prefer to produce are supplied to specifications calling for tensile properties only. These can be produced in the as-rolled condition with no special rolling procedures or subsequent heat treatment. Such steels involve the minimum of process control and the lowest of processing costs. Where strength is the only consideration, the addition of vanadium to a carbon steel can be used to produce weldable plates with yield strengths of 350 to 450 N/mm², depending on the plate thickness. In these steels, the vanadium increases the strength of the carbon steel primarily by precipitation strengthening. This strength can be further enhanced if the nitrogen content is increased to about 0,015 per cent, but the vanadium-to-nitrogen ratio must be kept to a minimum of 4 : 1. The exact strength level achievable is controlled by the carbon, vanadium and nitrogen contents, and the plate thickness. Steels of this type have been, and still are, widely produced in North America, and are supplied to the ASTM specification A572. Examples of these steels and their properties are given in Table II.

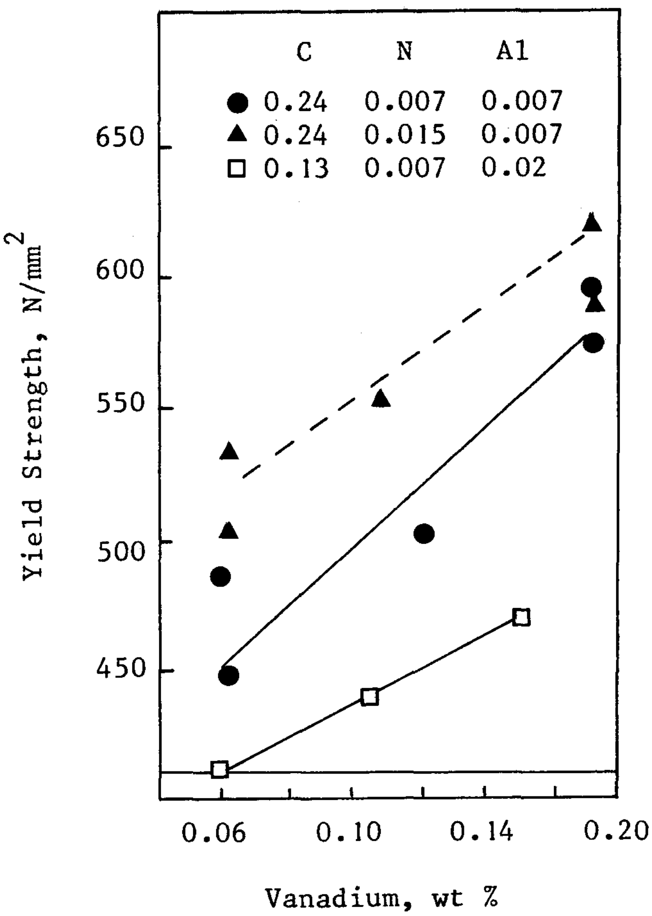

Fig. 3—The effect of vanadium on the yield strength of 30 mm bars (d)

Steels for Low-temperature Service (Yield Strengths up to 350 N/mm²)

When steels for welded structures are required for low-temperature service (ambient temperatures of 0°C or lower), the specifications usually include requirements for guaranteed Charpy impact values at given temperatures. The toughness of steel is improved by grain refinement (which lowers the Charpy V transition temperature), and tends to be impaired by precipitates and/or dislocations. Ferrite grain size can be refined by heat treatment (normalizing), or by certain rolling practices (particularly low-temperature control-rolling of steel while it is still austenitic).

Normalizing can be adopted only where suitable furnaces are available, and controlled rolling can be used only for plates up to a certain maximum thickness. This maximum is in the range 25 to 40 mm, and depends on the power of the rolling mill. Controlled rolling reduces the productivity of most mills; even when they are computer-operated and scheduled, controlled rolling is impossible in mills that are lightly powered.

The grain refinement in normalized steels is achieved by the presence of fine particles (5 to 50 mm in diameter) that form as the steel cools during and after rolling, and/or that form when the steel is being heated to the normalizing temperature but while it is still ferritic. In either case, the particles prevent grain growth of the austenite when formed, and also probably inhibit grain growth of ferrite formed on cooling.

