

Strength of microalloyed steels with medium Carbon content

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STRENGTH OF MICROALLOYED STEELS WITH MEDIUM CARBON CONTENT

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Due to that Ovako of today has had a number of different company names and used various trade marks we have until now chosen to not have these reports publicly available. However, many of these technical reports contain valid data about material and steel grades that we still promote, but with other names etc.

The following Technical Report from 1983 is about how micro-alloying of medium carbon steel.

Data and processes in this report represent state of art at time of publishing, but is “time-less” knowledge and very much describing properties in grades we offer today, as eg. 51CrV4 or , 42MnV7 to mention some. See Ovako Steel Navigator and search on elements in the Composition Search mode of eg. Carbon 0.45-0.55 % and eg. Vanadium; 0.05 – 0.2 % and you will find many more.

In this Technical Report there is used the following Company names and trade marks that no longer is used by Ovako AB.

SKF Steel; This company name is no longer used. The organization is now part of Ovako AB.

SKF; Is today a separate company with no link to Ovako.

Technical Report 3/1983

**Strength of Microalloyed
Steels with Medium
Carbon Contents**

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SKF Steel

Microalloyed Steels with Medium Carbon Contents

Investigation into the Effect of
Various Factors on the Strength*

Abstract

In certain applications, microalloyed steels with medium-high carbon contents offer an advantageous alternative to hardening and tempering steels. In this investigation, a survey has been made of how the mechanical properties of such steels are affected by the composition, the cooling rate and the austenitizing temperature.

Depending on the composition and the treatment, yield strengths between 540 and 1040 MPa (78 and 151 ksi) and ultimate tensile strengths between 840 and 1300 MPa (122 and 188 ksi) have been recorded. The ultimate tensile strength is primarily controlled by the pearlite content of the steel, whereas the yield strength is primarily dependent on the ferrite strength which is largely determined by the precipitates.

Introduction

Small additions of V, Nb and Al to medium-carbon steels significantly improve the mechanical properties. This improvement is caused partly by grain refinement and partly by nitrides, carbides and carbonitrides being precipitated. Since the toughness and strength can both be affected, this is an attractive method for improving the properties of a steel.

Several investigations have shown that ferritic-pearlitic steels with carbon contents between 0.4% and 0.5% and alloyed with approx. 0.10% V achieve good mechanical properties immediately after cooling in air from the forging or rolling temperature and, in certain applications, these steels offer an alternative to conventional hardening and tempering steels.

The primary benefit of changing over to microalloyed steels is that the need for hardening and tempering is eliminated. Moreover, the cost of the material is generally somewhat lower, due to the lower content of alloying elements.

The purpose of this investigation was to study how the strength is affected by the austenitizing temperature, cooling rate and chemical composition.

* The results are mainly a summary of a joint project at the Swedish Institute for Metal Research, IM 1591, Odd Sandberg.

Chemical compositions of the materials

The materials investigated were ferritic-pearlitic steels with carbon contents of around 0.45%. Ten steels with different contents of Mn, Cr, V, Ti, Si and N were studied. The steels were produced as 30 kg (66 lb) ingots, with normal contents of impurities (Table 1).

The addition of 0.10–0.20% of vanadium was aimed at increasing the strength by precipitation hardening by vanadium carbonitrides. Titanium was added with the aim of investigating its ability to inhibit austenite grain growth at the high temperatures of approx. 1250°C (2280°F) necessary during forging. The purpose of chromium and manganese is to displace the γ/α transformation temperature towards lower values, which results in the lamellar structure of the pearlite being finer and the proportion of pearlite by volume being greater. A reduction in the transformation temperature will also lead to more effective precipitation hardening by the vanadium carbonitrides.

Steel 2 is a reference material. The ingots were forged to 20 mm (0.787 in) round bars and cut to 65 mm (2.56 in) long test pieces.

Heat treatment

The test pieces were austenitized at 1050, 1150 and 1250°C (1922, 2102 and 2282°F) for 25 min. The soaking time at the relevant temperature was 10 min. The test pieces were then cooled in three different ways: by cooling in air, by air-blast cooling and by isothermal transformation in a salt bath at a temperature of 540°C (1004°F). For steel 10 (0.25% V, 0.5% Cr and 1.4% Mn), it was necessary to increase the temperature of the salt bath to 570°C (1058°F), in order to prevent the austenite transforming into upper-range bainite. The soaking time in the salt bath was 10 min, and the test pieces were then allowed to cool in air down to room temperature.

The cooling rates at 750°C (1382°F) when cooling in air, by air blast and in the salt bath were 3.0, 4.1 and 8.5°C/s (5.4, 7.4 and 15.3°F/s) respectively.

Mechanical testing

The mechanical testing for each steel and heat treatment comprised:

- tensile testing, double check
- impact testing, 3 KU tests at room temperature
- hardness, 6 HV30 indentations

Besides, steel 2 was KU tested from –40°C (–40°F) to 250°C (482°F).

Steel	C	Si	Mn	P	S	Cr	Ni	Mo	V	Cu	Sn	Al	Ti	N ppm
1	0.48	0.30	0.74	0.005	0.063	0.11	0.01	0.05	0.11	0.01	0.002	0.015		55
2	0.47	0.26	0.79	0.006	0.055	0.16	0.13	0.06	0.10	0.21	0.015	0.016		100
3	0.43	0.28	0.68	0.018	0.054	0.14	0.11	0.05	0.10	0.02	0.013	0.014		288
4	0.46	0.30	0.75	0.008	0.058	0.49	0.14	0.05	0.10	0.20	0.016	0.019		103
5	0.46	0.33	1.34	0.008	0.057	0.16	0.14	0.05	0.11	0.21	0.015	0.018		105
6	0.48	0.25	0.78	0.010	0.055	0.16	0.14	0.06	0.10	0.21	0.016	0.014	0.015	104
7	0.45	0.27	0.64	0.014	0.061	0.14	0.12	0.06	0.21	0.09	0.015	0.012		176
8	0.45	0.24	0.58	0.012	0.051	0.13	0.12	0.05	0.19	0.05	0.012	0.013		240
9	0.46	0.34	1.41	0.009	0.056	0.17	0.14	0.08	0.20	0.21	0.015	0.015		159
10	0.44	0.31	1.36	0.005	0.054	0.50	0.14	0.06	0.25	0.21	0.015	0.015		147
6A	0.48	0.26	0.87	0.014	0.041	0.15	0.15	0.05	0.10	0.22	0.004	0.021	0.019	133

Table 1 Chemical compositions of the steels investigated.

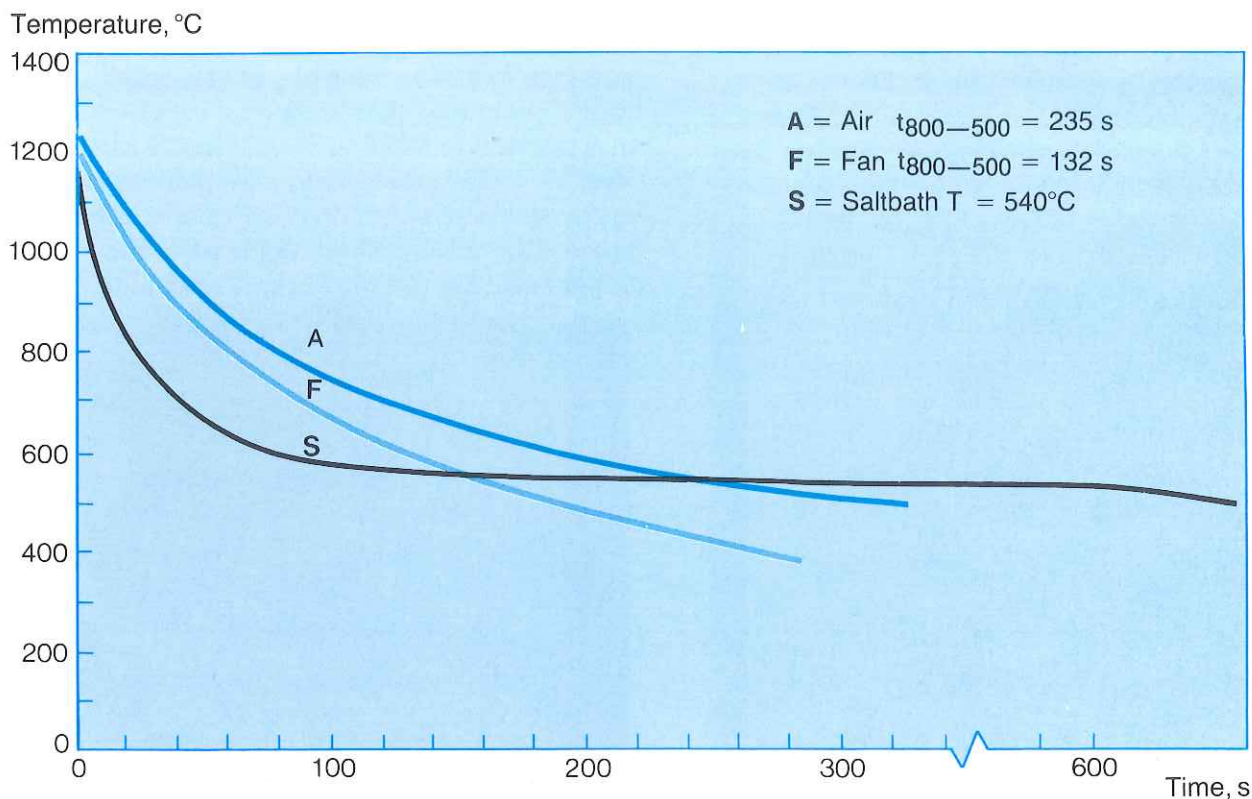


Fig. 1
Cooling curves for steel 2, 0.1 % V and 0.010 % N. Austenitizing temperature 1250°C.

Microscopic examination in optical and electron-microscopes

The quantities of ferrite and pearlite were measured by point counting, and the austenite grain size was measured in accordance with the intercept method (the average of ten measurements was calculated).

The pearlite interlamellar spacing was measured in a scanning electron microscope (SEM) on specimens etched with 1% nital solution.

In Steel 6 (0.10% V and 0.015% Ti), the titanium nitride and vanadium carbonitride precipitates were studied by transmission electron microscopy (TEM).

Results

Microstructure

With a couple of exceptions, the microstructures in the air-cooled steels were ferrite and pearlite. In the majority of cases, the ferrite had only precipitated at the grain boundaries, thus forming a continuous network (Fig. 2).

In steels 7 and 8 with 0.20% V, ferrite had also formed inside the austenite grains (Fig. 3). In steel 5 with 0.11% V and 1.3% Mn, the ferrite had formed, to a certain extent, as Widmanstätten ferrite

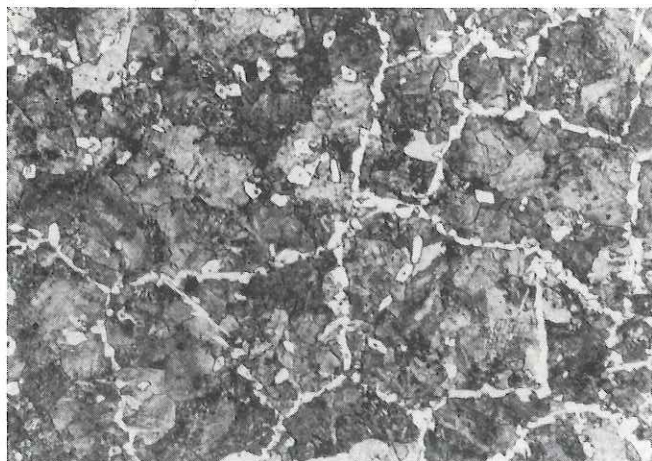


Fig 2
Steel 2, air cooled



Fig 3
Steel 7, air cooled from 1150°C, 200 x.

