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Vanadium high-strength low-alloy steels for low-temperature use

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High-strength low-alloy (HSLA) steels having low impact transition temperature are possible substitutes for costlier $2\frac{1}{2}$% and $3\frac{1}{2}$% nickel steels. The effects of solid solution strengthening, grain size and precipitation in ferrite on the strength and toughness of low-carbon steels and the special advantages of vanadium as an alloying element in HSLA steels, are discussed. An investigation has been carried out with 1.5% manganese low-carbon steels containing vanadium in the range 0.12% to 0.29% and 0.013% to 0.017% nitrogen. Room temperature tensile and sub-zero temperature impact tests down to $-100°$ C, and a metallographic study to determine the grain sizes and pearlite contents of the steels normalized at different temperatures, have been carried out. Calculations are made with empirical equations for yield and tensile strengths and the values obtained are compared with those experimentally observed. The solubility products of vanadium carbide and vanadium nitride are calculated and compared with available data to throw light on the mechanism of strengthening of the steels.

1. Introduction

Recent discoveries of large reserves of natural gas and its utilization as an important energy source have necessitated transportation and storage of large volumes of liquified gases at low temperatures (down to $-100°$ C) which have resulted in an increased demand for steels for low-temperature use. The low-temperature steels also find application in the construction of land-based storage tanks for acetylene and carbon dioxide [1].

Currently, $2\frac{1}{2}$% nickel steels are used for service down to $-60°$ C (ASTM A203 – 70 Grade A and B). $3\frac{1}{2}$% nickel steels are used for lower service temperatures down to $-100°$ C (ASTM A203 – 70 Grades D and E) [2]. The nickel content of the steels increases with the severity of service condition, i.e. with decreasing temperature of use.

Alternative nickel-free steels having adequate low-temperature toughness properties would be attractive from the economic point of view. Moreover, for certain applications, the low-temperature steels are also required to possess high yield strengths in order to save weight. The paper describes the results of an investigation carried out with a number of vanadium steels exhibiting high strength and low transition temperatures.

The compositional factor controlling the strength and toughness of steels is the solid solution effect and the microstructural factors are grain size, precipitation in ferrite and pearlite fineness and content. These factors are discussed below.

1.1. Solid solution strengthening

Solid solution strengthening increases approximately linearly with increase in the concentration of the solute and is a function of the difference in the atomic diameters of the solvent and solute atoms and valency. This could be on account of pinning of dislocations by the solute atoms, or a general rise in the friction stress resisting their movement on the slip planes. Attempts to quantify the effect have been made by Cottrell [3], Mott and Nabarro [4] and Orowan [5].

Common elements that solution strengthen ferrite can be arranged in decreasing effectiveness in the order: (C, N), P, Si, Ti, Al, Cu, Mn, Mo, V, Ni and Cr. Nickel has no strengthening effect and

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the effect of chromium is negative. Although carbon and nitrogen exhibit the highest strengthening effects, they are not of much significance in this respect because of their limited solubility in iron and the adverse effect on toughness. Phosphorus and silicon are not utilized for strengthening also on account of their adverse effect on toughness. Vanadium has a small effect on solid solution strengthening and, in quantities added to micro-alloyed steels, makes little contribution as a solid solution strengthener because of its affinity for carbon and nitrogen. Manganese is a mild solid solution strengthener. Nevertheless, it is extensively used in high-strength steels because of its cheapness.

1.2. Effect of solid solution strengthening on toughness

Solid solution hardening, which results in an increase in lattice friction stress, reduces toughness. However, nitrogen reduces toughness far out of proportion to its effect on lattice friction stress and this has been attributed to the strong locking effect of nitrogen on dislocations [6]. Elements in solid solution, however, can produce an indirect beneficial effect on toughness by lowering the transformation temperature and thereby decreasing the grain size of the steel. Nickel is extremely beneficial in promoting toughness, although its effect cannot be attributed to the lowering of transformation temperature alone.

1.3. Effect of grain size on strength and toughness

Grain size is the most important microstructural factor for micro-alloyed steels as, unlike other factors which improve yield strength alone, grain refinement simultaneously improves both yield strength and toughness. The quantitative effect of grain size on yield strength can be expressed by the Petch relationship [7–9]:

$$\sigma_y = \sigma_i + k_y d^{-1/2} \qquad (1)$$

where σ_y is the lower yield stress, σ_i the friction stress needed to move a dislocation through the lattice, k_y the grain-boundary locking term, and d the grain diameter.