Aluminium nitride, which does not usually form in hot-rolled steel but subsequently when the steel is heated during the normalizing heat treatment, is probably the most important compound controlling grain size. Vanadium can be added to aluminium-treated steels to give some additional precipitation, but its effectiveness depends on the carbon and nitrogen contents, and it is not usually added to steels with a carbon content of less than 0,12 per cent.

Normalized steels have been widely used in Europe for important structures, and the addition of about 0,03 per cent niobium is frequently made to enhance the grain refinement achieved with aluminium and to give some precipitation strengthening. Such steels are widely used for plates supplied to specifications calling for yield strengths up to 350 N/mm².

The strength attainable by grain refinement is limited, and decreases with increasing plate thickness. It is therefore common to add up to 0,09 per cent vanadium to maintain the strength in the thicker plates through the precipitation of V(CN).

In some structures, however, such as offshore platforms, fabricators are endeavouring to use high heat-input welding procedures to increase production and reduce costs. Under these conditions of welding, the niobium tends to give bainite-type or side-plate struc-

TABLE II

CHEMICAL COMPOSITION AND PROPERTIES OF STEELS SUPPLIED TO ASTM A572 SPECIFICATION

ASTM A572 grade	Thickness mm	Composition, wt %							Yield strength N/mm²	Ultimate tensile strength N/mm²
		C max	Mn max	P max	S max	Si max	V min	N max		
42	⩽ 38	0,21	1,35	0,04	0,05	0,30	0,01/0,10	–	289	414
	⩽ 100	0,21	1,35	0,04	0,05	0,15-0,30	0,01/0,10	–	289	414
45	⩽ 38	0,22	1,35	0,04	0,05	0,30	0,01/0,10	–	310	414
50	⩽ 38	0,23	1,35	0,04	0,05	0,30	0,01/0,10	0,015	345	448
55	⩽ 38	0,25	1,35	0,04	0,05	0,30	0,01/0,10	0,015	379	483
60	⩽ 25	0,26	1,35	0,04	0,05	0,30	0,01/0,10	0,015	414	517
65	⩽ 13	0,26	1,35	0,04	0,05	0,30	0,01/0,10	0,015	448	552

tures in the heat-affected zone. Vanadium does not form such microstructures but in fact tends to inhibit them, and there is therefore a potential for the development of normalized fine-grain steels treated with aluminium to which vanadium is added to inhibit the side-plate structures in the heat-affected zone and possibly to give some precipitation strengthening to the plate.

The toughness of the heat-affected zone of welds is also controlled by the grain size, especially on the fusion side of the zone. Grain growth in this region during welding is prevented only by fine particles that do not go into solution at the higher temperatures attained in this zone. Titanium nitride is the only compound of the normal micro-alloys that does not go into solution under these conditions, and current research work is concerned with the possibility of developing titanium–vanadium steels for conditions where toughness of the heat-affected zone is important.

The alternative method of producing a fine grain size, as mentioned above, is controlled rolling of steels, i.e. rolling of the steel to give about 75 per cent reduction to the final thickness in the temperature range 980° to Ar_3 temperature to produce pancaked austenite grains, which transform to ferrite grains with a grain diameter equal to about half the minor axis of the pancaked grains. In practice, the pancaked grains are produced by the addition of about 0,03 per cent niobium. The grain refinement, and hence the strength achievable by this procedure, is limited and decreases with thickness, as shown in Fig. 4 for laboratory casts of steel. The strength can, however, be maintained in thicker plates by the addition of vanadium to supplement the strength through precipitation

