Estimation of mechanical properties of ferritic steel welds

Part 2: Elongation and Charpy toughness

S. H. Lalam, H. K. D. H. Bhadeshia, and D. J. C. MacKay

Previous work presented models which can be used to estimate the yield and ultimate tensile strengths of ferritic steel welds. The present paper deals with properties that are much more difficult to predict: the elongation and Charpy impact toughness. While the models are found to be useful and emulate expectations from current physical metallurgy principles, it is clear that much more systematic experimental data are needed before the predictability becomes as good as the strength models of Part 1.

Dr Lalam and Professor Bhadeshia are in the Department of Materials Science and Metallurgy, University of Cambridge, Pembroke Street, Cambridge CB2 3QZ, UK and Dr MacKay is at the Cavendish Laboratory, Madingley Road, Cambridge CB3 0HE, UK. *Manuscript received 1 November 1999; accepted 11 December 1999.*

INTRODUCTION

The most common experiments carried out on weld metals include the testing of a specimen in tension to measure the strength and ductility, and the measurement of the Charpy impact toughness. Although these tests are fairly simple to conduct, the principles governing the properties measured are understood only on a qualitative basis. Part 1 of the present work described the development of neural network models which allow the estimation of the yield and ultimate tensile strengths of ferritic steel weld metals using a vast quantity of data collected from the published literature and from commercial sources. The predictions that can be made using these models are associated with error bars which consist of the perceived level of noise in the output and a component representing the uncertainty of fitting. The predictions are reliable when the error bars are small, but have to be used with caution when they are not; large error bars can indicate a need for further experiments to fill gaps in knowledge. In this sense, all predictions are useful irrespective of the magnitudes of the error bars.

The purpose of the present work was to develop similar models for the elongation and Charpy properties. There has been little practical progress in modelling the tensile ductility of weld metals.[1] The ductility can, to a good approximation, be divided into two components whose magnitudes are assumed to be controlled by different physical processes. These components are the uniform plastic strain, as recorded before the onset of necking in the tensile specimen, and the non-uniform component, which is the remainder of the plastic strain.

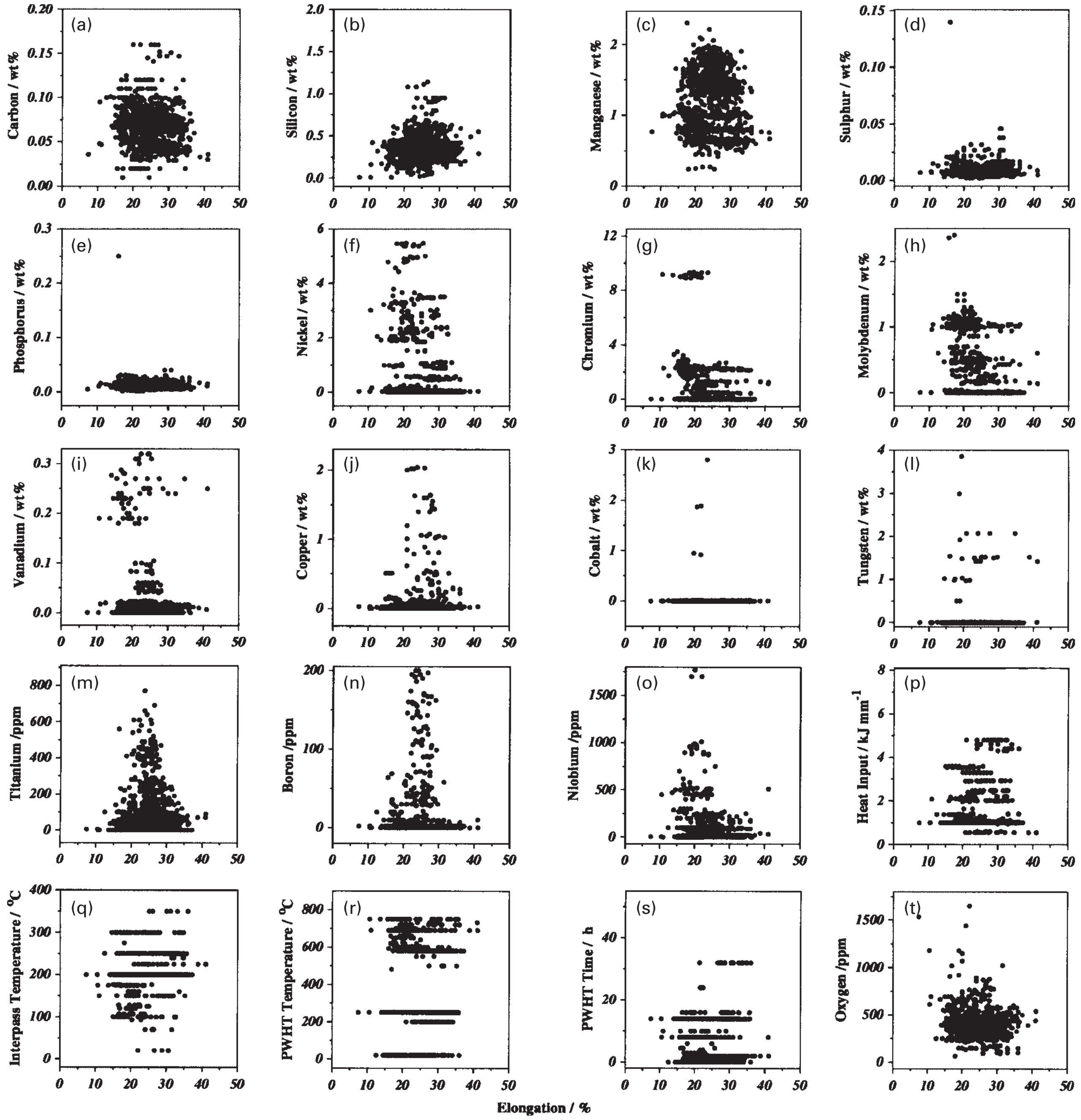
By factorising the ductility in this way, it is possible to express the non-uniform component in terms of the inclusion content of the weld deposit, after taking into account variations in specimen cross-sectional area A_0 and gauge length L_0 (Ref. 2)

$$\text{non-uniform elongation, \%} = 100 \times \beta \, \frac{A_0^{0\cdot5}}{L_0} \quad . \; . \; . \; (1)$$