The above relationship has been used to arrive at empirical equations connecting composition and structure to yield strength, ultimate tensile strength and notch-impact transition temperatures. The effects of the variables derived are shown below.

$$\begin{aligned}\text{LYS [10]} &= K_1 + 37\,(\%\text{Mn}) + 83\,(\%\text{Si}) \\ &\quad + 15.1\,d^{-1/2} + 2918\,(\%\text{N}_\text{f})\end{aligned} \qquad (2)$$

$$\begin{aligned}\text{UTS [11]} &= 295 + 27.5\,(\%\text{Mn}) + 82.6\,(\%\text{Si}) \\ &\quad + 1.54\,d^{-1/2} + 3.9\,(\%\,\text{pearlite})\end{aligned} \qquad (3)$$

$$\begin{aligned}\text{ITT [11]} &= 19 + 44\,(\%\text{Si}) + 700\,(\%\text{N}_\text{f}^{1/2}) \\ &\quad - 11.5\,d^{-1/2} + 2.2\,(\%\text{pearlite})\end{aligned} \qquad (4)$$

where LYS is the lower yield strength (MPa), UTS the ultimate tensile strength (MPa), ITT the impact transition temperature (°C), N_f free nitrogen, and d the ferrite grain size (mm). In equation 3 the constant 295 MPa depends on the processing conditions and so a more generalized form of the equation is:

$$\begin{aligned}\text{UTS} &= K_2 + 27.5\,(\%\text{Mn}) + 82.6\,(\%\text{Si}) \\ &\quad + 1.54\,d^{-1/2} + 3.9\,(\%\text{pearlite}).\end{aligned} \qquad (5)$$

The values of K_1 in Equation 2 and K_2 in Equation 5 have been determined from the experimental data.

It has been suggested that the transition temperature is not dependent on ferrite grain size but rather on the prior austenite grain size [12].

1.4. Strengthening by precipitation in ferrite

Precipitation of fine particles in ferrite strengthens steels as additional stress is required for the dislocations to cut or move round the particles. Size of particle and interparticle distance are highly important and determine the level of strength attained. It is obvious that adequate precipitating elements must be present in solution in austenite so that sufficient precipitation can occur in ferrite on cooling.

1.5. Effect of precipitation strengthening of ferrite on toughness

The detrimental effect of precipitation strengthening of ferrite on toughness is on two accounts. Firstly, the increased yield strength releases larger elastic strain energy on crack growth and secondly, the surface of the precipitate behaves as a pre-existing crack, reducing the energy required to extend it. Precipitation of a nitride, however, increases toughness by removing the dissolved nitrogen which has a large embrittling effect.

1.6. Effect of pearlite content on strength and toughness

Pearlite in quantities less than 25% by volume has little effect on yield strength [13], although, if the inter-lamellar spacing is reduced by lowering Ar_1 temperature through additions of alloying elements such as nickel, or by imposing a faster cooling rate, the yield strength goes up. On the other hand, pearlite raises the tensile strength, albeit weakly, on account of its higher rate of work hardening. Pearlite content, however, has a deleterious effect on toughness because the lamellar structure provides sites for incipient crack initiation. Moreover, high dislocation density in the ferrite region and its restricted plasticity due to the presence of carbide platelets make crack initiation easy in this region. As a result, with increasing pearlite content (i) the impact transition temperature rises, (ii) ductile-to-brittle transition occurs over a wide temperature range, and (iii) the shelf energy is lowered [6].

1.7. Effect of transformation temperature on strength and toughness

The $\gamma \rightarrow \alpha$ transformation temperature is of great importance in micro-alloyed steels containing V, Nb and Ti as it controls the precipitation character in ferrite and the ferrite grain size. Transformation temperature depends on (i) austenite grain-size, (ii) solutes held in austenite, and (iii) the cooling rate. Generally, the lower the transformation temperature, the finer is the precipitation in ferrite. As ferrite nucleation frequency increases and the growth rate decreases with the decrease in transformation temperature, fine-grain ferrite is produced at low transformation temperatures. Since the nucleation of ferrite takes place at the austenite grain boundary, the $\gamma \rightarrow \alpha$ transformation is facilitated with the increase in grain-boundary area. Consequently, a smaller austenite grain size leads to higher transformation temperature and vice versa. However, the transformation temperature is also influenced by elements held in solid solution in steel. Of special importance in this respect is manganese, which strongly decreases the transformation temperature. Transformation temperature can also be controlled by regulating the cooling rate which, in the case of normalizing, is dependent on the section thickness.