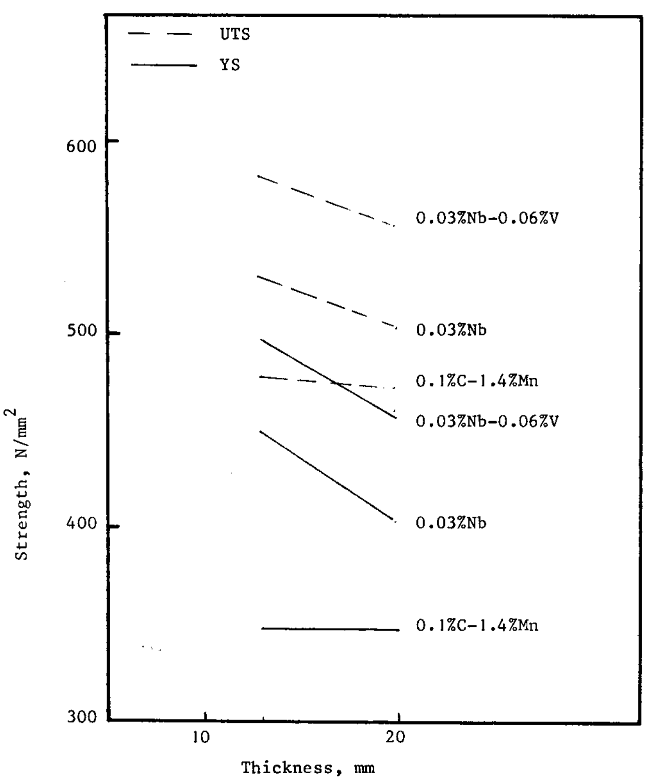

Fig. 4—The effect of thickness on the strength of various steels

strengthening of vanadium carbonitride. This is also shown in Fig. 4.

Plates for Low-temperature Service (Minimum Yield Strength 350 to 450 N/mm²)

When minimum yield strengths greater than 350 N/mm² and up to 450 N/mm² are required, the strengths achievable by either grain refinement or precipitation strengthening alone are insufficient, especially in thicker plates, and combinations of grain refinement and precipitation strengthening are adopted.

In Europe, where the steel plates for important structures have always been normalized, vanadium–nitrogen steels were adopted for many years for plates up to 100 mm thick. In these steels, vanadium nitride, which forms during the cooling of the steel after rolling, and aluminium nitride, which forms during reheating or normalizing, combine to produce grain refinement by the mechanism described above. However, for maximum grain refinement, the aluminium, vanadium, and nitrogen contents have to be carefully controlled. By the addition of a little extra vanadium, precipitation of vanadium carbonitrides can be ensured to give additional strengthening. The fine grain size lowers the transition temperature and enables the steel to be used in locations where low ambient temperatures prevail. This type of steel has been widely supplied to BS 4360 Grade 55 E, which specifies a yield strength of up to 450 N/mm² in plates up to 16 mm, and 400 N/mm² up to 100 mm, and to the ASTM A633 specification Grade E, which specifies yield strengths up to 450 N/mm² in plates up to 102 mm, and 380 N/mm² in plates up to 150 mm. These steels have been widely used for earth-moving equipment, bridges, and cranes.

The steel compositions and properties required for these specifications are summarized in Table III. It will be noted that the Charpy V notch properties are obligatory for the British specification but optional for the ASTM specifications. However, the high nitrogen content of the steel restricts its weldability in that considerable preheat and/or post-heat have to be supplied, especially in thick plates, to avoid cold cracking. Further, there is a tendency for the nitrogen to dissociate from its compounds and to remain in solid solution in the heat-affected zone, giving rise to some loss of toughness.

For improved weldability in this type of steel, especially when supplied in thick plate, alternatives have been developed with lower carbon and nitrogen contents. Most of these contain niobium and molybdenum and/or copper, together with vanadium, and have a carefully controlled aluminium content. The steels have a ferrite–pearlite structure, and some bainite is also present. The AlN and NbC ensure a fine grain size of the ferrite, and the vanadium gives precipitation strengthening, which is enhanced by the presence of the molybdenum and/or copper, both of which appear to delay the formation and refine the size of the V(CN) precipitates so that a high strength (450 N/mm²) is maintained in thick sections (up to 100 mm). The sensitivity of the strength of the steels to vanadium content is shown in Fig. 5, in which the effect of vanadium on a steel not containing molybdenum and copper is given for comparison. The molybdenum increases the hardenability of the steel and intro-