Table 1 Variables used in developing elongation model

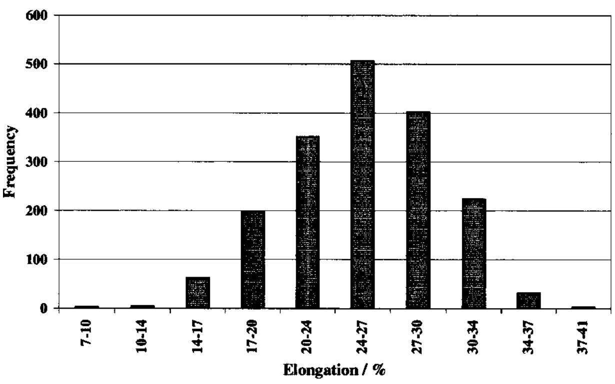
Input element	Minimum	Maximum	Mean	Standard deviation
C, wt-%	0·01	0·16	0·07	0·0184
Si, wt-%	0·01	1·14	0·35	0·124
Mn, wt-%	0·24	2·31	1·23	0·386
P, wt-%	0·001	0·25	0·01	0·007
S, wt-%	0·002	0·14	0·008	0·005
Cr, wt-%	0·0	9·4	0·45	1·19
Mo, wt-%	0·0	2·4	0·17	0·358
Ni, wt-%	0·0	5·48	0·322	0·88
Co, wt-%	0·0	2·8	0·005	0·097
Cu, wt-%	0·0	2·04	0·063	0·204
V, wt-%	0·0	0·32	0·015	0·044
W, wt-%	0·0	3·86	0·024	0·207
B, ppm wt	0·0	200	11	30
Nb, ppm wt	0·0	1770	48	141
Ti, ppm wt	0·0	1000	86	127
O, ppm wt	63·0	1650	414	118
Heat input, kJ mm^{-1}	0·55	4·8	1·23	0·71
Interpass temperature, °C	20	350	204	35
Tempering temperature, °C	20	750	321	191
Tempering time, h	0·0	32	10	6·2
Elongation, %	7·4	41·1	26	5

ISSN 1362–1718



a C; *b* Si; *c* Mn; *d* S; *e* P; *f* Ni; *g* Cr; *h* Mo; *i* V; *j* Cu; *k* Co; *l* W; *m* Ti; *n* B; *o* Nb; *p* heat input; *q* interpass temperature; *r* PWHT temperature; *s* PWHT time; *t* O

1 Database values of each variable versus elongation: ppm refers to parts per million by weight

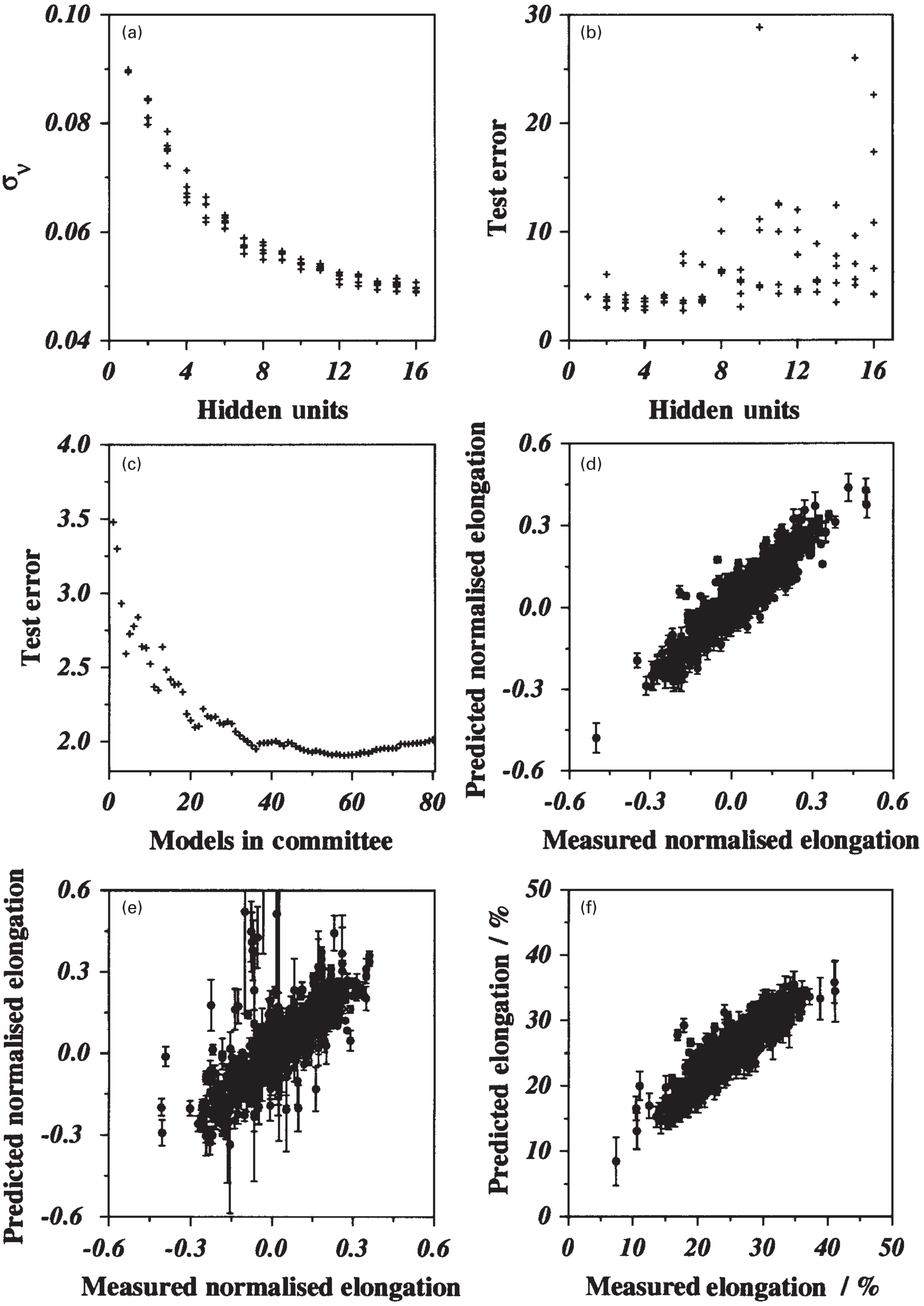


2 Elongation data frequency distribution

where β is Barba's constant, but which may be expressed as a function of the inclusion content[3]

$$\beta \simeq 1{\cdot}239 - 9{\cdot}372(\text{wt-\%O}) + (\text{wt-\%S}) \qquad . \; . \; . \; . \; (2)$$