(Fig. 4). In steel 9, after air-cooling from 1 150°C (2 102°F) and 1 250°C (2 282°F), upper-range bainite (38 and 79 % respectively) had formed in addition to pearlite, as shown in Fig. 5. On the other hand, after air-cooling from 1 050°C (1 922°F), the structure is entirely ferritic-pearlitic. When steel 10 was air-cooled, only upper-range bainite and martensite occurred in the structure. No testing of the mechanical properties of this structure was carried out.

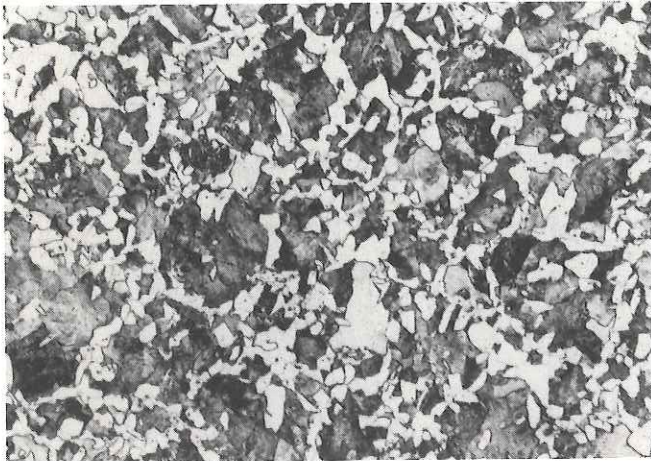


Fig 4
Steel 5, air cooled from 1250°C, 200 x.

During air-blast cooling, certain amounts of upper-range bainite occurred even in the lower-alloyed steels. For this reason, no studies of the properties were undertaken on air-blast cooled steel 5 with

0.11% V and 1.3% Mn, steels 7 and 8 with 0.20% V and steels 9 and 10.

In all steels with the exception of steel 10, the austenite had been transformed to a ferritic-pearlitic structure after isothermal transformation in a salt bath at 540°C (1 004°F). In the case of steel 10, it was necessary to raise the temperature of the salt bath to 570°C (1 058°F), in order to prevent the austenite from being transformed into upper-range bainite. However, the soaking time of

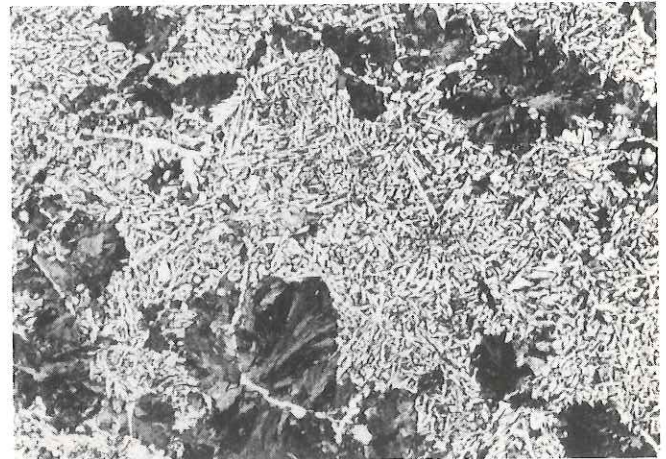
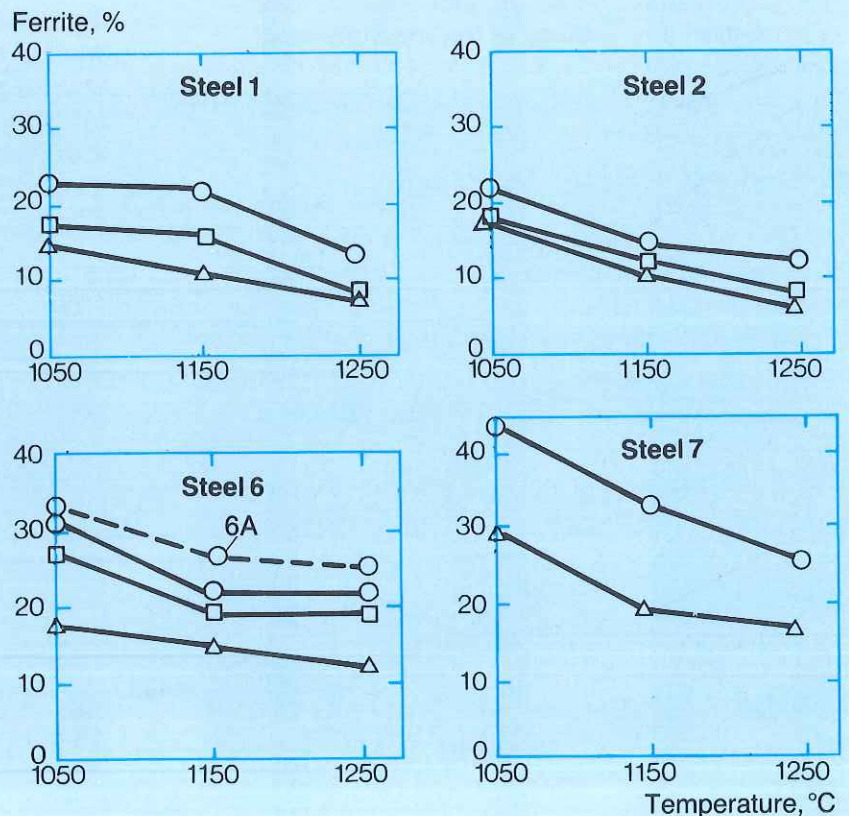


Fig 5
Steel 9, air cooled from 1250°C, 200 x.

10 min was too short for the structure to become entirely ferritic-pearlitic. For this reason, the structure of steel 10 includes pearlite, lower-range bainite and small areas of martensite.

Fig 6
Influence of austenitizing temperature and cooling conditions on ferrite content, steel 1–10.

○ Air
□ Fan
△ Saltbath



Influence of the austenitizing temperature, method of cooling and chemical composition on the ferrite content, thickness of ferrite border and pearlite interlamellar spacing

The quantity of ferrite varies between 4% and 44%, depending on the austenitizing temperature, cooling rate and chemical composition (Fig. 6). The ferrite content is reduced by increased austenitizing temperature, increased cooling rate and additions of alloying elements, e.g. Cr, Mn. Steels 7 and 8 with 0.20% V are an exception in this respect, since the ferrite content increases with an increase in the vanadium content. Steel 3 with 0.10% V and 0.029% N also has a high ferrite content. The reason is probably that, in this case, the carbon content is only 0.43% as against 0.47% in steel 2. In steels 1, 2, 3, 7 and 8, the thickness of the proeutectoid grain boundary ferrite varies between 3 and 7 μm (120–276 μin). Steels 4, 5, 6, 9 and 10 have a thinner grain boundary ferrite, i.e. between 2 and 4 μm (80–160 μin).

The pearlite interlamellar spacing is reduced by increasing cooling rate, increasing austenitizing temperature and increasing content of alloying elements. The largest interlamellar spacing of 0.30 μm (12 μin) was found in steels 1, 2 and 3 with 0.10% V. The addition of Cr or Mn reduces the interlamellar spacing to 0.15–0.20 μm (6–8 μin). The same values are also achieved by

the addition of 0.20% V. The smallest interlamellar spacing of 0.13 μm (5 μin) was found in steel 9 with 0.20% V and 1.4% Mn and in steel 10 with 0.5% Cr and 1.4% Mn. Fig. 7 is a representative scanning electron microscope micrograph (steel 8) used for establishing the pearlite interlamellar spacing.

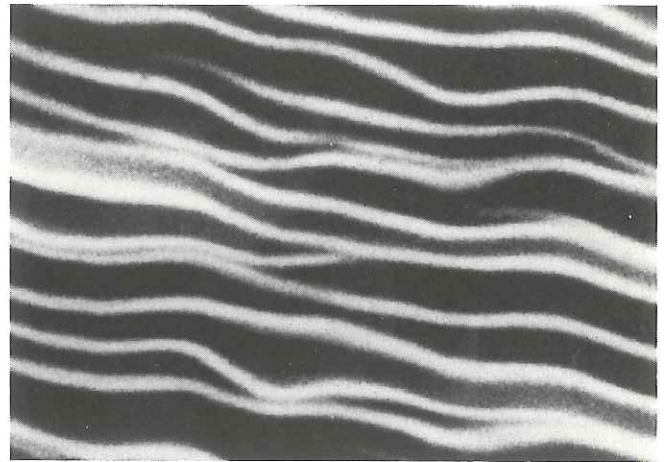
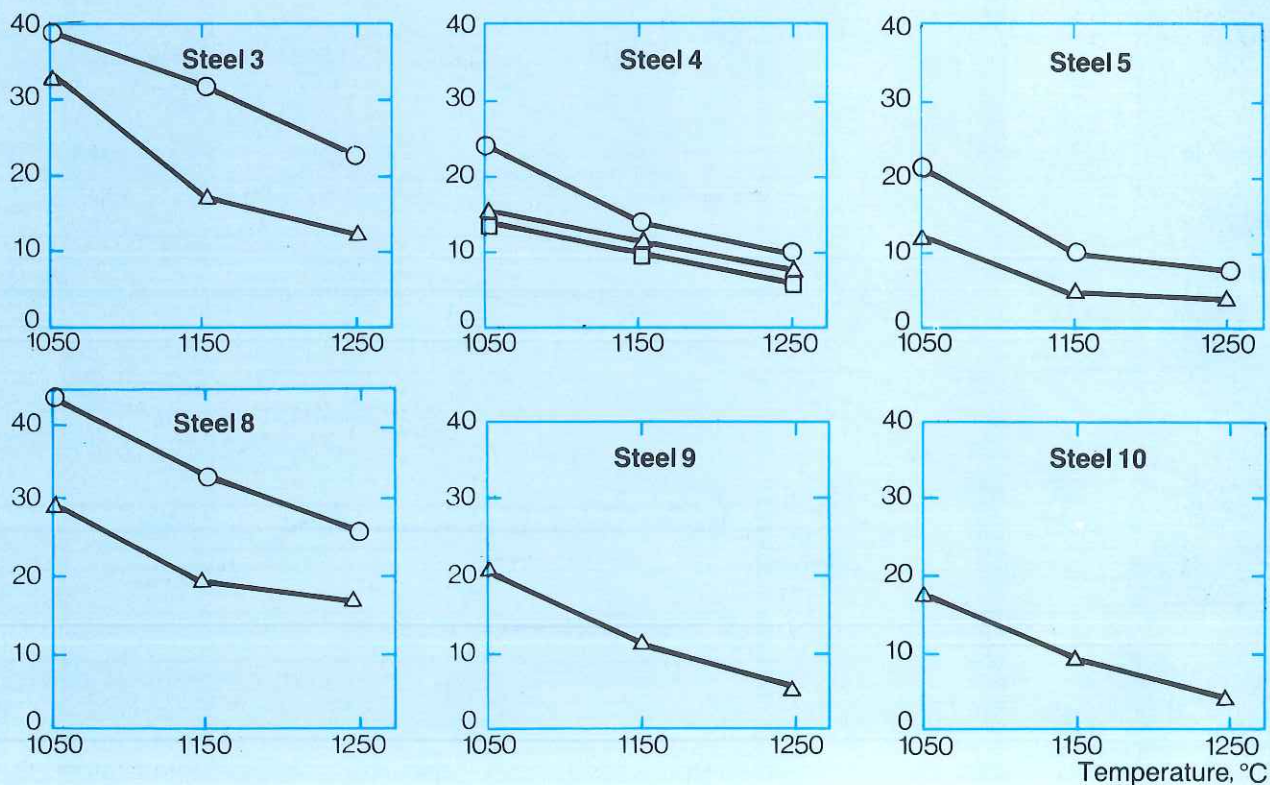


Fig 7
Representative picture from scanning electron microscope for determination of pearlite lamella distance, 3000 x. Steel 8, air cooled from 1250°C.