1.8. Advantages of vanadium

Vanadium, niobium and titanium, are all used as micro-alloying elements, but several advantages have been claimed for vanadium [14]. These are (i) even dissolution in molten steel, (ii) greater solubility in austenite making extraction of the steel from curved moulds of continuous casting machines easier and higher resistance to hot cracking, (iii) resistance to tempering of vanadium carbo-nitride resulting in higher strength in thick sections, (iv) superior weldability over niobium steels [15], and (v) improved low-temperature toughness [16].

Both controlled rolling and normalizing techniques are used in the production of micro-alloyed steels having high strength in combination with high toughness. However, controlled rolling requires optimization of the working schedule involving careful adjustment of the reheating conditions, holding between the passes required for thicker sections, sufficient amount of deformation below about 900° C and a low finishing temperature. It appears, therefore, that a good measure of experimentation and standardization of the working process is required in order to obtain the best results, and in places where mill facilities are meagre and control not very strict, recourse to normalizing must be taken. Moreover, when a hot forming operation is involved in the manufacturing process, normalizing has to be carried out. Normalizing has the further advantage that it produces uniform properties throughout a thick section. It is particularly effective in the case of vanadium additions because it readily goes into solution at normalizing temperatures and restricts austenite grain growth. For the reasons mentioned above, vanadium micro-alloyed steels in their normalized conditions have been investigated for strength and toughness.

2. Experimental procedure

Six steels were made in a 10 kg air-induction melting furnace. De-oxidation was carried out with ferro-silicon. Nitrogen was introduced through nitrided electrolytic manganese containing about 5% nitrogen. The steels were cast in the form of 75 mm x 75 mm ingots. After stripping, the ingots were air cooled to room temperature. They were

TABLE I Composition of the steels (wt%)

Steel no.	C	Mn	V	N	Si	S	P
S_1	0.15	1.4	–	0.005	0.18	0.03	0.04
V_1	0.13	1.4	0.12	0.013	0.04	0.03	0.02
V_2	0.08	1.7	0.18	0.016	0.08	0.02	0.02
V_3	0.12	1.6	0.24	0.015	0.10	0.02	0.02
V_4	0.06	1.5	0.27	0.017	0.05	0.02	0.03
V_5	0.11	1.6	0.29	0.016	0.12	0.03	0.02

then reheated to 1200° C and forged into 28 mm square bars. Specimen blanks were removed from these bars and were normalized at 900, 950 and 1000° C. Tensile properties of the normalized samples were determined in a Hounsfield Tensometer using round specimens (B) of 5 mm diameter and 18 mm gauge length. Impact properties at ambient and sub-zero temperatures were determined on Charpy V-notch specimens. Grain sizes and pearlite contents were determined on metallographic specimens by the linear intercept count method.

Nitrogen was analysed by vacuum fusion and vanadium by spectroscopic methods. All other elements were analysed by standard wet techniques.

3. Results and discussion

Table I shows the analyses of the six steels investigated. Table II shows the tensile properties, 54 J CVN transition temperature, mean ferrite grain sizes and pearlite contents of the steels normalized at 900, 950 and 1000° C.

Steel S_1, which is free from vanadium contains, on average, 20% pearlite (Table II). As it has 0.15% carbon, its eutectoid carbon should be 0.75% on the basis of the pearlite content of the steel. The lower eutectoid of 0.75% C for steel S_1 compared to 0.8% for pure iron carbon alloy, is on account of the presence of manganese in the steel, an element known to reduce the eutectoid carbon content. As all the steels in this work contain 1.5% Mn, as in steel S_1, their eutectoid carbon content may also be taken to be 0.75%.

In the range of temperatures in which precipitation occurs in ferrite, the free energy of formation of VN is the lowest amongst the compounds VN, V_4C_3 and Fe_3C and that of Fe_3C the highest, while V_4C_3 has an intermediate value. It is, therefore, reasonable to assume that their formation in ferrite occurs in the order stated above. Hence in steels V_1 to V_5 it may be assumed that the vanadium first combines with all the nitrogen in steel to form VN. The remaining vanadium now combines with a part of carbon to form V_4C_3, and the carbon left, after meeting the requirement of V_4C_3, combines with iron to form Fe_3C. This calculation is shown in Table III, where the second column shows the quantity of vanadium required to combine with nitrogen present in the steel. The left-over vanadium is shown in column 3. The carbon required to combine with this vanadium to