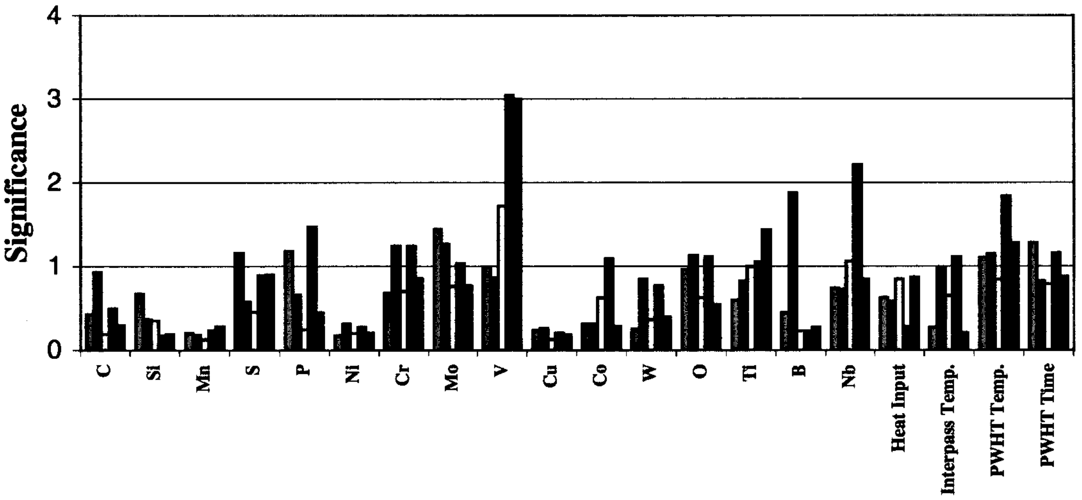
There is as yet no reliable model for estimating the uniform component of strain, but such a model would require a detailed knowledge of the strain hardening behaviour of the individual phases of the microstructure, together with some theory for multiphase deformation. As far as the non-uniform component is concerned, equation (1) emphasises the role of particles in reducing ductility. There are only two inputs to equation (2), whereas a vast number of other variables are known to influence the elongation measured in a tensile test. Hence, there is a need for a different approach which encompasses a wider set of variables.



a σ_v *v.* hidden units; *b* test error *v.* hidden values; *c* test error *v.* models in committee; *d* predicted *v.* measured elongation (training); *e* predicted *v.* measured elongation (test); *f* predicted *v.* measured elongation (optimum committee)

3 Characteristics of elongation model: σ_v is model perceived level of noise in elongation; *d* and *e* represent behaviour of best single model whereas *f* shows performance of optimum committee model on entire dataset

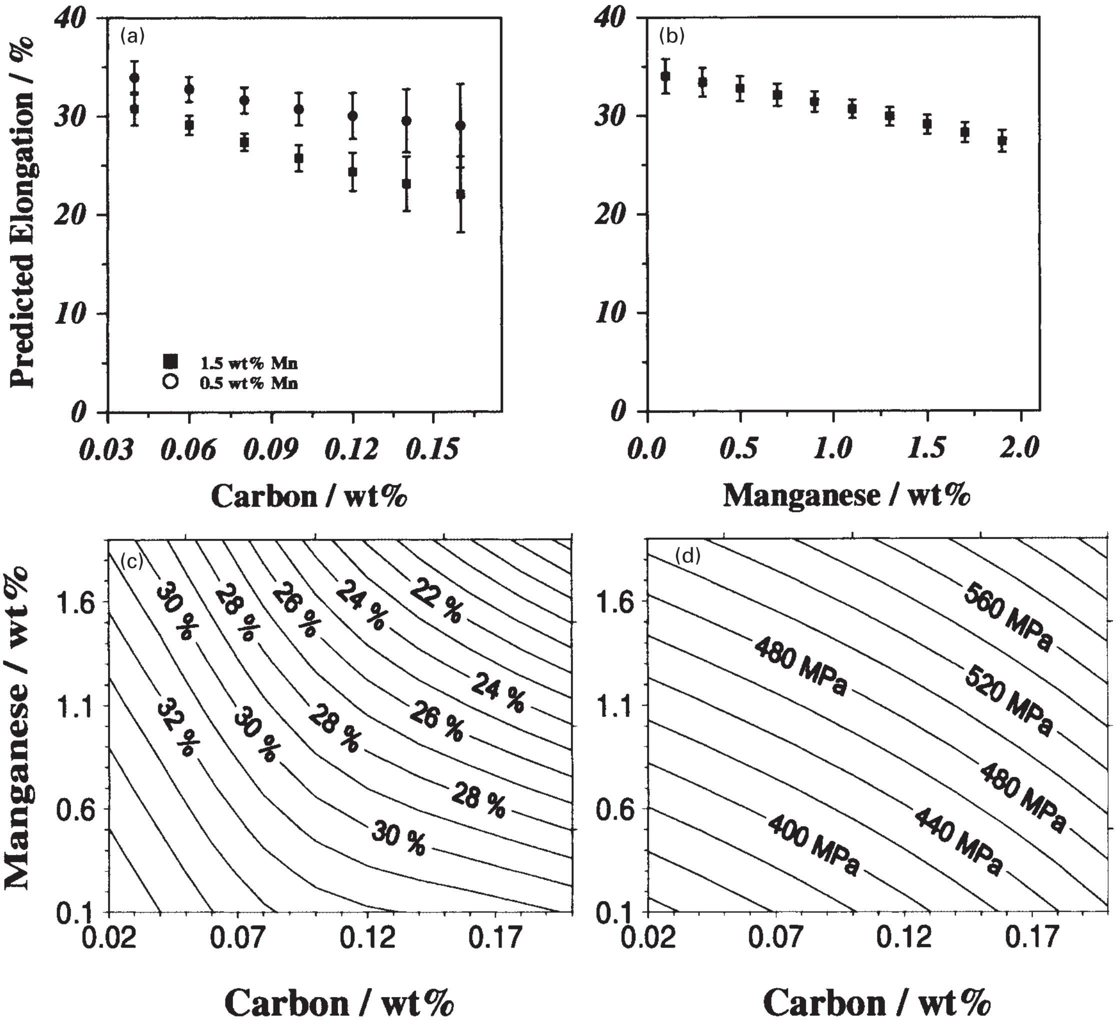
The concept of toughness as a measure of the energy absorbed during fracture is well developed.[4,5] It is often measured using notched bar impact tests, of which the most common is the Charpy test. A square section notched bar is fractured under specified conditions and the energy absorbed during fracture is taken as a measure of toughness. The Charpy test is empirical in that the data cannot be used directly in engineering design. It does not provide the most searching mechanical conditions. The specimen has a notch, but this is less severe than the atomically sharp brittle crack. Although the test involves impact loading, there is a requirement to start a brittle crack