V (C, N) and TiN precipitations

A transmission electron microscope examination was carried out on some of the steels. Fig. 8 shows a micrograph of steel 2, air-cooled from 1 250°C (2 282°F). Coherent particles in rows in the ferrite indicate that the precipitation took

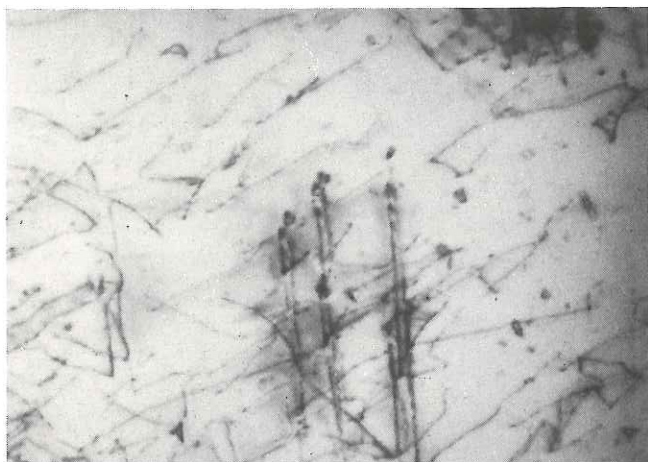


Fig 8
Interphase precipitation of V (C, N) in proeutectoid ferrite 62300 x.
Steel 8, 1250°C saltbath 540°C.

place in the ferrite at the transformation from austenite to ferrite + carbide. The particle size is 50–100 Å.

Steel 6 contains a large number of cube-like precipitations. A diffractogram indicates that the precipitates consist of TiN or TiC. The smallest are about 50 Å and the largest about 1 000 Å. A rough mean value is 250 Å. The orange-coloured TiN cubes are also visible under an optical microscope. In this case, the largest TiN particles are around 0.5 µm (20 µin).

Austenite grain size

The austenite grain size (D_γ) increases with increasing austenitizing temperature (Fig. 9). After austenitizing at 1 050°C (1 922°F), the austenite grain size is 25–40 µm (980–1 575 µin). This does not apply to steel 1 with 0.11% V and 0.005 N, in which the austenite grain size is about 55 µm (2 200 µin). At 1 250°C (2 282°F), the mate-

Austenite grain size, µm

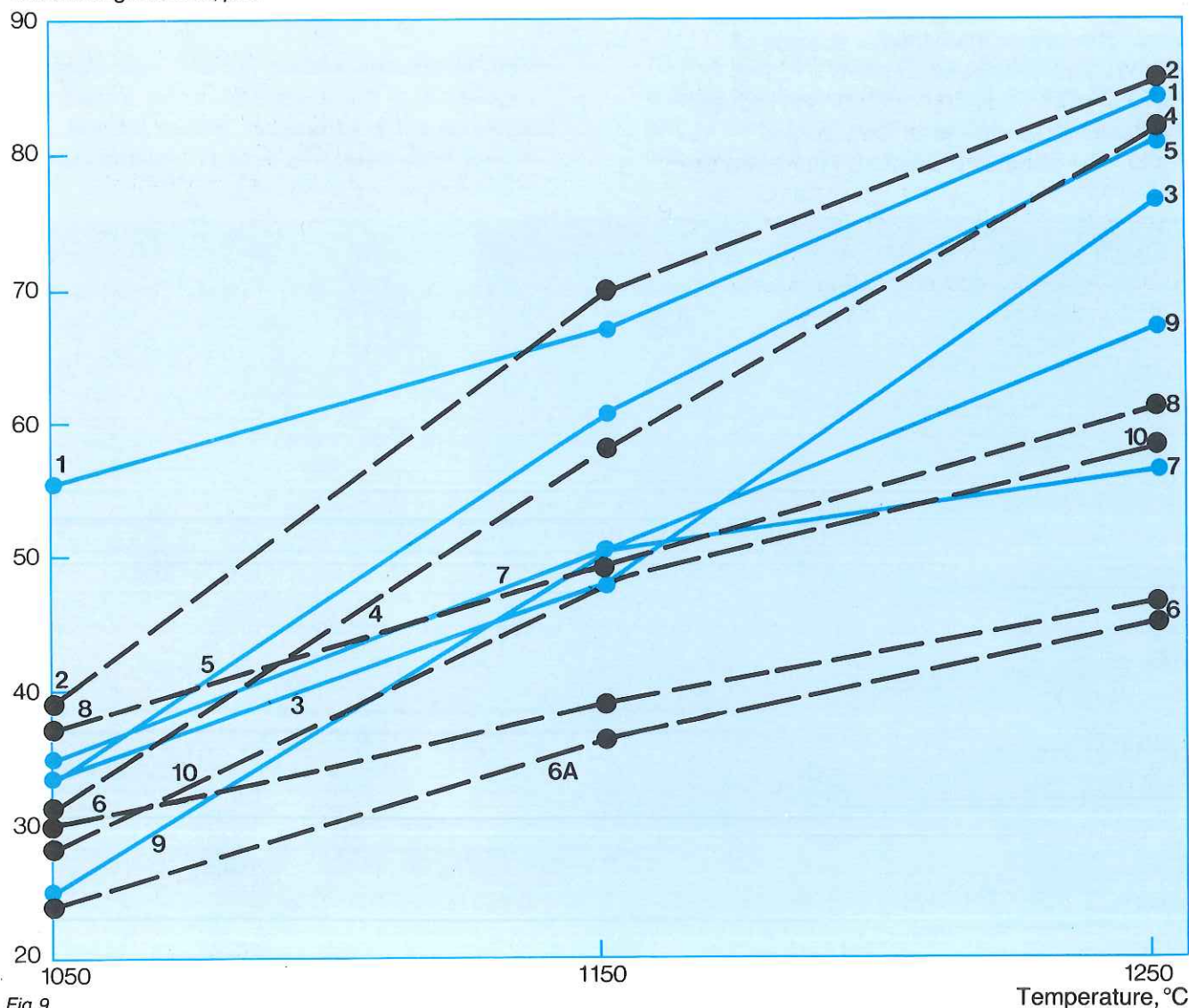


Fig 9
Influence of austenitizing temperature on austenite grain size, steel 1–10.

rials can clearly be assigned to three classes on the basis of the grain size. Material 6A with 0.10% V and 0.01% Ti has the smallest grain size of around $47\text{ }\mu\text{m}$ ($1\text{ }850\text{ }\mu\text{in}$), followed by the steels with 0.20% V which have a grain size of around $60\text{ }\mu\text{m}$ ($2\text{ }400\text{ }\mu\text{in}$). The steels with 0.10% V have the highest value of D_y , i.e. approx. $80\text{ }\mu\text{m}$ ($3\text{ }150\text{ }\mu\text{in}$).

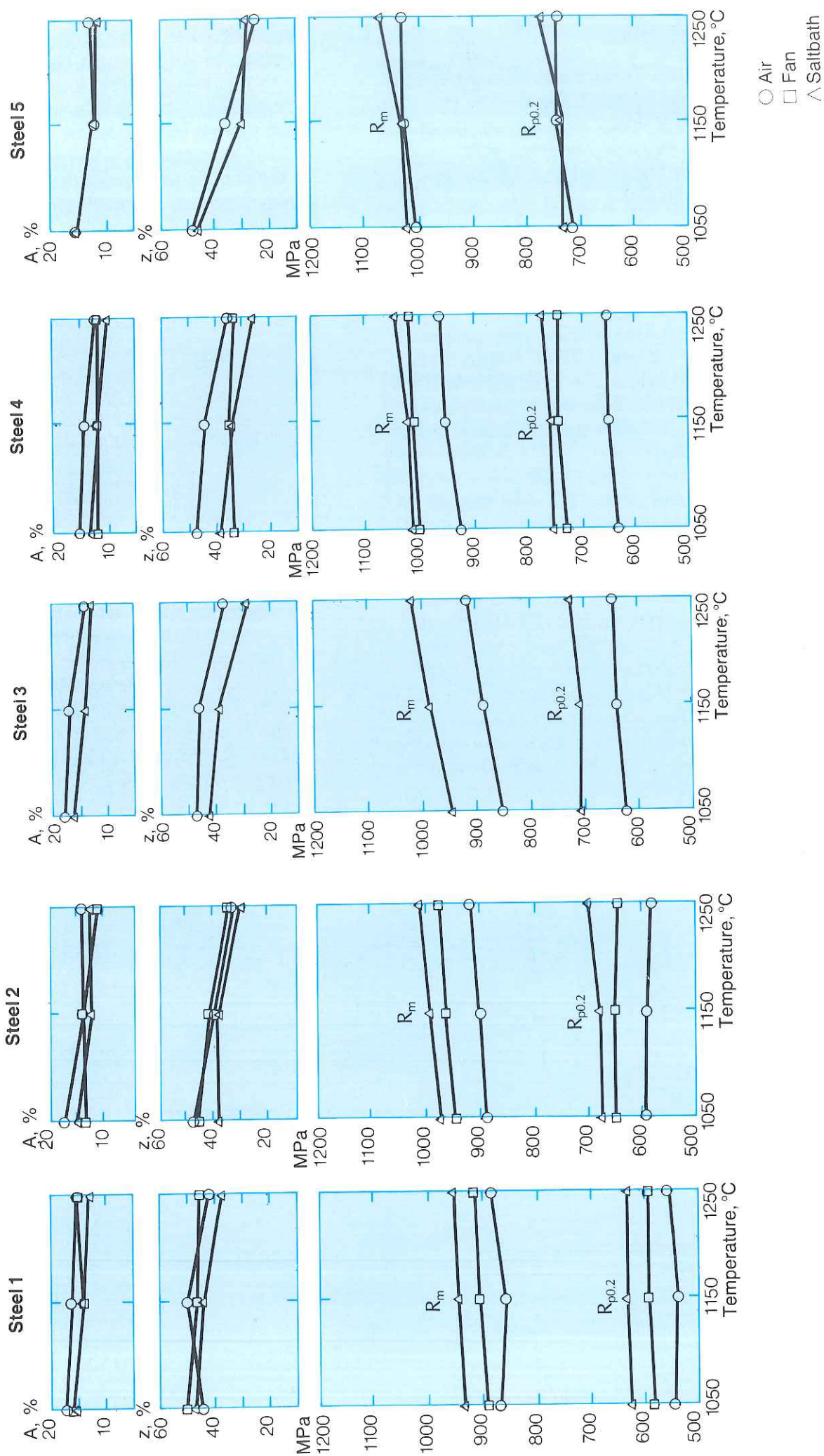
Mechanical properties

Fig. 10 shows the yield strength $R_{p0.2}$, the ultimate tensile strength R_m , the reduction in area Z and the elongation A on fracture, after austenitizing at $1\text{ }050$, $1\text{ }150$ and $1\text{ }250^\circ\text{C}$ ($1\text{ }922$, $2\text{ }102$ and $2\text{ }282^\circ\text{F}$). The figures also illustrate how cooling in air, air-blast cooling and isothermal transformation in a salt bath affect the mechanical properties of the steels.