TABLE III
EXTRACT FROM BRITISH AND U.S. SPECIFICATIONS FOR V–N HSLA STEELS FOR THICK PLATE

Steel type	C	Mn	Si	V	Al	N
V–N BS 4360 Grade 55E	0,27 max	1,6 max	0,1– –0,6	0,2 max	(0,04)*	(0,015)*
V–N ASTM A633 Grade E	0,27 max	1,15– –1,5	0,15– –0,5	0,04– –0,11	(0,04)†	0,011–

Tensile Properties				Charpy properties		
Plate thickness mm	Yield strength N/mm^2	Ultimate tensile strength N/mm^2	Elongation on 200 mm %	−20 °C J	−30 °C J	−50 °C J
BS 4360 Grade 55E						
< 16	450	550–700	17	61	42	27
16–40	430	550–700	17			
40–63	415	550–700	17			
63–100	400	550–700	17			
ASTM A633 Grade E				−18 °C	−34 °C	−51 °C
< 102	415	550–690	18	54†	41†	27†
102–152	380	520–660	18			

* Average level – not on specification
† Not obligatory for A633

duces some bainite in the structure, which ensures a high ultimate tensile strength and relatively low ratio of yield strength to ultimate tensile strength.

The steels are supplied in the normalized condition but are often tempered to ensure full precipitation of the V(CN) and maximum strength. Typical steel compositions and properties are given in Table IV.

Controlled-rolled niobium–vanadium steels of the type described above for thicker plates with minimum yield strengths of up to 350 N/mm^2 have also been used for plates with yield strengths up to 450 N/mm^2, but the thickness at which this is possible is limited to about 25 mm. These steels, like the as-rolled steels, sometimes contain additions of copper and nickel to increase the yield strength by solid-solution strengthening and, in the case of copper, to refine the V(CN) precipitates. These steels, however, have the same disadvantage as all niobium steels where high-heat-input welding is used.

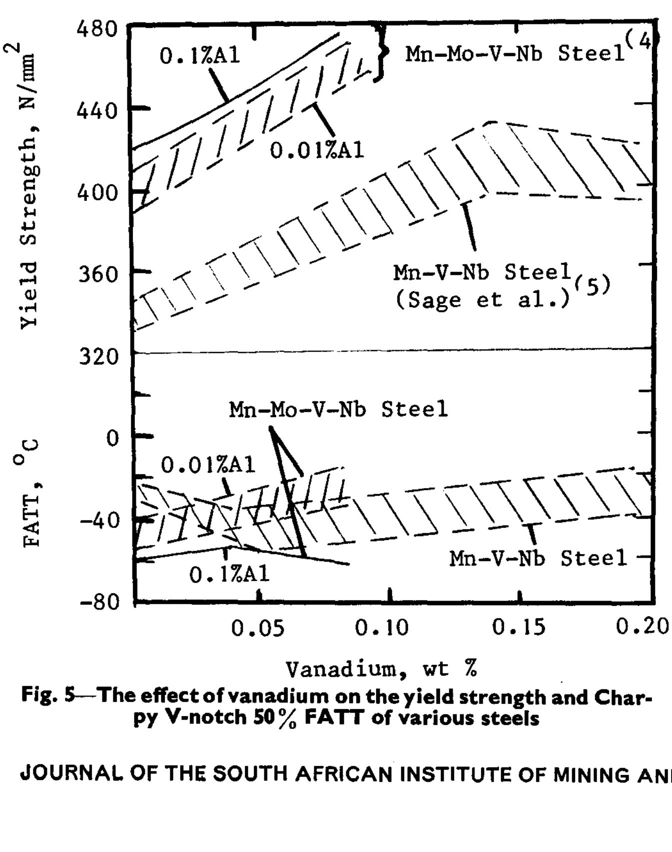

Fig. 5—The effect of vanadium on the yield strength and Charpy V-notch 50% FATT of various steels

Very-high-strength Plates (Yield Strength up to 700 N/mm^2)

Steels with minimum yield strengths of up to 700 N/mm^2 have been widely used for structures, including the centre spans of some suspension bridges. These steels are supplied in the quenched and tempered condition, and contain additions of chromium, nickel, and/or molybdenum to give them hardenability, and frequently contain additions of vanadium to give secondary hardening. A typical steel and its properties are shown in Table V.