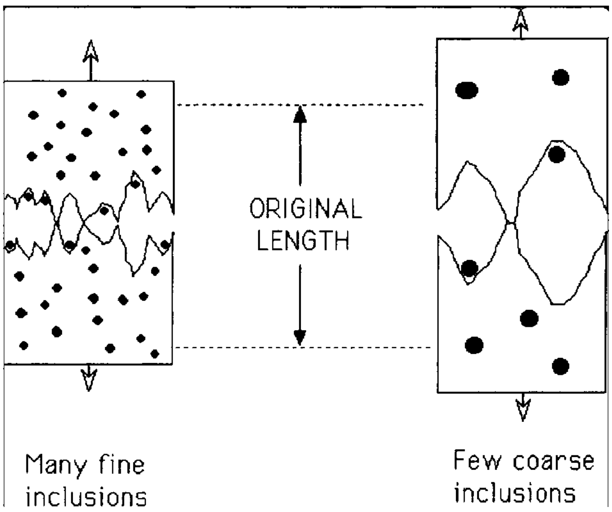
4 Significance σ_w of each input variable as perceived by first five neural network models in committee, in influencing elongation

from rest at the tip of the notch, suggesting that the test is optimistic in comparison with a propagating brittle crack.[5] Most materials can be assumed to contain subcritical defects so that the initiation of a crack seems seldom to be an issue.

The Charpy test is nevertheless a vital quality control measure which is specified widely in international standards, and in the ranking of specimens in research and development exercises. It is the most common first assessment of toughness and in this sense has a proven



5 *a* and *b* predicted elongation as function of C and Mn in C–Mn weld metal; *c* and *d* contour plots showing variation in elongation and yield strength as function of C and Mn concentrations: error bars have been omitted for clarity but range ±2–6% in elongation and ±10–30 MPa in strength plots



6 Illustration of how large density of void nucleating particles can result in fracture with low overall ductility, even though material fails by gross plastic deformation on microscopic scale

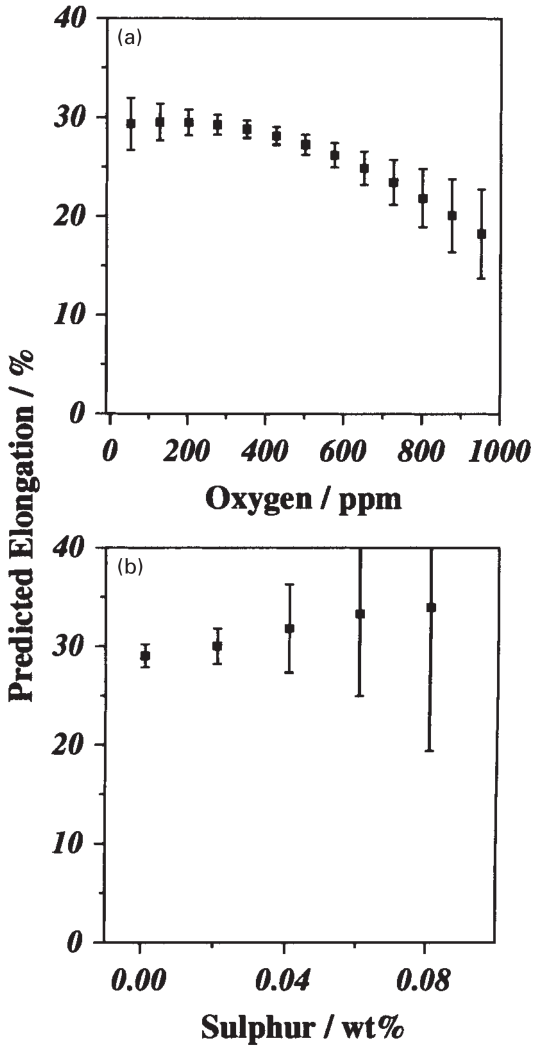
record of reliability. The test is usually carried out at a variety of temperatures, to characterise the ductile–brittle transition intrinsic to body centred cubic metals with their large Peierls barriers to dislocation motion.

It would therefore be useful to be able quantitatively to model the Charpy toughness as a function of metallurgical variables that are believed to influence the cleavage and ductile fracture modes of commercial steels. Some of these variables have in the past been studied quantitatively (for example, the flow stress as a function of temperature[6]) whereas others (such as the degree of organisation in the microstructure[7]) have been expressed using language alone.

Complex problems such as those described above can usefully be modelled empirically using an artificial neural network. The method has been discussed thoroughly in Part 1.

Table 2 Inputs relevant for typical C–Mn as welded weld metal

Input element	Elongation model	Charpy model
C, wt-%	0·06	0·07
Si, wt-%	0·50	0·50
Mn, wt-%	1·50	1·50
P, wt-%	0·008	0·008
S, wt-%	0·006	0·006
Cr, wt-%	0·0	0·0
Mo, wt-%	0·0	0·0
Ni, wt-%	0·0	0·0
Co, wt-%	0·0	0·0
Cu, wt-%	0·0	0·0
V, wt-%	0·0	0·0
W, wt-%	0·0	0·0
B, ppm wt	0·0	0·0
N, ppm wt	…	80
Nb, ppm wt	0·0	0·0
Ti, ppm wt	0·0	0·0
O, ppm wt	300	300
Heat input, kJ mm^{-1}	1·00	1·00
Interpass temperature, °C	175	175
Tempering temperature, °C	250	20
Testing temperature, °C	…	0·0
Tempering time, h	14·0	0·0