The results demonstrate that the yield strength alters very little on an increase in the austenitizing temperature from $1\text{ }050$ to $1\text{ }250^\circ\text{C}$ ($1\text{ }922$ to $2\text{ }282^\circ\text{F}$). This does not apply to steel 8 with 0.19% V and 0.024% N. In this case, the yield strength increases from approx. 625 MPa to approx. 700 MPa (91 to 101 ksi) on a change in the austenitizing temperature from $1\text{ }050$ to $1\text{ }250^\circ\text{C}$ ($1\text{ }922$ to $2\text{ }282^\circ\text{F}$). Fig. 10 demonstrates that an increase in the austenitizing temperature causes the ultimate tensile strength to increase more than the yield strength. The reason for the reduction in the yield strength and ultimate tensile strength of material 9 with 0.20% V and 1.4% Mn is that upper-range bainite was formed on cooling in air from $1\text{ }050^\circ\text{C}$ and $1\text{ }250^\circ\text{C}$ ($1\text{ }922$ to $2\text{ }282^\circ\text{F}$).

On change-over from cooling in air to air-blast cooling, the yield strength increases by around 50 MPa (7 ksi). A further increase in the cooling rate on transformation in a salt bath causes the yield strength to increase by approx. 100 MPa (15 ksi) as compared with cooling in air. Variation in the cooling rate causes the ultimate tensile strength to vary in a similar manner to the yield strength.

The yield strengths of the steels studied in this investigation can be varied between 540 and $1\text{ }040\text{ MPa}$ (78 and 151 ksi) by altering the chemical composition, cooling rate and austenitizing temperature. In the same manner, the ultimate tensile strength can be varied between 840 and $1\text{ }300\text{ MPa}$ (122 and 190 ksi). Steel 1 with 0.11% V and 0.005% N attains the lowest strength, whereas steel 10 with 0.25% V, 0.015% N, 0.5% Cr and 1.4% Mn achieves the highest strength. It should be noted that steel 10 does not have a fully ferritic-pearlitic structure. The elongation on fracture decreases with increasing austenitizing temperature and increasing cooling rate. Depending on the chemical composition, the elongation varies between 18% on steel 8 and 8% on steel 10. The reduction in area demonstrates the same tendency as the elongation. Steels 1, 2, 3, 4, 5, 6 and 8 attain a maximum value of around 48%. After austenitizing at $1\text{ }250^\circ\text{C}$ ($2\text{ }282^\circ\text{F}$) and transformation in a salt bath at 570°C ($1\text{ }058^\circ\text{F}$), steel 10 has the lowest reduction in area of around 15%.



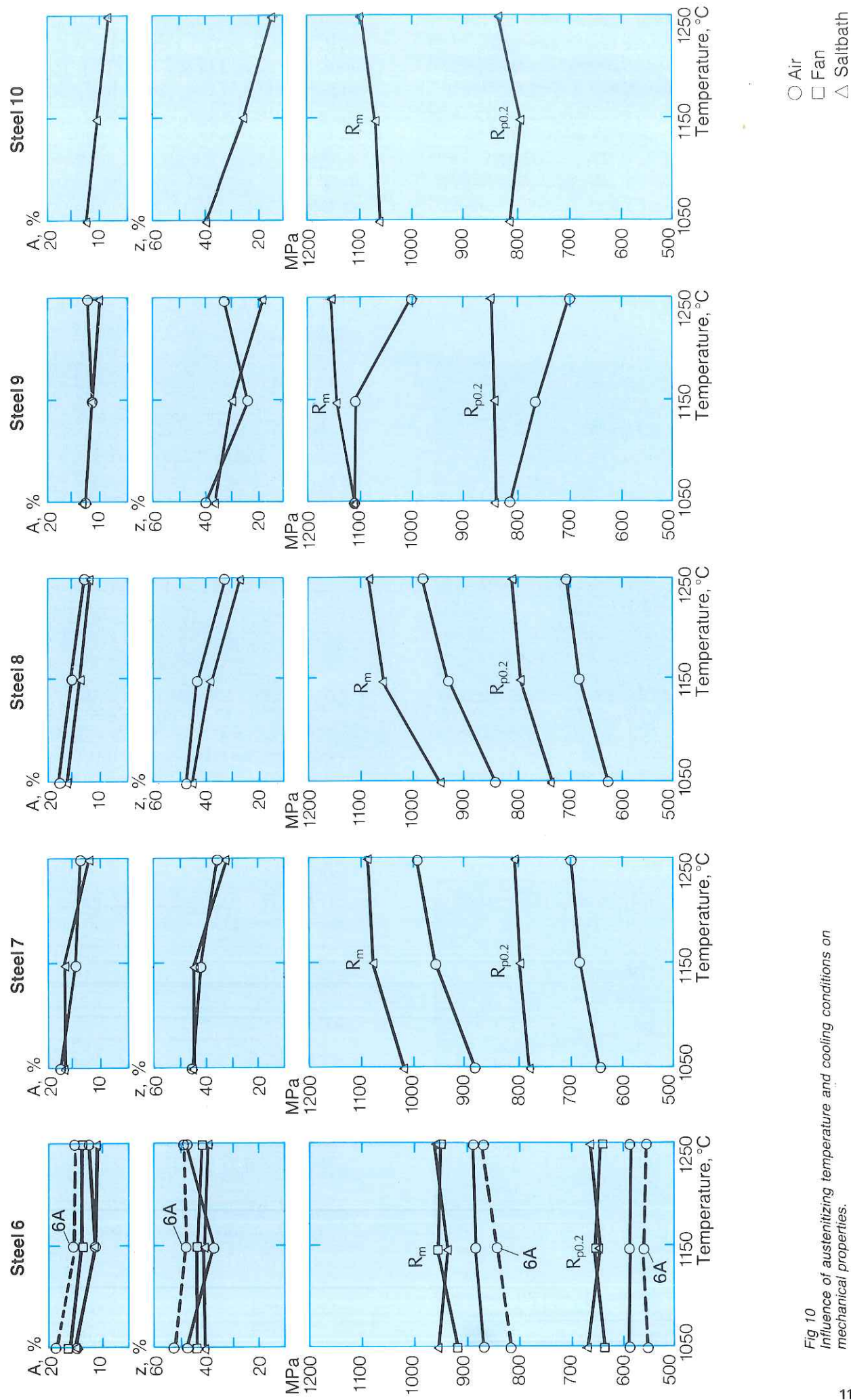


Fig 10
Influence of austenitizing temperature and cooling conditions on
mechanical properties.

Influence of the chemical composition on the yield strength and ultimate tensile strength

Fig. 11 and 12 show how the yield strength and ultimate tensile strength change with the content of nitrogen and vanadium in air-cooled and isothermally transformed materials austenitized at 1 050, 1 150 and 1 250°C (1 922, 2 102 and 2 282°F). An increase in the nitrogen content from 0.005% to 0.029% in steels with 0.10% V causes the yield strength to increase by approx. 100 MPa (15 ksi), regardless of the cooling rate. If the nitrogen content is increased from 0.018% to 0.024% in steels with 0.20% V, the yield strength will not

change after austenitizing at 1 150 and 1 250°C (2 102 and 2 282°F), although it will decrease after austenitizing at 1 050°C (1 922°F). The probable reason for this is that steel 8 had a somewhat higher ferrite content than steel 7.

As in the case of the yield strength, steels with 0.10% V display the greatest increase in the ultimate tensile strength when the nitrogen content is increased from 0.005% to 0.010%. Further increase in the nitrogen content has no significant effect on the ultimate tensile strength. The reason for this is that steel 3 with 0.010% V and 0.024% N has a higher ferrite content than steels

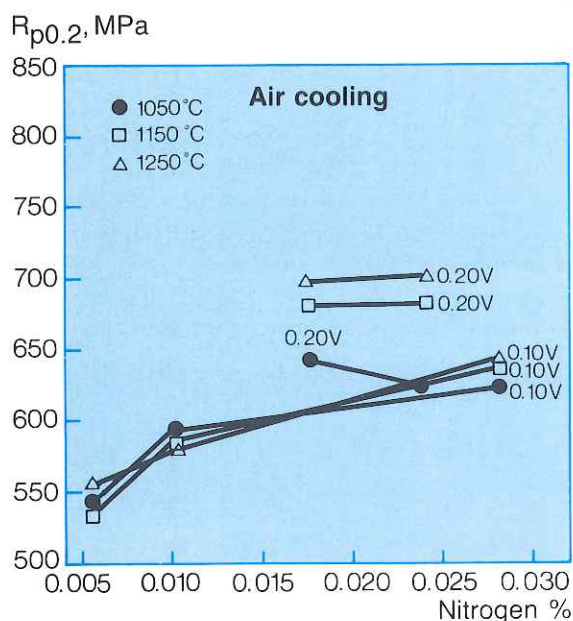


Fig 11
Influence of N- and V-content on yield strength. Austenitizing at 1050, 1150 and 1250°C, cooled in air resp isothermal transformation in saltbath at 540°C.