TABLE II Grain size and mechanical properties

Steel no.	Normalizing temperature (° C)	Mean ferrite grain diameter (μm)	Yield strength (MPa)	Tensile strength (MPa)	Elongation (%) 18 mm gauge lengh	Reduction in area (%)	CVN 54 J transition temperature (° C)	Pearlite (%)
S_1	900	22.5	314	515	34	64	R.T.	19.0
	950	29.5	308	498	37	64	R.T.	20.0
	1000	30.0	314	508	37	62	R.T.	20.0
V_1	900	12.5	400	510	43	78	−95	15.0
	950	13.0	459	580	36	72	−40	15.0
	1000	14.0	460	568	37	75	−30	16.0
V_2	900	11.0	393	502	43	78	−95	7.0
	950	13.0	503	543	40	77	−95	7.0
	1000	13.0	508	538	43	76	−95	8.0
V_3	900	6.0	485	592	38	75	−100	12.0
	950	7.0	541	532	36	76	−100	12.0
	1000	7.5	524	603	37	74	−95	13.0
V_4	900	7.0	412	511	40	75	−95	3.0
	950	9.0	430	510	43	76	−95	4.0
	1000	9.0	520	520	40	74	−95	4.0
V_5	900	7.0	441	569	40	76	−95	11.0
	950	7.5	471	588	43	76	−95	12.0
	1000	8.0	486	591	47	75	−95	13.0

TABLE III Calculated and actual pearlite percentage in steels

Steel no.	V combined as VN (%)	V left over (%)	Carbon combined as V_4C_3 (%)	Carbon left over (%)	Calculated pearlite (%)	Average actual pearlite (%)
V_1	0.047	0.073	0.013	0.12	16.0	15.3
V_2	0.058	0.12	0.021	0.06	8.0	7.3
V_3	0.055	0.19	0.034	0.09	12.0	12.3
V_4	0.062	0.21	0.037	0.02	2.7	3.7
V_5	0.058	0.23	0.041	0.07	9.3	12.0

V_4C_3. This combines with iron to form Fe_3C. The good agreement between the pearlite contents of the steels calculated in this manner which are shown in column 6 and the experimentally determined pearlite contents shown in column 7 indicate the correctness of the contention that the compounds VN, V_4C_3 and Fe_3C form in ferrite in accordance with their free energies of formation.

It may also be noticed that the experimentally determined pearlite contents slightly increase with normalizing temperatures. This may be attributed to the slower cooling rate to which the plates normalized at higher temperatures are subjected, in comparison to those normalized at lower temperatures.

The solubility products of VN and V_4C_3 at 900, 950 and 1000° C have been shown in Table IV. The values for V_4C_3 have been obtained from Koul [17] and those for VN from the equation log [V] [N] $= -8330/T + 3.4$, due to Irvine *et al.* [18].

The solubility products of V_4C_3 and VN for steels V_1 to V_5 have been calculated from their chemical compositions and tabulated in Table V. As an example, the value of solubility product for V_4C_3 for steel V_1 containing 0.13% C and 0.12% V is given by $(0.12)^{4/3} \times (0.13)$, which equals 0.007 690. A comparison of Tables IV and V shows that the solubility products of V_4C_3 for the steels V_1 to V_5 in Table V never exceed the values given in Table IV at any temperature, whereas values for VN are always exceeded. This indicates that all V_4C_3 goes into solution in austenite whereas some VN always remains out of solution under normalizing conditions In these steels both V_4C_3 and VN are responsible for precipitation strengthening. However, as the extent of precipitation hardening depends also on the amount of solute held in solid solution, it is assumed that, at least at the lowest normalizing temperature of 900° C, where the solubility product of VN is very small, V_4C_3 contributes to greater strengthening than VN.

Values for yield and tensile strengths have been calculated for all steels using Equations 2 and 5. However, it is first necessary to derive the values of the constants K_1 and K_2. These constants have been calculated from the experimentally determined yield and tensile strength values for steel S_1, which does not contain any vanadium and so is not expected to show any precipitation strengthening effect. Substituting the correct values for Mn, Si, and N from Table I and the grain diameter and average pearlite content of 20% from Table II into Equations 2 and 5 and subtracting them from the experimentally determined average yield and tensile strength values from columns 4 and 6 of Table VI for steel S_1, the average values of K_1 and K_2 obtained are 137 and 370 MPa, respectively. These values have been substituted into Equations 2 and 5 to give the following equations:

$$\begin{aligned} \text{YS (MPa)} &= 137 + 37\,(\%\text{Mn}) + 83\,(\%\text{Si}) \\ &\quad + 15.1\,(d)^{-1/2} + 2918\,(\%\text{N}_f) \qquad (6) \\ \text{UTS (MPa)} &= 370 + 27.5\,(\%\text{Mn}) + 82.6\,(\%\text{Si}) \\ &\quad + (1.54)\,d^{-1/2} \\ &\quad + 3.9\,(\%\text{pearlite}). \qquad (7) \end{aligned}$$