Attempts were made recently[6] to produce steels of this strength in the as-rolled condition. High-manganese vanadium–nitrogen steels of the typical composition given in Table VI have been produced in plates up to 14 mm thick with a yield strength of 550 to 600 N/mm^2. The high manganese content lowers the transformation temperature, which refines and hence increases the effectiveness of V(CN) precipitation. The high manganese content, combined with control rolling (down to 760°C), gives a fine grain size and good toughness, as can be seen from Table VI. Such steels have a potential application for earth-moving and mining equipment, trucks, and railroad cars.

Steels of this strength can be produced in thick plates (40 mm) by direct quenching of the plate after rolling, and about 0,1 per cent vanadium is added to increase the hardenability of the steel so that the as-quenched (martensite) structure is produced in the steel as the plate leaves the mill. In thick plates (40 to 100 mm), there is no distortion of the plates in the as-rolled condition. It is understood that these plates are being produced in Japan, but no details have been published.

TABLE IV

COMPOSITION AND PROPERTIES OF EXTRA-WELDABLE HSLA THICK PLATES

	Steel composition							
Steel type	C	Mn	Si	Mo	V	Nb	Cu	Al	N
Mn–Mo–V–Nb	0,09––0,12	1,5––1,8	0,2––0,5	0,2––0,4	0,04––0,09	0,02––0,03	– –	0,02––0,19	0,02––0,10
Cu–Mo–V	0,15	1,49	0,34	0,22	0,10	0,04	0,45	0,028	–

Tensile properties (N 955 °c tempered 1h 620 °C)						Charpy properties
	Plate thickness mm	Yield strength N/mm²	Ultimate tensile strength N/mm²	Elongation %	Reduction of area %	50 % fracture appearance transition temperature (FATT) °C
Mn–Mo–V–Nb	70	457	597	35	69	–55
						°C for 27J
Cu–Mo–V	30	440–468	613–659	17–20	–	–14 – –70

TABLE V

COMPOSITION AND PROPERTIES OF QUENHED AND TEMPERED VANADIUM STEELS TO ASTM SPECIFICATION A514

Chemical composition

Grade	C	Mn	P max	S max	Si	Ni	Cr	Mo	V	Ti	Cu	B
B	0,12–0,21	0,70–1,00	0,035	0,04	0,20–0,35	–	0,40–0,65	0,15–0,25	0,03–0,08	0,01–0,03	–	0,0005–0,005
F	0,10–0,20	0,60–1,00	0,035	0,04	0,15–0,35	0,70–1,00	0,40–0,65	0,40–0,60	0,03 0,08	–	0,15–0,50	0,0005–0,006
Q	0,14–0,21	0,95–1,30	0,035	0,04	0,15–0,35	1,20–1,50	1,00 1,50	0,40 0,60	0,03 0,08			

Properties

Thickness mm	Yield strength N/mm²	Ultimate tensile strength N/mm²	Elongation on 50 mm %	Reduction of area %	Hardness BHN
Up to 19	690	760–895	18	40	235–293
19–64	690	760–895	18	40	–
64–152	620	690–895	16	50	–

TABLE VI

TYPICAL COMPOSITION AND PROPERTIES OF AS-ROLLED 550 N/mm² YIELD-STRENGTH PLATE IN Mn–V–N STEEL

Composition, wt %

C	Mn	P	S	Si	Al	V	Nb	N
0,22	1,40	0,010	0,012	0,25	0,03	0,14	0,015	0,015

Tensile properties			
Yield strength N/mm²	Ultimate tensile strength N/mm²	Elongation on 8 in %	Bendability (transverse) shear burr in tension
550–607	718–773	15–22	2 × t (min inside radius)

CVN impact properties (full size or equivalent)			
Longitudinal		Transverse	
+21 °C J	–18 °C J	+21 °C J	–18 °C J
72–136	32–82	49–83	22–53

Rolled Sections

High-strength steel sections are largely used for bridges, and the beams of high-rise buildings and industrial plant. They are mostly supplied to specifications calling for a minimum yield strength of about 350 N/mm², and, in addition, if operating in structures where ambient temperatures are low, guaranteed minimum Charpy impact properties at low temperatures have to be met. Most rolled sections are supplied in the as-rolled condition, although one or two plants are able to supply normalized sections, and some can give accelerated cooling after normalizing.