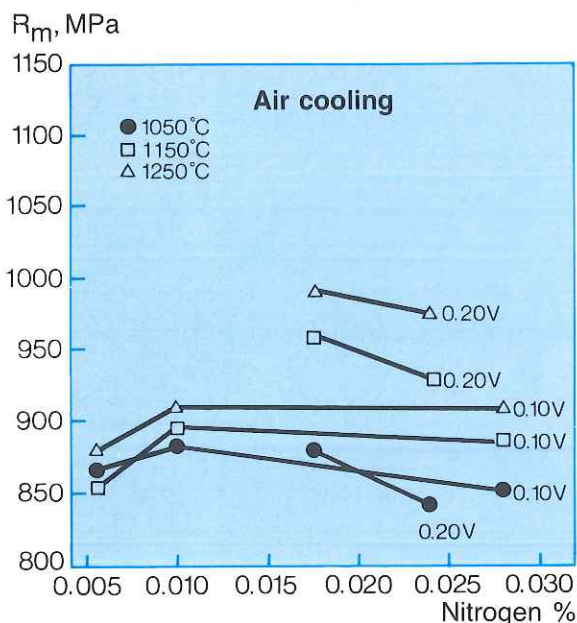
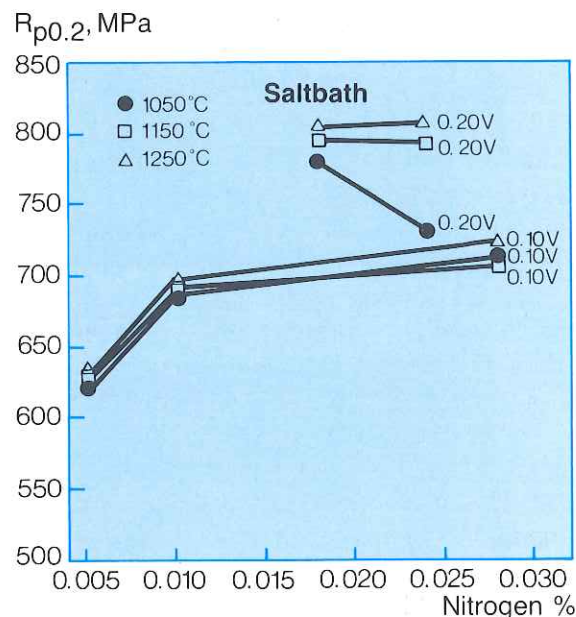
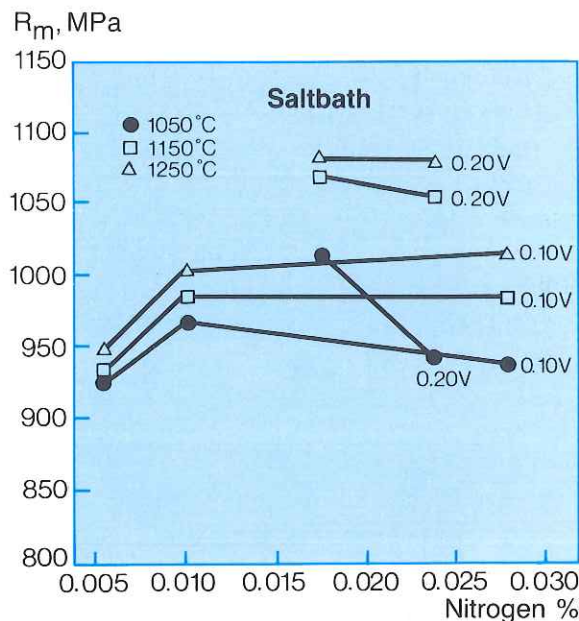


Fig 12
Influence of N- and V-content on tensile strength. Austenitizing at 1050, 1150 and 1250°C, cooled in air resp isothermal transformation in saltbath at 540°C.



1 and 2, due to the lower carbon content in steel 3. An increase in the nitrogen content from 0.005% to 0.024% leads to the ultimate tensile strength increasing by about 30 MPa (4 ksi) after air cooling from 1 250°C (2 282°F) and by 70 MPa (10 ksi) after transformation in a salt bath, also after austenitizing at 1 250°C (2 282°F). The decreasing tendency of the ultimate tensile strength with increasing nitrogen content in steels with 0.20% V can be explained by steel 8 having a somewhat higher ferrite content than steel 7. An increase in the vanadium content from 0.10% to 0.20% leads to the yield strength increasing by about 100 MPa (15 ksi) and the ultimate tensile strength by about 70 MPa (10 ksi), after austenitizing at 1 250°C (2 282°F). The values are approximately the same on air cooling and on isothermal transformation in a salt bath.

The addition of 0.5% Cr and/or 1.3% Mn causes the strength to increase further. An addition of 1.3% Mn is more effective in this respect than 0.5% Cr. A comparison between steel 2 with 0.10% V and steel 4 with 0.10% V and 0.5% Cr, both austenitized at 1 250°C (2 282°F) and cooled in air, demonstrates that the yield strength increases by approx. 70 MPa (10 ksi) from 580 to 650 MPa (84 to 94 ksi), and that the ultimate tensile strength increases by 45 MPa (7 ksi), from 920 to 965 MPa (133 to 140 ksi). If the same comparison is made on steel 5 with 0.1% V and 1.3% Mn, it will be found that the yield point increases from 580 MPa to 740 MPa (84 to 107 ksi), i.e. by 160 MPa (23 ksi) and that the ultimate tensile strength increases from 920 MPa to 1 030 MPa (133 to 149 ksi), i.e. an increase of 110 MPa (16 ksi).

A similar comparison between steel 7 with 0.20% V and steel 9 with 0.20% V and 1.4% Mn and steel 10 with 0.25% V, 0.5% Cr and 1.4% Mn shows that the greatest increase occurs on steel 10. The yield strength increases by approx. 230 MPa (33 ksi) and the ultimate tensile strength by approx. 210 MPa (30 ksi). On steel 9, the yield strength increases by approx. 40 MPa (6 ksi) and the ultimate tensile strength by around 65 MPa (9 ksi). The values are applicable to transformation in a salt bath, after austenitizing at 1 250°C (2 282°F).

An addition of 0.015% Ti to the reference material has no significant influence on the mechanical properties. An equalisation of the yield strength and ultimate tensile strength and of the elongation and reduction in area occurs in the temperature range between 1050 and 1250°C (1922 and 2282°F).

A comparison between steel 6 and steel 6A demonstrates that the latter has a lower strength but a higher ductility. This is probably due to steel 6A having a larger quantity of ferrite than steel 6. However, it is difficult to determine whether this is due to steel 6A having somewhat higher Ti and N contents.

Hardness

The hardness has been tested as HV 30. *Fig. 13* shows the hardness of all steels after different cooling rates from different austenitizing temperatures. This figure demonstrates that the hardness increases with increasing cooling rate and increasing austenitizing temperature. Steel 8 has the lowest hardness of 235 HV after air-cooling from 1050°C, whereas steel 10 attains the highest hardness of 430 HV. The reference material has a hardness of 275 HV after air cooling from 1250°C.

Fig 13
Influence of austenitizing temperature and cooling conditions on hardness steel 1–10.