TABLE IV Solubility products of vanadium carbide ($VC_{0.75}$) and vanadium nitride (VN)

Temperature (° C)	Solubility product of $VC_{0.75}$	Solubility product of VN
900	0.072 11	0.000 229
950	0.102 5	0.000 4467
1000	0.177 2	0.000 8318

TABLE V Solubility products of vanadium carbide ($VC_{0.75}$) and vanadium nitride (VN) by chemical composition

Steel no.	Solubility products of vanadium carbide ($VC_{0.75}$)	Solubility products of vanadium nitride (VN)
V_1	0.007 690	0.001 56
V_2	0.008 127	0.002 88
V_3	0.017 88	0.003 60
V_4	0.010 47	0.004 59
V_5	0.021 10	0.004 64

TABLE VI Values of calculated and observed yield strengths and ultimate tensile strengths
Calculated YS (MPa) = 137 + 37 (% Mn) + 83 (% Si) + $15.1/\sqrt{d}$ + 2918 (% N free)*
Calculated UTS (MPa) = 370 + 27.5 (% Mn) + 82.6 (% Si) + $1.54/\sqrt{d}$ + 3.9 × % Pearlite

Steel no.	Normalizing temperature (° C)	Calculated YS (MPa)	Observed YS (MPa)	Calculated UTS (MPa)	Observed UTS (MPa)
S_1	900	321	314	508	515
	950	308	308	510	498
	1000	307	314	510	508
V_1	900	327	400	484	510
	950	324	459	484	580
	1000	320	460	487	568
V_2	900	351	393	465	502
	950	349	503	464	543
	1000	339	508	468	538
V_3	900	401	485	489	592
	950	383	541	487	632
	1000	378	524	491	603
V_4	900	378	412	445	511
	950	356	430	447	510
	1000	353	430	447	520
V_5	900	389	441	485	569
	950	378	471	488	588
	1000	377	486	492	591

*This factor has not been used in the calculation of YS of steels V_1–V_5 in column 3.

The effect of nitrogen on yield strength has not been considered in steels V_1 to V_5 since all nitrogen is assumed to have been combined as VN. These equations have been used for calculating the yield and tensile strengths of steels V_1 to V_5. The calculated values are given in columns 3 and 5 of Table VI. A comparison of values in column 3 with column 4 and column 5 with column 6 in the table for steels V_1 to V_5 shows that in every case and for all normalizing temperatures, the observed values of yield and tensile strengths are higher than the values calculated according to Equations 6 and 7. This is on account of precipitation hardening in these steels which is not taken into account when calculating according to the above two equations.

It has been pointed out earlier that both V_4C_3 and VN are responsible for strengthening, but since the content of VN is almost the same in all the steels as their nitrogen contents are the same, the strengthening effect due to nitrogen is expected to be the same for all the steels. In order to study the strengthening effect of vanadium carbide, the observed values of yield and tensile strengths versus V/C ratio for steels V_1 to V_5 for the three normalizing temperatures have been plotted in Figs. 1 and 2, respectively. Fig. 1 shows that the yield strength is maximum at a V/C ratio of about 2 and falls if this increases or decreases. Further, normalizing temperatures of 950 or 1000° C confer more strength than normalizing at 900° C. The reason for the decrease in strength when the V/C ratio exceeds 2 is not clear.

The steels can be divided in two groups on the basis of their C contents. Steels V_2 and V_4 con-

TABLE VII Values of calculated and observed transition temperatures
ITT° C = −19 + 44 (% Si) + 700 (% $N_f^{1/2}$) − 11.5 ($d^{-1/2}$) + 2.2% pearlite

Steel no.	Normalizing temperature (° C)	Transition temperature, calculated (° C)	Transition temperature, observed (° C)	Shelf energy (J)
S_1	900	3	R.T.	37
	950	15	R.T.	49
	1000	15	R.T.	59
V_1	900	−87	−95	196
	950	−85	−40	157
	1000	−80	−30	147
V_2	900	−110	−95	206
	950	−101	−95	196
	1000	−99	−95	177
V_3	900	−138	−100	186
	950	−125	−100	167
	1000	−118	−95	157
V_4	900	−147	−95	167
	950	−129	−95	186
	1000	−129	−95	157
V_5	900	−126	−95	206
	950	−120	−95	177
	1000	−114	−95	177