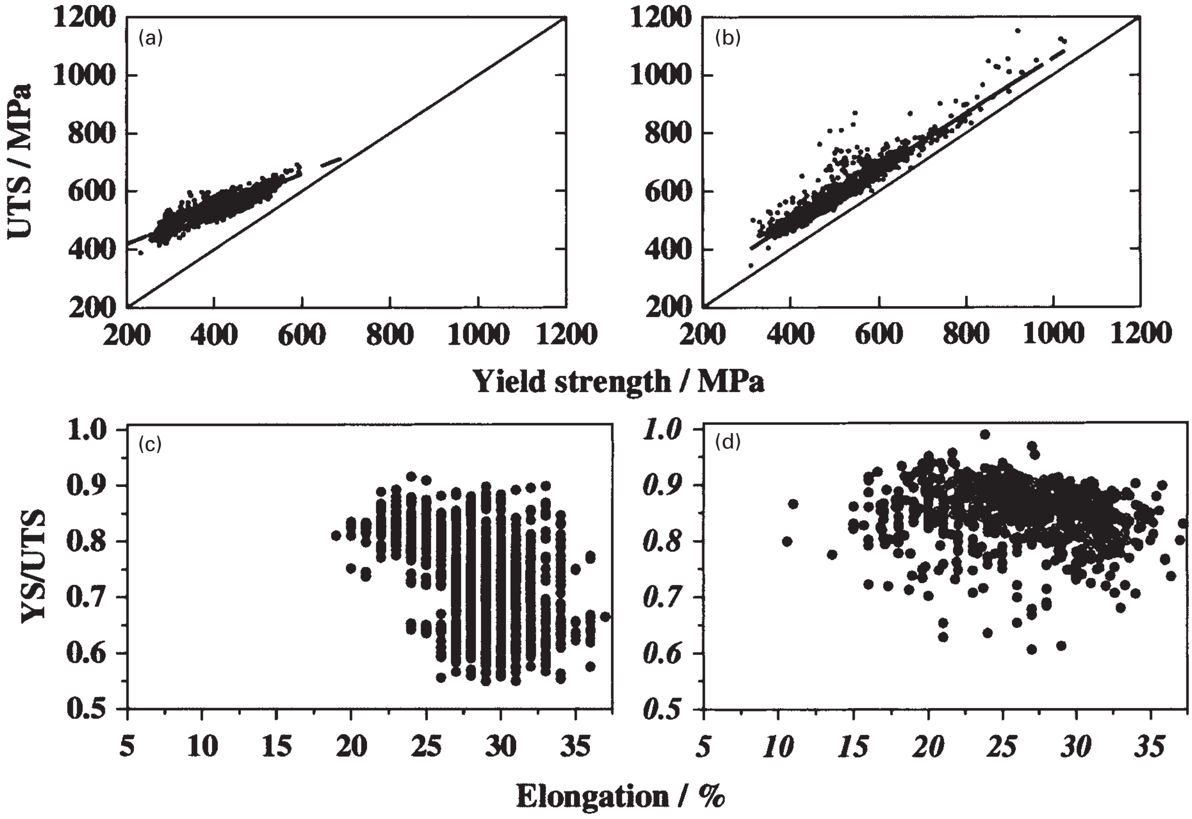


a O; *b* S

7 Change in elongation in C–Mn weld metal as function of given additions: it is evident that S has no significant effect on ductility of welds of type considered in present work

ELONGATION MODEL

This model consists of the 20 input variables listed in Table 1, which are considered to influence ductility. The detailed chemical composition, the heat treatment, and the welding heat input and interpass temperature essentially determine the microstructure and properties. It is easy to imagine other variables which might be important, such as the size distribution of oxide particles. However, the compilation of a dataset for neural network analysis is always a compromise between two factors. First, a larger dataset is of value in creating a model based on a greater span of knowledge. However, the probability of finding appropriate data diminishes as the number of variables is increased, because incomplete sets of inputs are not of use in the analysis. The database reflects multipass welds made using the submerged arc, gas tungsten arc, and manual metal arc welding processes. The welding parameters are represented by the heat input and the interpass temperature; the post-weld heat treatment conditions are represented by temperature and time. The sources of the data are provided.[8–30,32–80] The elongation values are those measured on standard, cylindrical tensile test specimens, where the gauge length is generally specified to be $5{\cdot}65\times(A)^{1/2}$, where A is the cross-sectional area.



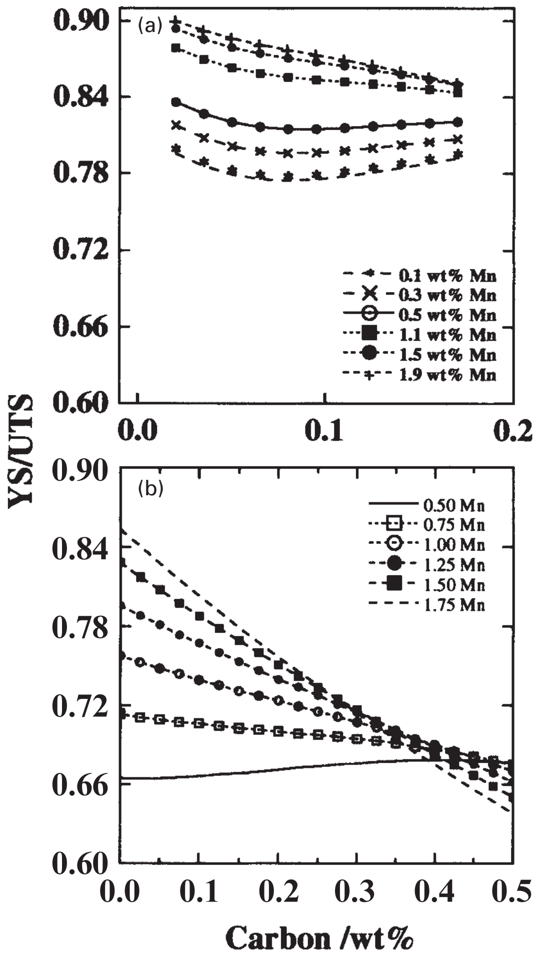
8 **Ultimate tensile strength (UTS) *v.* yield strength (YS) for *a* hot rolled C–Mn steel plates and *b* weld metals; elongation *v.* yield strength for *c* hot rolled C–Mn steel plates and *d* weld metals: all data plotted are experimental, those for plates from previous work,[84] those for weld deposits from present analysis**

A total of 1972 individual experimental data were gathered. In 19 cases, the sulphur and phosphorus concentrations were not reported, in which case they were set to the average values of the other data in the database. This is a better procedure than setting the concentrations to zero because all welds inevitably contain impurities. On the other hand, alloying additions such as molybdenum can be set to zero when they are not added deliberately, without affecting the overall microstructure or mechanical property outcomes. A visual impression of the entire elongation database is shown in Fig. 1. The mean and standard deviation of the percentage elongation are 26% and 5%, respectively, showing that most of the data lie in the range 21–31% (Fig. 2).