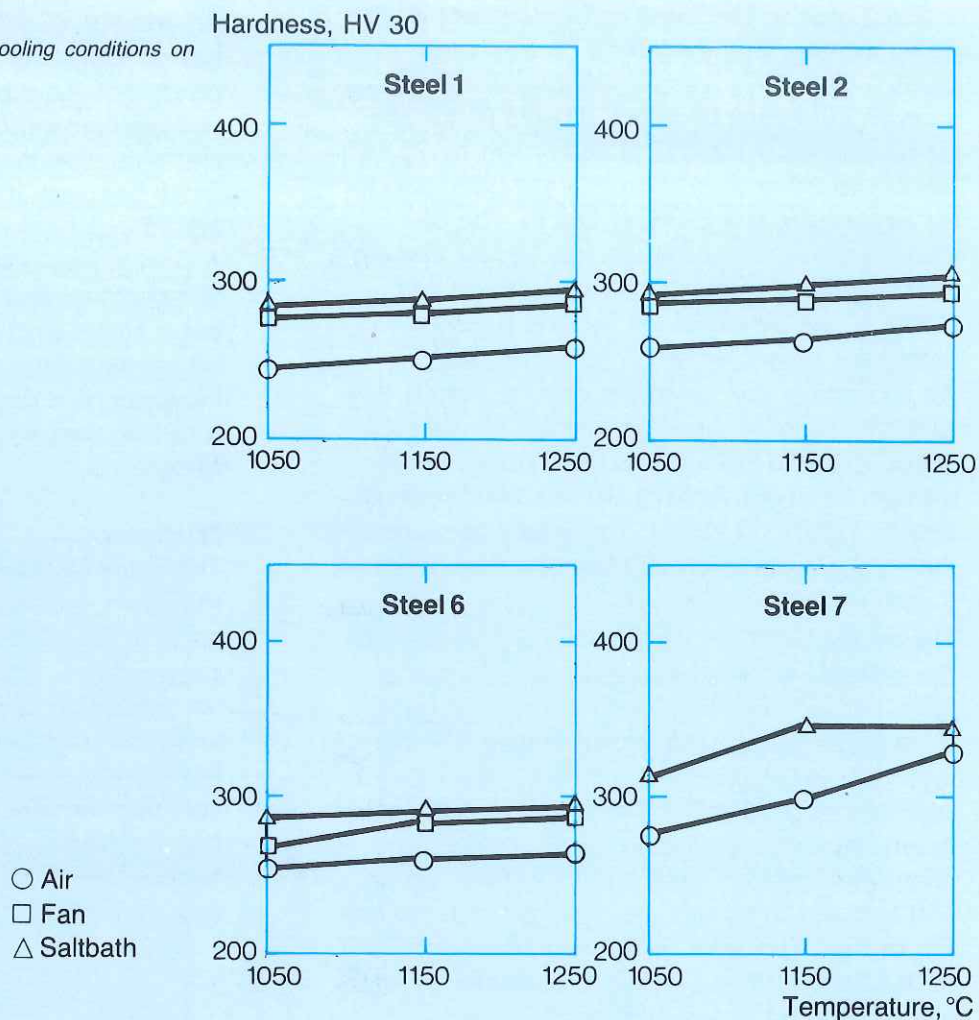
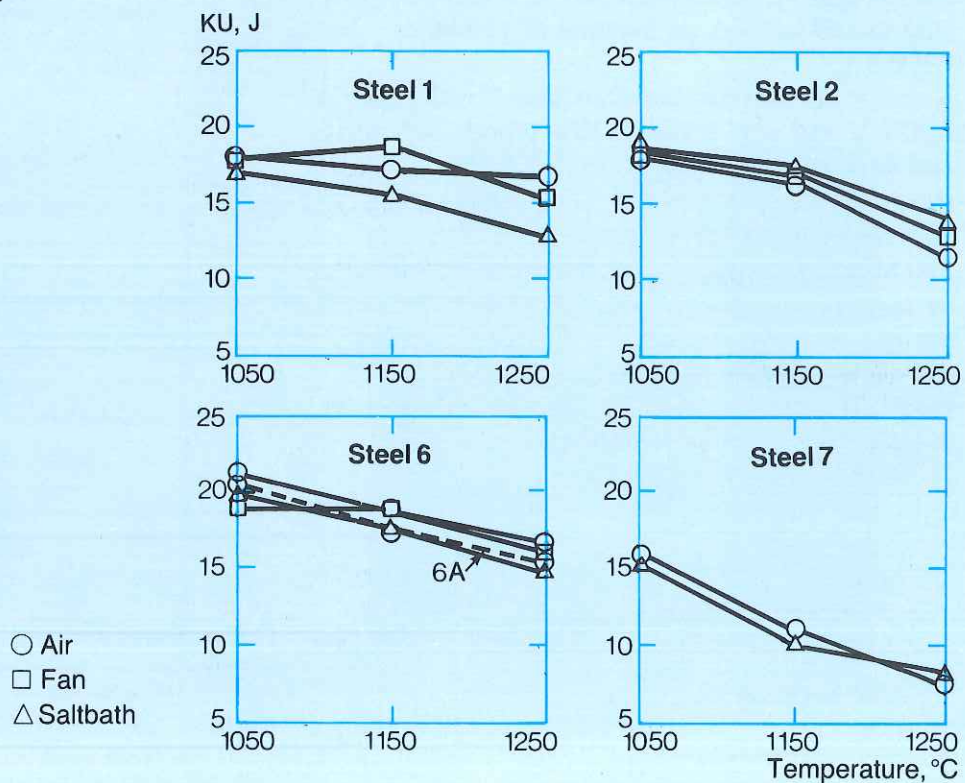
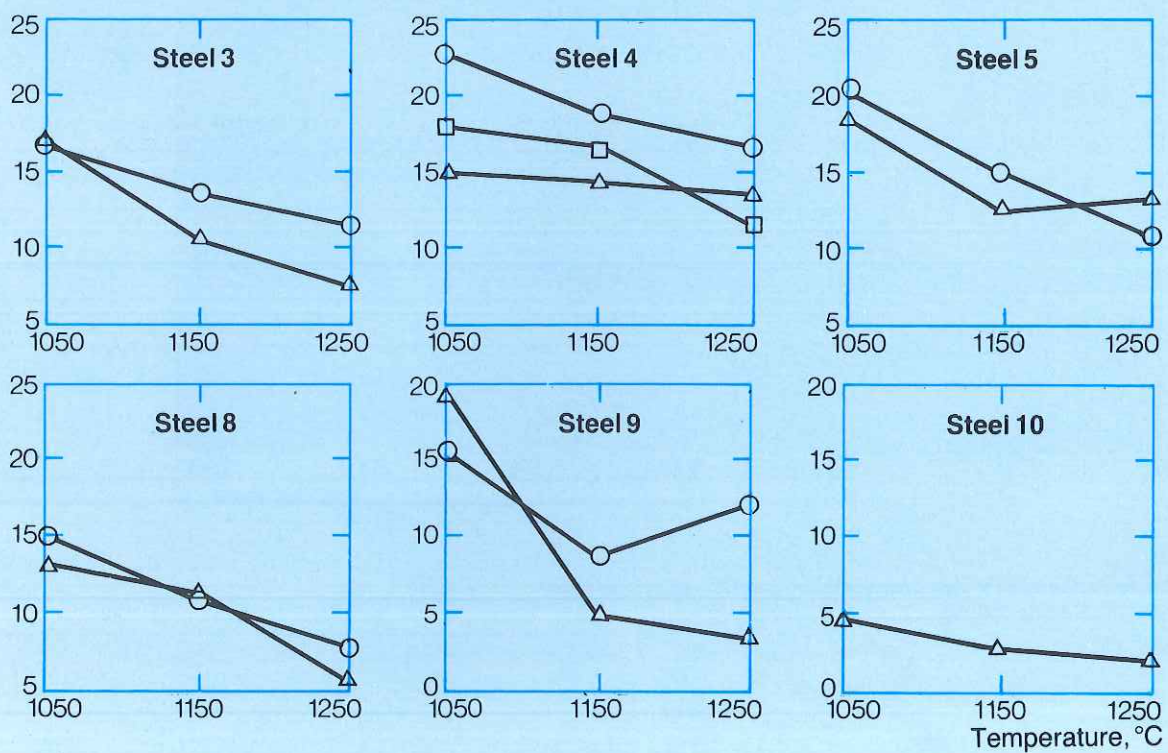
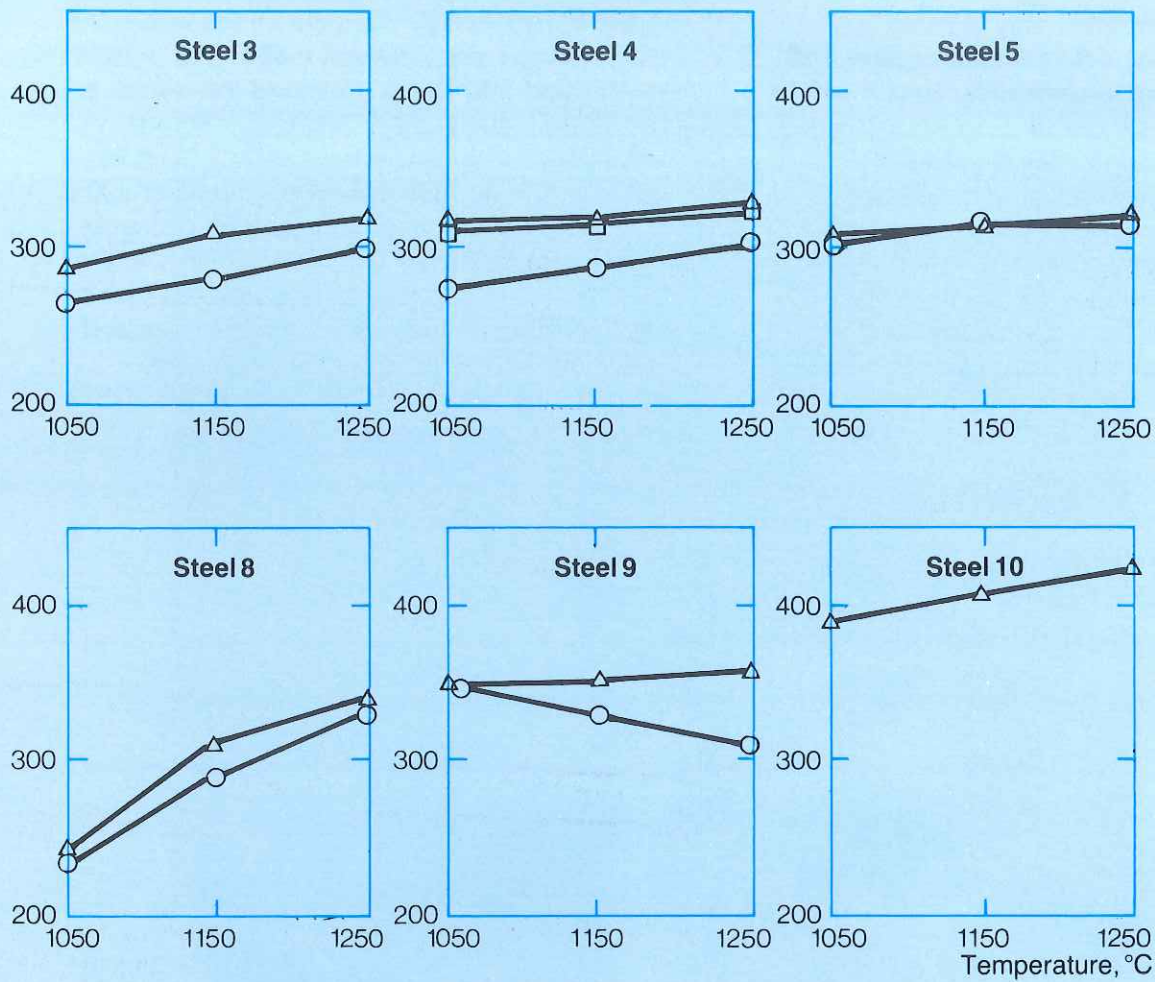


Fig 14
Influence of austenitizing temperature and cooling conditions on impact value for steel 1–10. Charpy ISO–U.





Impact strength

Fig. 14 shows the impact energy at room temperature following different cooling rates and different austenitizing temperatures. Steel 4 with 0.10% V and 0.5% Cr and steel 6 with 0.10% V and 0.015% Ti attain the highest values of around 22–24 J (16–18 ft lb) after air cooling from 1050°C (1922°F). Increasing cooling rates and increasing austenitizing temperatures reduce the impact strength to around 15 J (11 ft lb). Steel 10 with 0.25% V, 0.5% Cr and 1.4% Mn has the lowest impact strength, the actual values being below 5 J (4 ft lb).

To determine the transition temperature for steel 2, the impact energy was determined within the temperature range between -40°C and $+260^{\circ}\text{C}$ (-40°F and 500°F). Fig. 15 shows the results. A transition temperature of 140°C (284°F) was obtained at an impact energy of 27 J (20 ft lb). A maximum of 40 J (30 ft lb) was attained at 200°C (392°F), and the impact strength then decreases slowly with increasing temperature. At -40°C (-40°F), the impact energy is around 8 J (6 ft lb). Fig. 16 shows how an addition of nitrogen and vanadium affects the impact strength after austenitizing between 1050°C and 1250°C (1922 and 2282°F), followed by cooling in air.

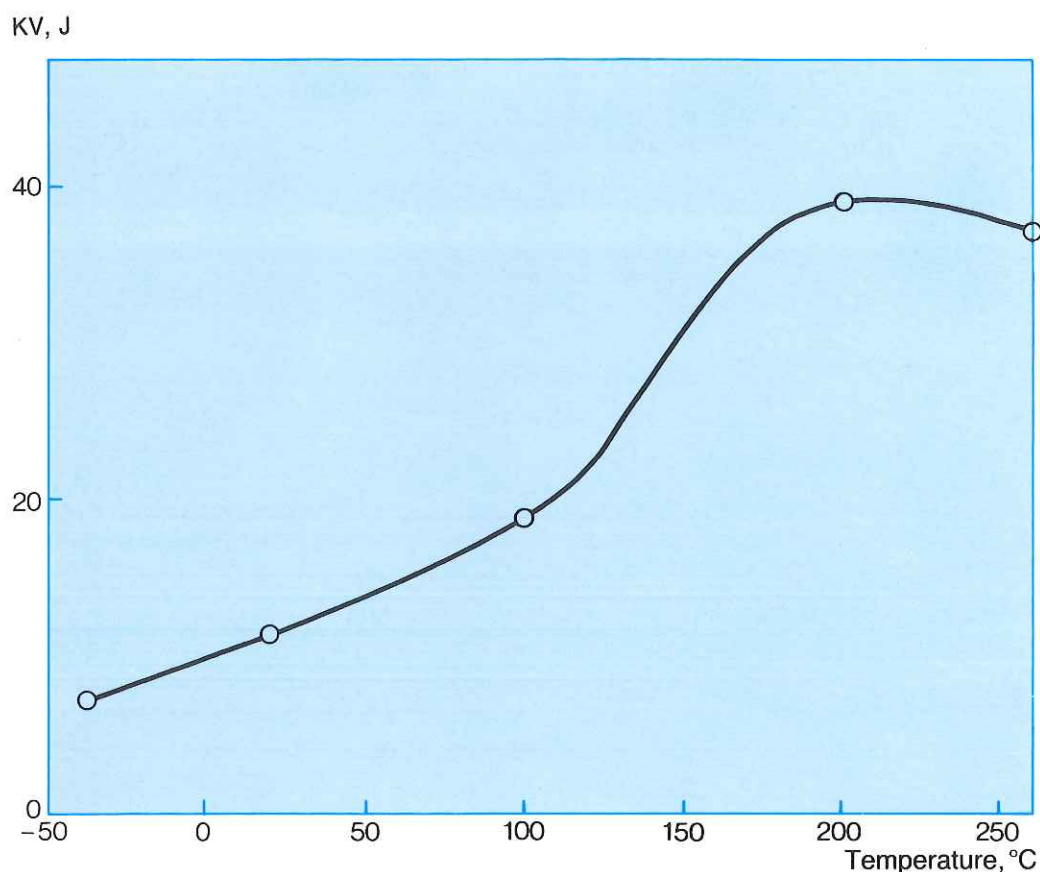


Fig 15
Impact value as a function of temperature steel 2, cooled in air from 1250°C , Charpy ISO-V.