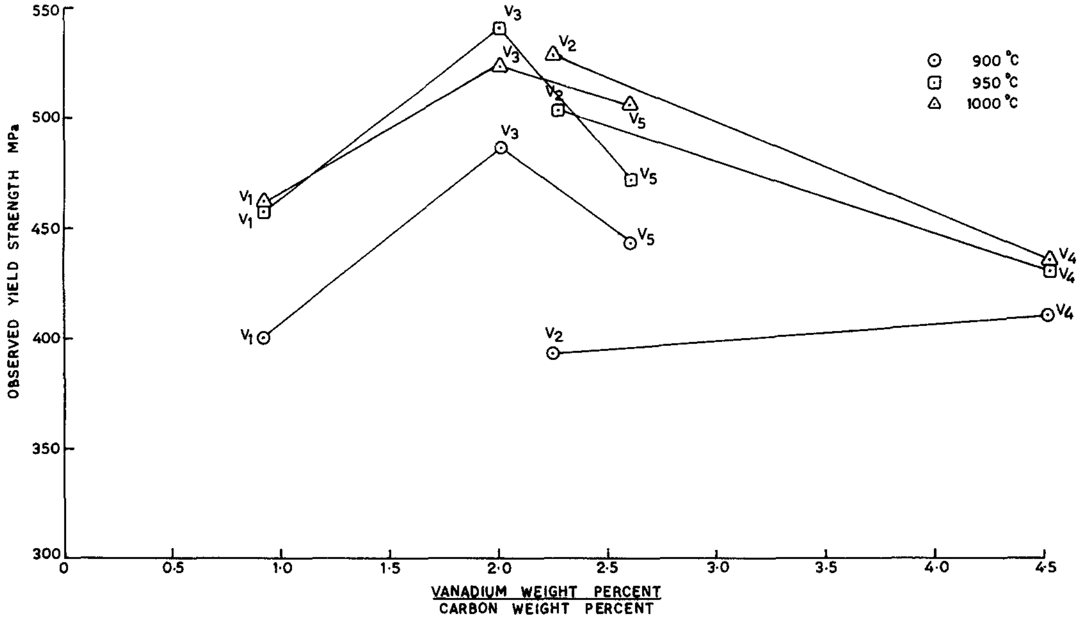

Figure 1 Observed yield strengths of steels normalized at 900, 950 and 1000° C plotted against their V/C ratios.

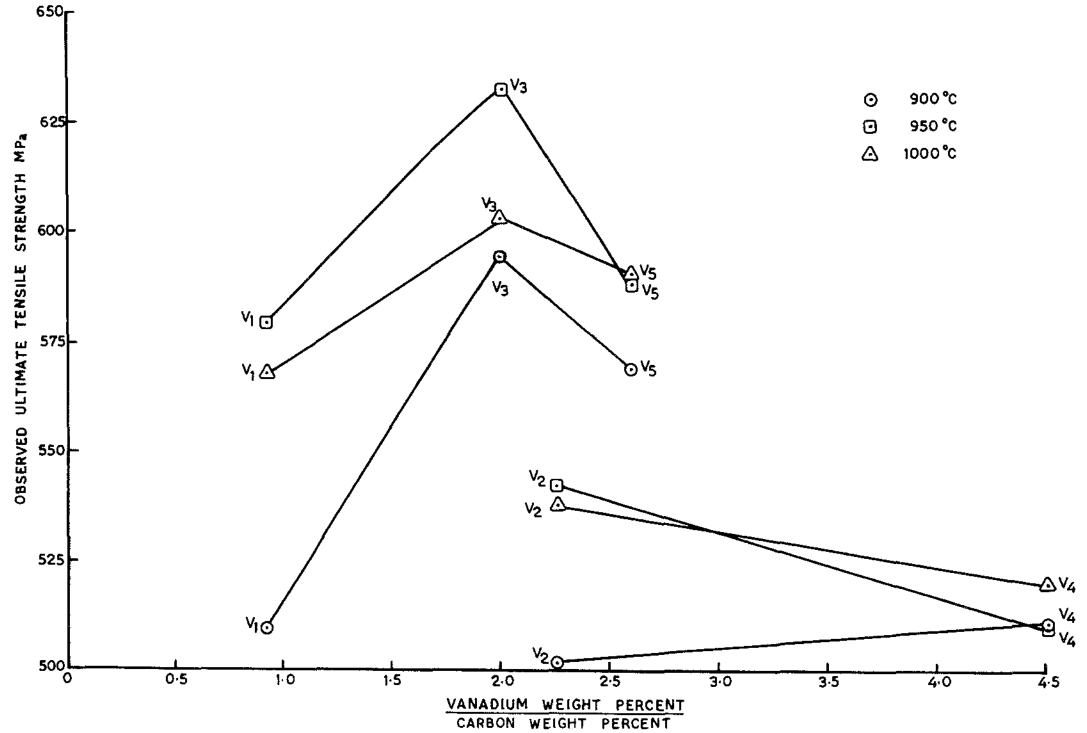

Figure 2 Observed ultimate tensile strengths of steels normalized at 900, 950 and 1000° C plotted against their V/C ratios.