The training, test, and log predictive errors[81,82] associated with each of the 80 models created are shown in Fig. 3. The

Table 3 Variables used in developing Charpy toughness model

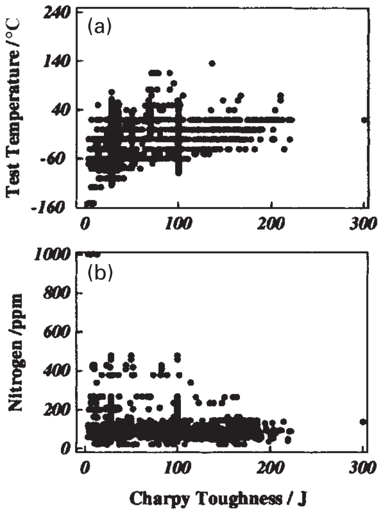
Input element	Minimum	Maximum	Mean	Standard deviation
C, wt-%	0·022	0·19	0·07	0·0192
Si, wt-%	0·01	1·63	0·36	0·126
Mn, wt-%	0·23	2·31	1·25	0·403
P, wt-%	0·003	0·25	0·01	0·0134
S, wt-%	0·002	0·14	0·008	0·008
Cr, wt-%	0·0	11·8	0·453	1·387
Mo, wt-%	0·0	1·54	0·153	0·336
Ni, wt-%	0·0	5·58	0·366	1·012
Co, wt-%	0·0	0·016	0·0005	0·0023
Cu, wt-%	0·0	2·18	0·0658	0·222
V, wt-%	0·0	0·53	0·0136	0·0424
W, wt-%	0·0	3·86	0·0076	0·1555
B, ppm wt	0·0	200	14·3	35
N, ppm wt	21·0	1000	96·5	63
Nb, ppm wt	0·0	1770	40·55	139·6
Ti, ppm wt	0·0	770	102	138
O, ppm wt	63·0	1535	409	112
Heat input, kJ mm^{-1}	0·6	6·6	1·194	0·69
Interpass temperature, °C	20	350	199·7	30
Tempering temperature, °C	20	760	182·5	261
Testing temperature, °C	−151	136	−43·9	34·4
Tempering time, h	0·0	100	2·2	5·66
Charpy toughness, J	2·6	300	74	43



a weld metal; *b* steel plate

9 Effect of C and Mn on YS/UTS ratio for given materials[86]

behaviour of the single best model is illustrated in Fig. 3*d* and *e*. From the set of 80 models, a committee of 58 of the best models was found to give the lowest test error (Fig. 3*c*); each member of the committee was then retrained on the entire dataset to create the final committee model (Fig. 3*f*).



a test temperature; *b* N

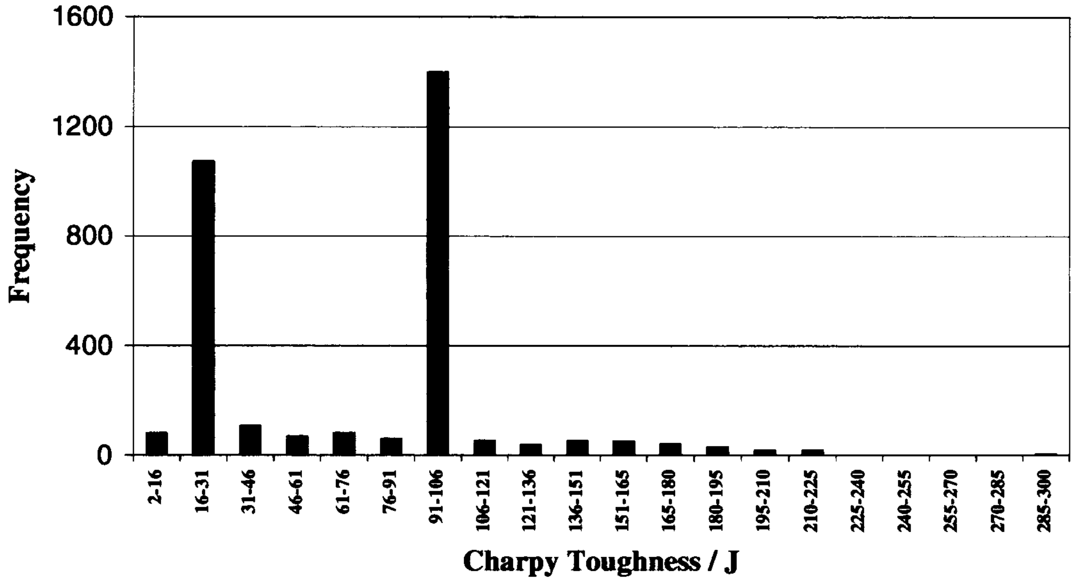
10 Additional variables used in Charpy toughness model

The details of all these procedures are described elsewhere.[1] Figure 4 shows the significance σ_w of each of the input variables. The behaviour of the committee model in making predictions for specific cases is discussed below for C–Mn weld metals.