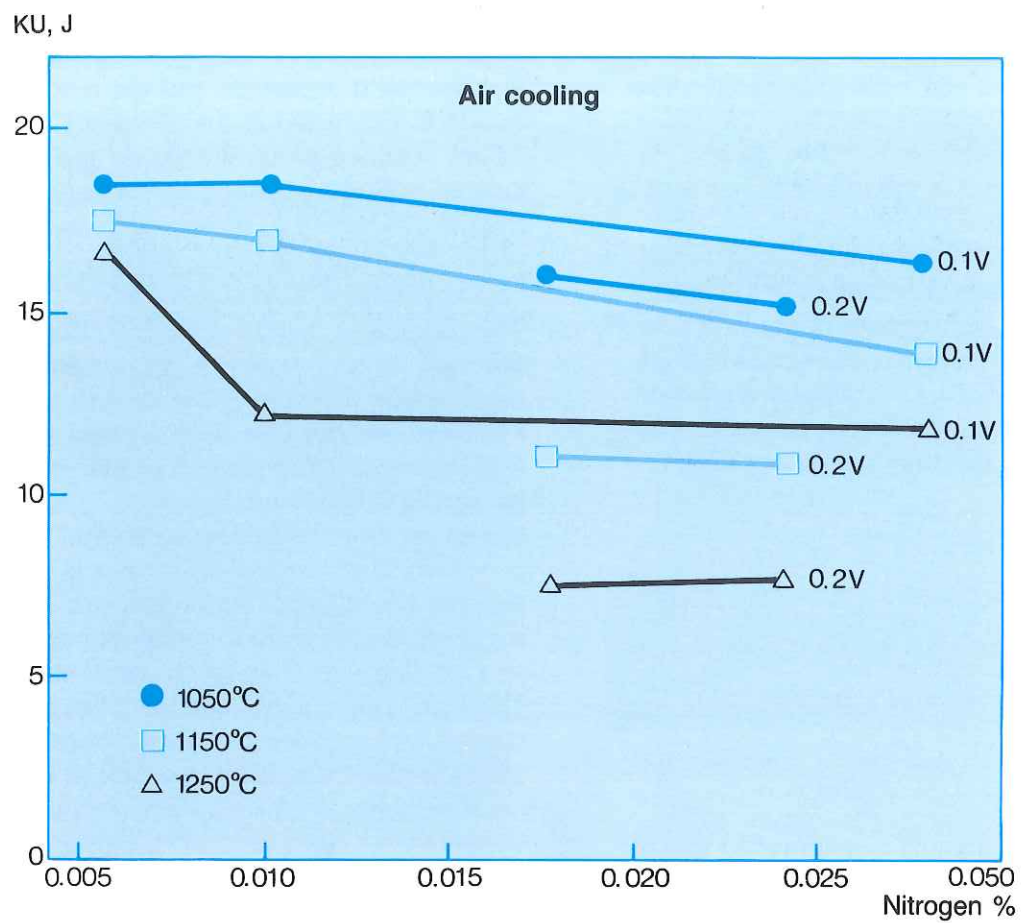


Fig 16
Influence of N- and V-content on impact value after austenitizing at 1050, 1150 and 1250°C, cooled in air resp isothermal transformation in saltbath at 540°C. Charpy ISO-U.

Discussion

Cr and Mn substantially lower the temperature of the γ/α transformation. The reason for this is well-known: Cr and Mn displace the "pearlite nose" towards shorter times and higher temperatures as compared to a steel without vanadium (2). Fig. 6 shows that the ferrite content doubles from 22% to 44% on an increase in the vanadium content from 0.10% to 0.20%.

The formula suggested by Gladman, McIvor and Pickering can be used for determining the contributions of various constituents of the structure to $R_{p0.2}$ and R_m (3). The formula is valid for pearlitic steels with 0.4–0.8% C, without the addition of precipitation-hardening alloying elements. The yield strength is calculated from the expression:

$$R_{p0.2} = f^{1/3} [35.4 + 58.5 (\%Mn) + 17.4 d^{-1/2}] + (1-f^{1/3}) (178.6 + 3.85 S_o^{-1/2}) + 63.1 (\%Si) + 425 (\sqrt{\%N}) \text{ (MPa)} \quad (1)$$

The ultimate tensile strength is determined from the expression:

$$R_m = f^{1/3} (264.4 + 1142.7 (\sqrt{\%N}) + 18.7 d^{-1/2}) + (1-f^{1/3}) (719.2 + 3.54 S_o^{1/2}) + 15.8 (\%Si) \text{ (MPa)} \quad (2)$$

where

- d = ferrite grain size, mm
- f = volume fraction of ferrite
- 1-f = volume fraction of pearlite
- S_o = pearlite interlamellar spacing, mm
- N = dissolved nitrogen, %
- Mn = manganese, %
- Si = silicon, %

The yield strength is the sum of different hardening mechanisms:

- 1) Solution hardening from Si and N
- 2) Peierls-Nabarro stress (PN) + solution hardening from Mn
- 3) Ferrite grain boundaries (F_{gb})
- 4) Pearlite
- 5) Residual contribution, R

The contribution of hardening to the ultimate tensile strength differs from this by Mn in solution not having any influence and by the hardening contribution from N being restricted to the ferrite. Engineer (4) demonstrate that the residual contribution R, calculated as the difference between the values obtained on tensile testing and values calculated from equation (1), agrees very well with the difference in $R_{p0.2}$ measured in steels with and without additions of V.

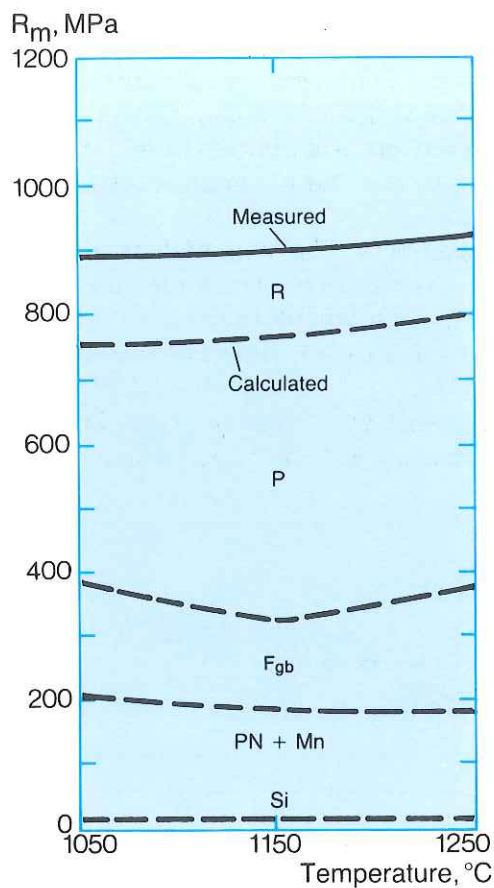
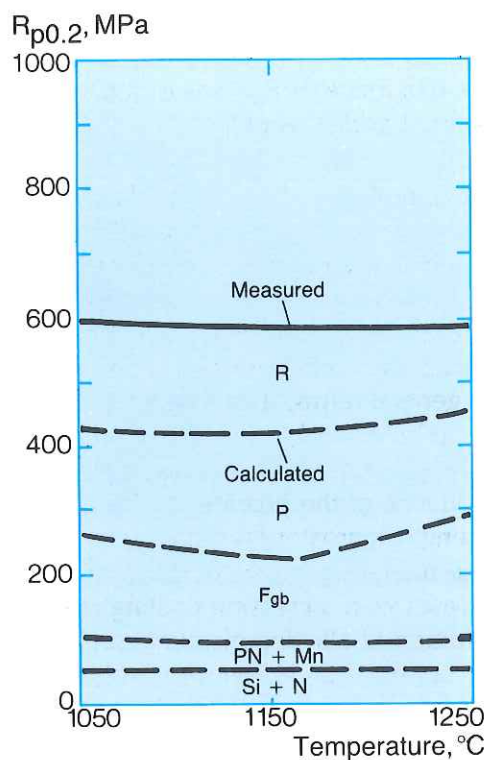
The conclusion that can be drawn from this is that the residual contribution R only originates from precipitation hardening of vanadium carbonitrides. Fig. 17 shows how the yield strength and ultimate tensile strength are made up of different hardening contributions on steels 2, 4, 5, 6 and 7. In general terms, it can be stated that pearlite contributes to the greatest increase in yield strength and ultimate tensile strength, but that the influence of the pearlite on the ultimate tensile strength is greater than on the yield strength. The hardening contribution from the pearlite increases with increasing cooling rate or the addition of alloying elements such as Cr or Mn, i.e. a reduction in the γ/α transformation temperature.

The hardening contribution of the ferrite (PN + Mn + F_{gb}) to the yield strength is of approximately the same magnitude as the pearlite contribution, i.e. 160 MPa. The hardening contribution of the ferrite (PN + N + F_{gb}) to the ultimate tensile strength is somewhat smaller than the pearlite contribution. Solution hardening from Si and N contributes to the yield strength by about 50 MPa (7 ksi) on all steels, whereas solution hardening from Si gives a marginal contribution to the ultimate tensile strength.

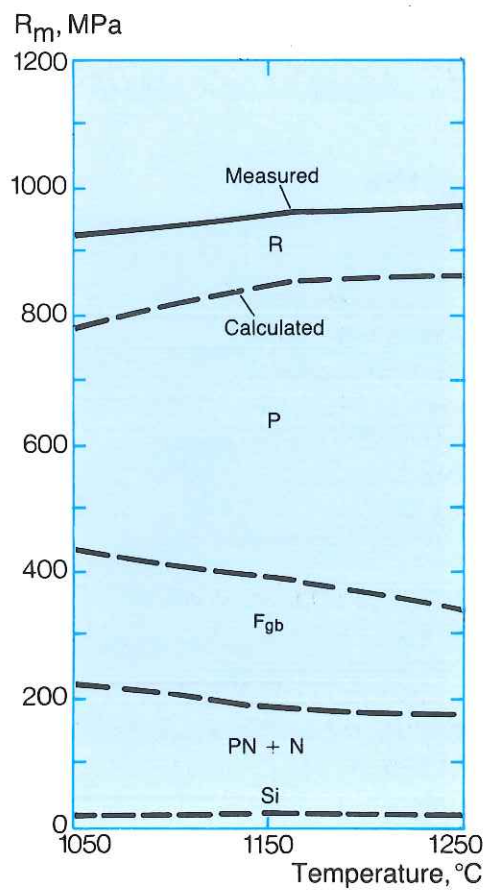
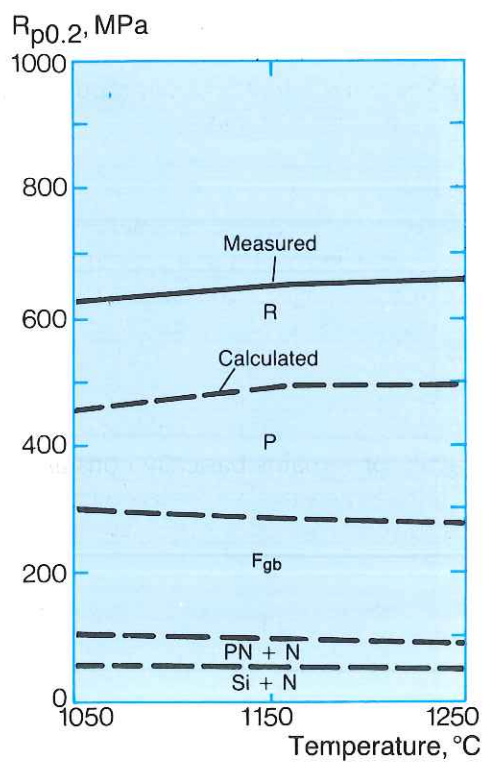
As mentioned earlier, the residual contribution can be attributed to precipitation hardening from V (C, N). The residual contribution is greater for the yield strength than for the ultimate tensile strength. The highest value is obtained on steels with 0.20% V. It is the yield strength which increases most as a result of increased cooling rate, whereas the ultimate tensile strength increases slightly or remains basically constant. An addition of nitrogen causes an increase in the yield strength as well as the ultimate tensile strength.