taining about 0.07% C, fall in the low-carbon group while steels V_1, V_3 and V_5 fall in the higher carbon group containing about 0.11% C. The difference in the behaviour of the two groups is clearly brought out in Fig. 2 where the observed tensile strengths have been plotted against the V/C ratio. This figure, in common with Fig. 1, shows that the highest tensile strengths are obtained when the V/C ratio is about two. However, in the two groups, higher tensile strength values are shown by steels in the higher carbon group. On the other hand, no dependence of yield strength on carbon content can be seen in Fig. 1.

In Figs. 3 and 4 the difference between the observed and calculated values of yield and tensile strengths versus V/C ratios have been plotted, respectively. These figures show the extent of the effect of precipitation strengthening on yield and tensile strengths. The maximum effect of precipitation strengthening on yield and tensile strengths is seen to occur again at a V/C ratio of about 2 and the effect is more at normalizing temperatures of 950 and 1000° C than at 900° C. The well-known fact about the absence of the effect of carbon content on yield strength and its influence on increasing and tensile strength, is evident from these two figures.

Although this work shows the importance of V/C ratio for optimum strength, it does not indicate the optimum carbon level. However, it is known that carbon content should be limited and often this value is maintained at 0.1% max. [16].

Comparison of the second columns in Tables IV and V shows that all the vanadium carbide goes into solution in austenite even at 900° C. The increase in strength on normalizing at 950 and 1000° C appears, therefore, to be related to the greater solubility of VN at the higher normalizing temperatures. VN can also contribute appreciably to strengthening. This can be seen from the

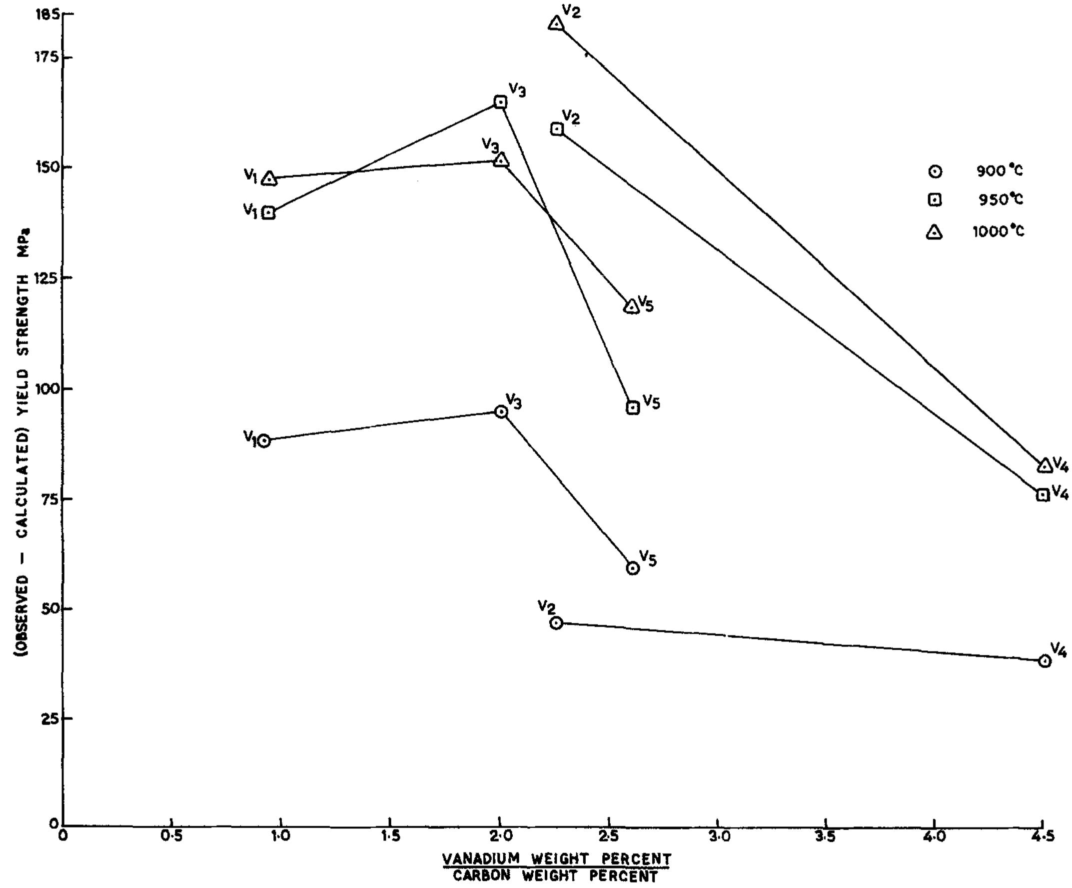

Figure 3 Difference of observed and calculated values of yield strengths of steels normalized at 900, 950 and 1000° C plotted against their V/C ratios.