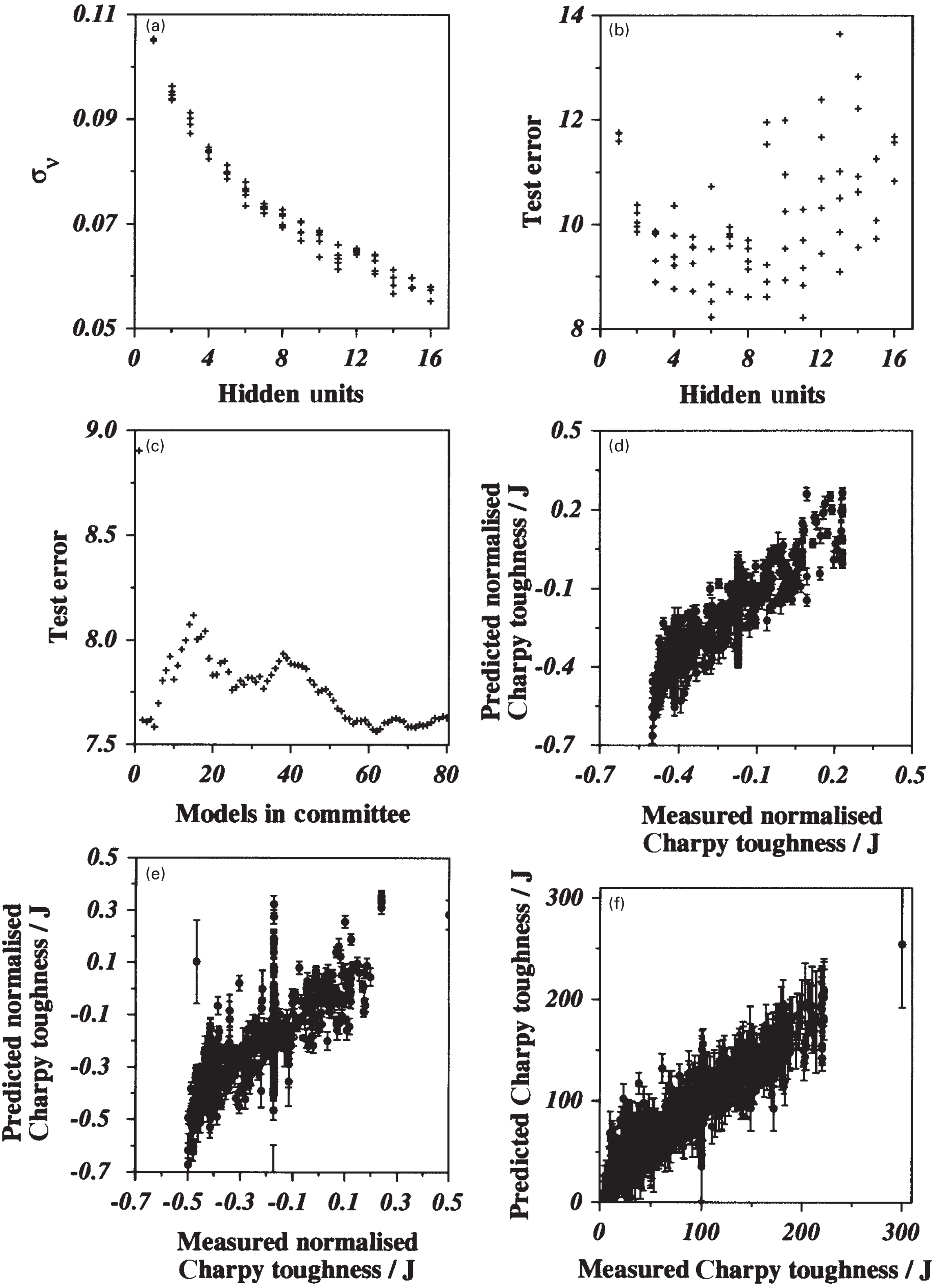
Application to C–Mn weld metal

The set of variables used for analysis is listed in Table 2; any variations illustrated in subsequent figures are about these values. An increase in the strength is expected to lead to a decrease in elongation.[83] It is not surprising, therefore, that the elongation decreases when the manganese and carbon concentrations are increased (Fig. 5). Note also that the effect is more pronounced at higher manganese concentrations, consistent with the corresponding effect on strength (*see* Part 1).

Ductile fracture can be described in terms of the nucleation, growth, and coalescence of voids. Macroscopic fracture occurs when the voids link on a sufficient scale. If the number density of voids is large, then their mean separation is reduced and coalescence occurs rapidly, giving a minimal amount of plastic deformation before fracture, and reducing the overall ductility (Fig. 6).



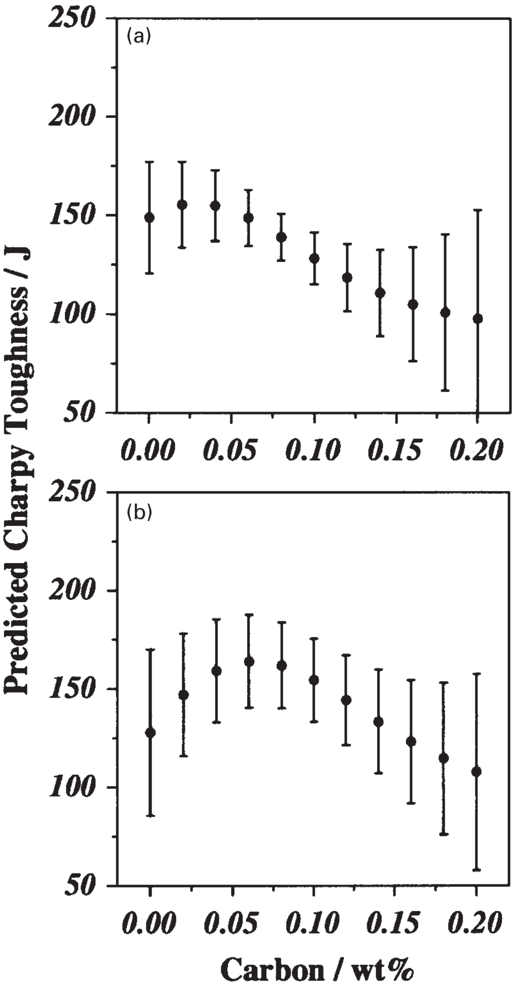
11 Frequency distribution for Charpy toughness data



a σ_v *v.* hidden units; *b* test error *v.* hidden units; *c* test error *v.* models in committee; *d* predicted *v.* measured toughness (training); *e* predicted *v.* measured toughness (test); *f* predicted *v.* measured toughness (optimum committee)

12 Characteristics of Charpy impact toughness model: σ_v is model perceived level of noise in toughness; *d* and *e* represent behaviour of best single model whereas *f* shows performance of optimum committee model on entire dataset

It has generally been assumed that in weld metals both sulphur and oxygen contribute to the inclusion content and, hence, must be detrimental to the toughness. While it is found that an increase in the oxygen concentration definitely reduces the elongation (Fig. 7*a*), the picture for sulphur is not clear. Indeed the data show a slight increase in elongation with an increase in sulphur concentration, but the trend is not meaningful when the error bars are taken into account (Fig. 7*b*). Oxides are the main inclusions in weld metals[84] whereas sulphur tends to be deposited in the



a 1·5%Mn; *b* 0·5%Mn

13 Effect of C at given Mn concentrations on Charpy impact energy, 0°C

form of very thin layers on top of the oxide particles.[85] The observed trends may not therefore be unreasonable in weld metals, as opposed to wrought steels which tend to have a very low oxygen concentration with a predominance of sulphide inclusions.

Another interesting feature of the difference between weld metals and C–Mn type hot rolled steels is revealed by comparing the dataset used in a previous analysis for wrought alloys[86] with the present work on weld metals (Fig. 8). The difference between the yield strength σ_{YS} and ultimate tensile strength σ_{UTS} for welds is approximately constant at 100 MPa, whereas for plates the difference becomes smaller as the strength increases.

The plastic strain ε can be described as a function of strain using a power law of the form

$$\sigma = K\varepsilon^{n} \quad \ldots\ldots\ldots\ldots\ldots\ldots (3)$$

where K and n are constants, the latter being the strain hardening coefficient. As the yield strength is measured at a plastic strain of 0·02, and the ultimate tensile strength (UTS) is given by Kn^{n}, it follows that

$$\sigma_{UTS} - \sigma_{YS} = K(n^{n} - 0{\cdot}02^{n}) \quad \ldots\ldots\ldots (4)$$

Since for the welds $\sigma_{UTS} - \sigma_{YS} \simeq 100$ MPa, it follows that the strain hardening coefficient must be approximately constant for all the welds considered. This in turn means that the uniform strain component of the measured elongation of most ferritic steel welds must be approximately constant, the total elongation being a function mostly of the non-uniform component that occurs beyond necking during a tension test. Of course, the non-uniform component of the elongation depends largely on void nucleation, growth, and coalescence, so it is not surprising that the total elongation depends strongly on inclusions.

Note that this interpretation does not explain why the strain hardening coefficient for welds is approximately constant whereas that of plates is not. This remains an issue for further work.