Vanadium steels are used largely for smaller sections, the strength being achieved from the grain refinement produced by aluminium treatment of silicon-killed steel, as for the plates described above, together with V(CN) precipitation. Where accelerated cooling is given after normalizing, some additional grain refinement giving improved strength and toughness is achieved. Vanadium steels are preferred to niobium steels for the rolled section produced in many plants when the finish rolling temperatures of the flanges is of the order of 1000°C, because the relatively rapid cooling (between 800°C and 500°C), as compared with that for plates, tends to produce bainitic structures in the niobium steel, which lower its toughness. Typical compositions and properties of as-rolled vanadium-steel sections are given in Table VII. For heavier sections, where the flanges are thicker and therefore cool more slowly, the susceptibility to bainite formation is less and niobium steels are sometimes used.

Strip Steel

Strip steels are made in continuous mills, where successive deformations are given to a steel in rapid succession and, unlike plate rolling, the time between successive deformations is the same order of magnitude as that required for recrystallization, so that pancake grains tend to be produced without the additon of niobium. The rapid deformation and the fact that continuous hot strip mills have only 6 or 7 stands means that the exit temperature from the mill is about 800°C, and, for practical purposes of coiling, the strip is quenched to between about 600 and 650°C. This operation also contributes to the production of a fine grain size. Carbon steels with strengths of about 350 N/mm² are produced in this way, and sheets having yield strengths of up to 450 N/mm² can be produced by the addition of up to 0,10 per cent vanadium. However, niobium is more commonly used because it enables a cheaper steel to be produced.

When higher strengths are required (550 to 600 N/mm²), a combination of vanadium and niobium is usually employed, and in the absence of niobium a vanadium–nitrogen steel can be used.

Dual-phase Steels

About ten years ago, these steels were developed to reduce the weight of certain automobile parts, which are subject to cold work while being formed to shape. The steels are designed to have a polygonal ferrite structure with about 10 per cent of martensite in islands. This microstructure causes the steel to work-harden rapidly during the pressing operations, and enables it to undergo considerable strain before fracture. Steels with such a microstructure are therefore very suitable for the production of high-strength pressings.

These microstructures can be produced in carbon–manganese steels during continuous annealing, but this process is applicable to strip only up to 2 mm in thickness. To produce this microstructure in thicker strip (up to 4 mm), vanadium is added to increase the hardenability of the steel, and some additional strength may come from V(CN) precipitates in the ferrite. These steels can have a yield strength of up to 550 N/mm². The practical development of these steels, however, is inhibited by the fact that they require continuous heat-treatment furnaces that can heat the strip to about 850°C and then quench it under controlled conditions. Furnaces for the continuous annealing of stainless steel can be used, or galvanizing furnaces can be adopted if not required for galvanizing.

The steel can be used for automobile wheels, bumpers (if not too simple in shape), and other components that undergo severe deformation of the load-bearing parts during pressing.

Pipelines

One of the major uses of HSLA steels and of vanadium has been for the high-strength pipelines used for oil and gas. Pipeline steels, unlike most other steels (except cold-

TABLE VII

YPICAL COMPOSITION AND PROPERTIES OF AS-ROLLED VANADIUM-STEEL SECTIONS SUPPLIED TO BS 4360 GRADES 50B AND 50D

Chemical composition							
Grade	C	Mn	Si	P	S	V	Al
50B	0,17	1,45	–	0,050 max	0,050 max	0,06	–
50D	0,12	1,38	0,37			0,06	0,03

Tensile properties			Charpy properties		
Yield strength N/mm²	Ultimate tensile strength N/mm²	Elongation on 200 mm %	Thickness mm	Energy J	Temperature °C
345 min	490 min	18 min	25	34	–40
			40	40	–20

pressed steels), are used in the cold-worked condition. Most high-strength pipelines are made from plate that has been cold-worked in a UOE press and expanded (to ensure roundness of the pipe). This process, and the flattening of test sections prior to testing, subject the steel to reverse deformations (tension and compression), which reduce the part of its strength that comes from precipitation and dislocations by about 50 per cent. Where the strength of plates arises in part from precipitation and dislocations, the plates must have additional strength over that required in the pipe to allow for this loss on pipe forming.