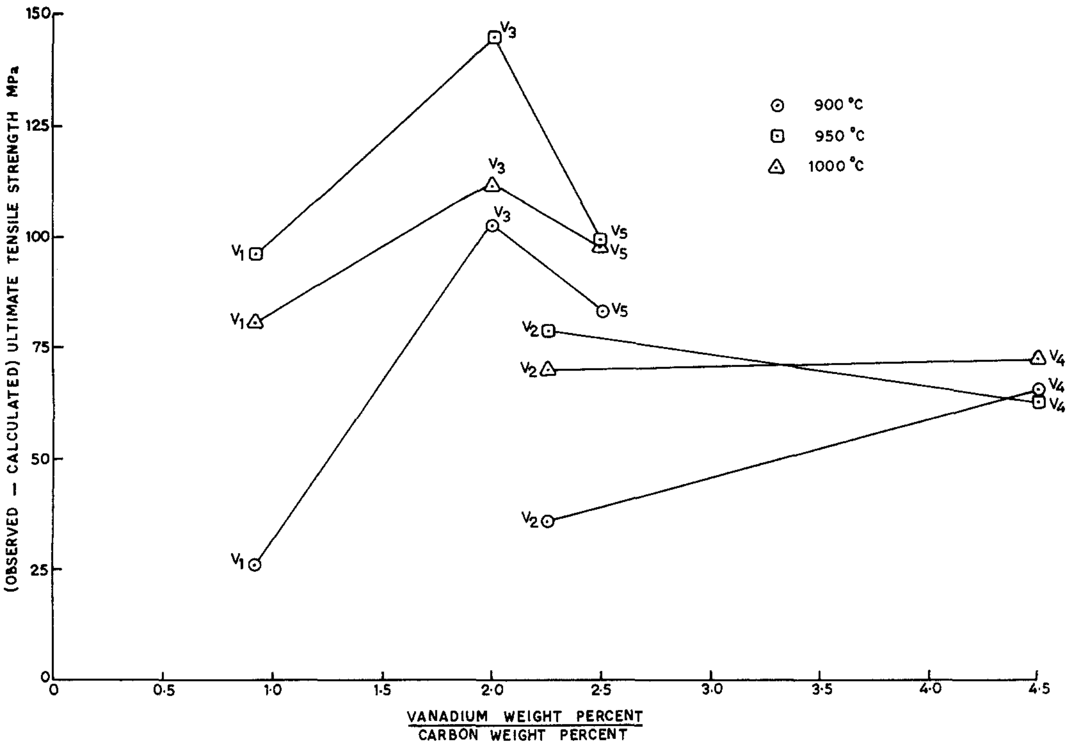

Figure 4 Difference of observed and calculated values of ultimate tensile strengths of steels normalized at 900, 950 and 1000° C plotted against their V/C ratios.

difference in the yield strength values at 900 and 1000° C for steels V_1 and V_2 which amount to 60 and 115 MPa, respectively.

The transition temperatures calculated from the formula ITT $= -19 + 44\ (\%\text{Si}) + 700\ (\%\text{N}_\text{f})^{1/2} - 11.5\ (d^{-1/2}) + 2.2\%$ pearlite, the values of experimentally determined transition temperatures and the values of shelf energy for all three normalizing temperatures for all the steels, are shown in Table VII in columns 3, 4 and 5, respectively. The significant fact to be noted is that the observed transition temperatures for the steels V_2, V_3 and V_5 is about −95° C in all cases, although the calculated values are lower. The shelf energy in all cases is high. In general, the shelf energy appears to be the highest for the lowest normalizing temperature. In the case of steel V_1, the transition temperature rises from −95° C to −30° C as the normalizing temperature is increased from 900 to 1000° C. This behaviour is not shown by steels V_3 and V_5 which have almost the same chemical composition except for their higher vanadium contents.

4. Conclusions

(1) A satisfactory combination of yield strength and notch toughness can be obtained in V–N steels.

(2) The maximum strength occurs when the V/C ratio is about 2.

(3) For vanadium contents over 0.12%, the transition temperature remains practically unaffected with increasing vanadium content.

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