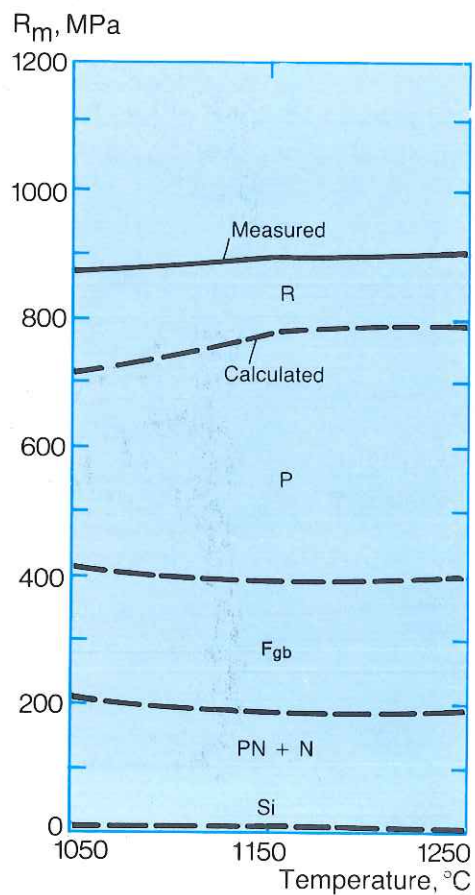
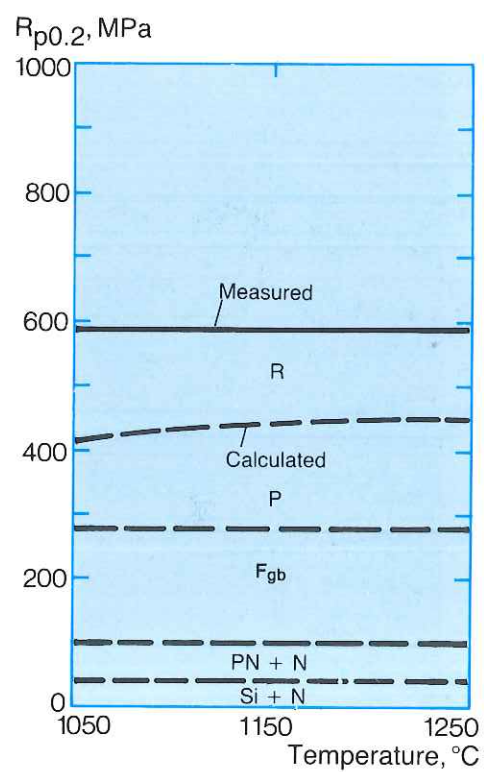
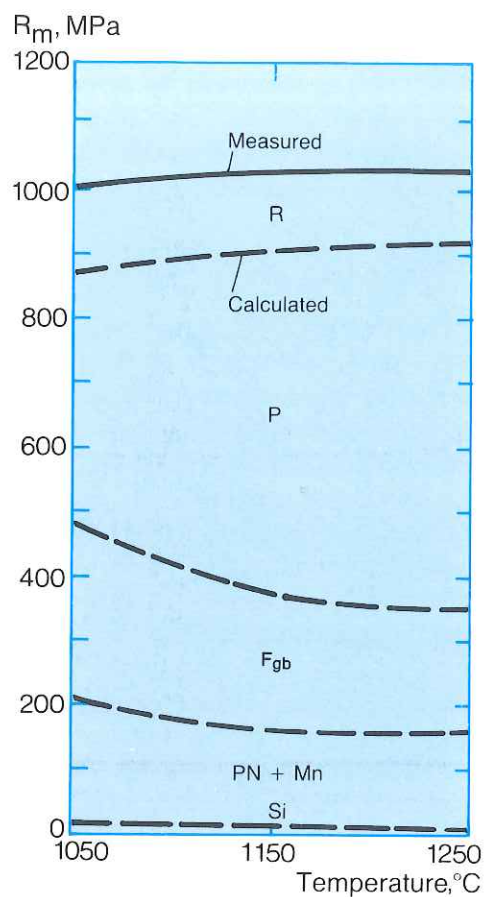
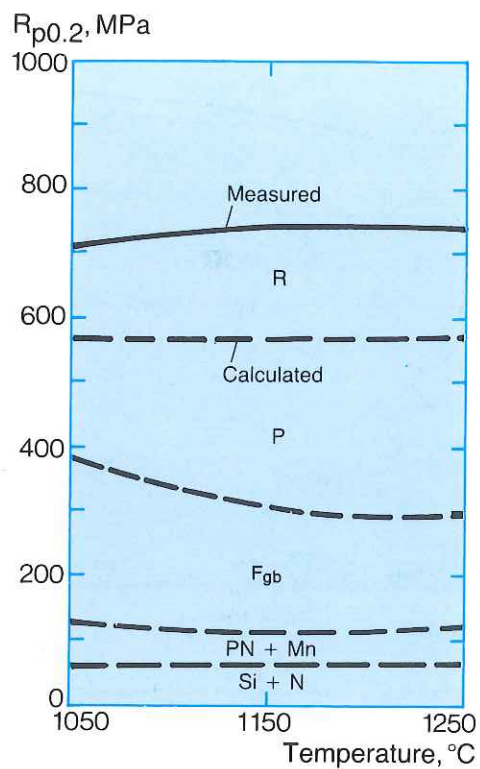
Fig 17
Splitting of yield strength and tensile strength in different hardening
contributions for steel air cooled from 1050, 1150 and 1250°C.
Figures continued on pages 20—21.

Steel 2

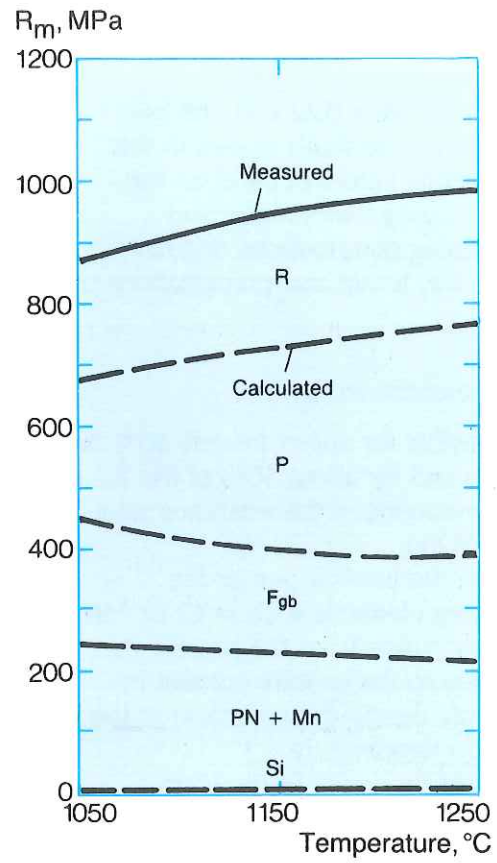
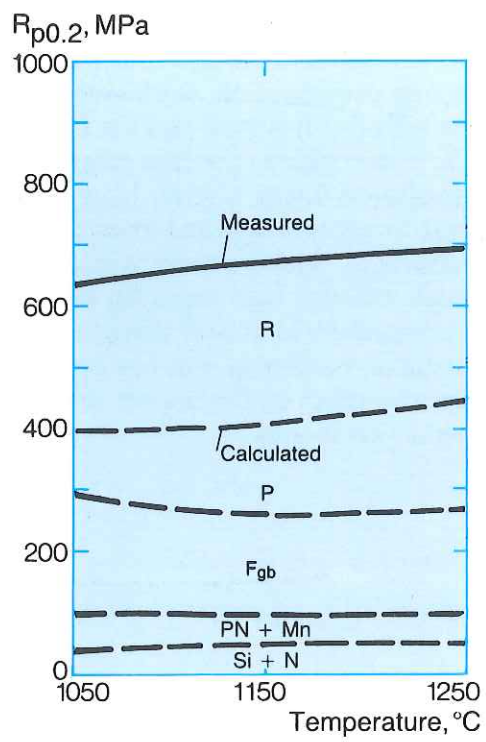


Steel 4





Steel 7



Conclusions

Yield strengths between 540 and 1040 MPa (78 and 151 ksi) and ultimate tensile strengths between 840 and 1300 MPa (122 and 188 ksi) have been recorded on the steels studied in this investigation. The actual values depend on the composition, austenitizing temperature and cooling rate. Hardening contributions originate primarily from pearlite, ferrite and precipitations of V (C, N).

The strength can be explained by:

- pearlite is responsible for approximately 30% of the $R_{p0.2}$ strength and for about 50% of the R_m strength, after air-cooling of the reference steel from 1250°C (2282°F)
- on an increase in the cooling rate or the addition of alloying elements such as Cr or Mn, the strength contribution from the pearlite increases, partly due to the pearlite content increasing and partly due to the reduction in the γ/α transformation temperature.
- the contribution of the ferrite to the yield strength is of the same magnitude as the pearlite contribution, whereas the contribution of the ferrite to the ultimate tensile strength is somewhat lower than the pearlite contribution.

The residual contribution caused by precipitation hardening from V (C, N) increases with the cooling rate. On air cooling, the addition of 0.10% V gives a contribution of approx. 140 MPa (20 ksi) to the yield strength and approx. 110 MPa (16 ksi) to the ultimate tensile strength. An increase in the vanadium content to 0.20% leads to $R_{p0.2}$ increasing by approx. 250 MPa (36 ksi) and R_m by approx. 220 MPa (32 ksi).

The investigation shows that the Ti-V steel of comparable strength has the best toughness properties, taking into account the reduction in area and the impact strength. If only the ultimate tensile strength and reduction in area values are taken into consideration, steels with 0.10% V together with the Ti-V steel and the Cr/Mn-alloyed 0.10% V steel display the best properties. The Cr/Mn-alloyed 0.10% V steels have the best ultimate tensile strength and impact strength characteristics, whereas steels with 0.20% V, although attaining high strengths, simultaneously lose substantially in impact strength. Increased precipitation hardening thus has a more detrimental effect on the impact strength than on the reduction in area.

References

1. Manning, R.D., Reichold, H.M. and Hodge, J.M. A Pearlite Hardenability concept for Alloy Development, Symposium on "Transformation and Hardenability in Steels" Molybdenum Climax, Feb 27—28 1967, pp. 169—177
2. Engineer, S. Zur Wirkung geringer Zusätze von Vanadin und N in niedriglegierten Baustählen mit 0.4 bis 0.5% C. Dr-Ing. Dissertation, 1977, Aachen.
3. Gladman, T., McIvor, I.D., Pickering, F.B., JISI, 12 (1972), pp. 916—930.

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