The wall thickness of most pipelines is between 12 and 20 mm, and the first HSLA steels used were 'as-rolled' vanadium steels having yield strengths of 450 N/mm^2 in the plate and 415 N/mm^2 in the pipe. In North America, where most pipelines were laid in rural areas and where temperatures were rarely lower than 0°C, these 'as-rolled' steels were satisfactory. In Europe, however, where more attention was paid to the possibility of brittle fracture because the pipes passed mostly through urban areas and ambient temperatures could be below 0°C, vanadium-nitrogen normalized fine-grained steel as described above was used.

About 1970, control-rolled niobium steel was adopted because it was less costly to produce, and had lower carbon contents and hence greater weldability (resistance to cold cracking). The strength attainable with this steel, however, was limited to 414 N/mm^2 (60 ksi), and for higher-strength X65 and X70 pipes (with yield strengths of 448 and 480 N/mm^2), which have formed the greatest demand for pipes in recent years, vanadium was added. The wall thickness in which X70 properties can be produced in these steels is limited to about 25 mm, and, for thicker-walled or higher-strength pipes, different types of steel have to be found.

Molybdenum-niobium steels having a structure consisting of acicular ferrite or polygonal ferrite with martensite islands have been developed. These steels, by virtue of their structure, work-harden rapidly during the cold-working operation of pipemaking, and X70 pipes with wall thicknesses of up to 25 mm or more have been produced. An experimental vanadium steel containing 0,45 per cent vanadium with similar structures and properties has been produced[7] as an alternative, and work is in hand on other steels containing niobium, molybdenum, and vanadium that have a structure consisting of polygonal ferrite-acicular ferrite and precipitates of vanadium in the ferrite to make X75 or X80 pipes, which are likely to be required in the near future.

Future Developments

The changing scene of engineering continues to create demands for new steels. For many years the potential for the construction of high-pressure gas pipes in Arctic conditions stimulated the development of higher-strength steels to contain gas at higher pressures without increasing the wall thickness of the pipes and to resist brittle and ductile fractures. These conditions led to the development of X70 steels (with a yield strength of 480 N/mm^2) with guaranteed impact properties at low temperatures. Although major Arctic projects (outside the U.S.S.R.) are in abeyance, it is likely that they will return and, because of the increased cost of gas transmissions, the engineers, wanting to increase the gas pressures, will demand X75 or X80 piping with yield strengths of 517 and 550 N/mm^2). Pipes of such strength are already being sought for offshore pipelines.

The development of offshore structures for deeper water and colder environments than at present is also bringing a challenge to steel companies for higher-strength steels able to withstand brittle fracture at low temperatures. Increasing importance is being attached to weldability, and to the toughness of welds and of heat-affected zones in major structures, particularly for some offshore structures.

These and other situations are continuing to create a demand for new steels, and the characteristics of vanadium mean that it has a high potential for many of these applications. It is unique in its effectiveness as a precipitation strengthener, and it has already been shown that this can be further enhanced by the presence of molybdenum or copper. A combination of vanadium and these two elements offers opportunities for the development of high-strength steel, especially if it can be produced in the as-rolled condition without heat treatment.

The effect of vanadium on hardenability has not been appreciated or used until recently, and there is a potential for the utilization of this characteristic, especially in the development of steels in which the toughness of heat-affected zones is of prime importance. Steels containing titanium and vanadium that combine the advantages of both alloys for use in welded structures, in which toughness of the HAZ is critical, are being developed. It is therefore likely that there will be important developments in new HSLA steel containing vanadium for various applications within the next five years.

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