A further consequence of these observations is that the ratio of the yield to ultimate tensile strengths will increase more rapidly for welds than for plates, which may in turn have consequences on the fatigue properties. The fatigue resistance is generally higher for materials where there is a large difference between the yield and ultimate tensile strengths. Indeed, Fig. 9 shows that, unlike for plate steels, there is less that can be done to control the ratio σ_{YS}/σ_{UTS} in weld metals by alloying.

CHARPY IMPACT TOUGHNESS MODEL

This model was developed with 22 input variables (Table 3), the nitrogen concentration and the test temperature being the additional variables when compared with the elongation model (Fig. 10). The test temperature is expected to be an important variable because of the ductile–brittle transition in ferritic iron, and the nitrogen concentration is known to have an influence via strain hardening effects. Unfortunately, the available Charpy data are not uniformly distributed (Fig. 11), because tests are frequently carried out at specified Charpy toughness values.

The models were created from a dataset containing 3142 individual experiments, and the results are shown in Fig. 12. An optimum committee consisting of 62 of the best models was used in all subsequent analyses.

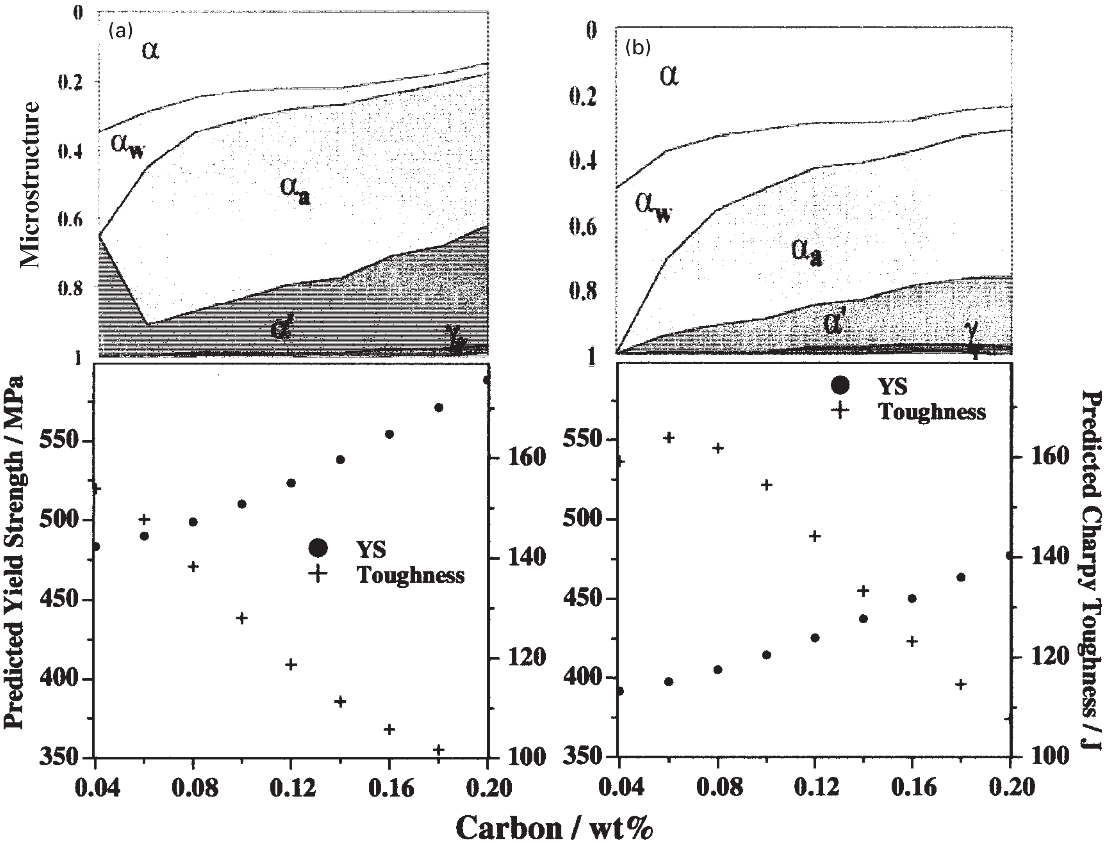
Application to C–Mn weld metal

The reference values of the variables used in making predictions are listed in Table 2. Figure 13 shows the calculated variation in Charpy values at 0°C as a function of the manganese and carbon concentrations. There are two competing effects:

(i) at first an increase in hardenability leads to a replacement of deleterious phases such as allotriomorphic and Widmanstätten ferrite by the desirable acicular ferrite,[84] resulting in an increase in toughness. It is for this reason that the peak in toughness occurs at a higher carbon concentration when the manganese concentration is low. For equivalent hardenability, the carbon concentration must be larger when that of manganese is small

(ii) the strength increases with an increase in manganese and carbon concentration. In general, an increase in strength leads to a deterioration in toughness because plastic flow becomes more difficult, making cleavage cracking more probable. This increase in strength may also be accompanied by the formation of undesirable phases such as martensite. It follows that the toughness should eventually begin to decrease as the carbon or manganese concentration is increased.

Both of these effects are well illustrated by the computed data shown in Fig. 13. The microstructures for the welds described in Fig. 13 were calculated using a published physical model.[87] Figure 14 shows that the above interpretations are correct in that the initial increase in toughness corresponds to an improvement in the microstructure, with the subsequent decrease explained by the increase in strength. Figure 15 shows clearly that, in the



a 1·5%Mn; *b* 0·5%Mn

14 **Effect of C at given Mn concentrations on yield strength and calculated microstructural fraction using published physical model:[31] α allotriomorphic ferrite, α_w Widmanstätten ferrite, α_a acicular ferrite+bainite, α' martensite, γ_r retained austenite**

context of Charpy tests, there is always an optimum combination of manganese and carbon.

Nickel is known to have an intrinsic beneficial effect on toughness by increasing the work necessary to create cleavage cracks.[31] Thus, the toughness at low temperatures is found to increase with the nickel concentration (Fig. 16*a*); however, the optimum concentration of nickel is found to depend significantly on that of manganese. Higher concentrations of nickel are beneficial only at low concentrations of manganese (Fig. 16*b*) because both elements enhance the hardenability and strength of the weld deposit.

As might be expected, Fig. 17*a* shows that the toughness at 0°C decreases with an increase in the oxygen concentration; oxides are sites for the nucleation of cracks and voids. The toughness can nevertheless be optimised by selecting the appropriate manganese concentration, 0·7 wt-% in the case illustrated. This is because low manganese concentrations lead to deleterious microstructures whereas too high a concentration raises the weld strength. Figure 17*b* shows that the toughness is maximised when the manganese/silicon ratio is ~2 : 1. This may be connected with deoxidation practice, but the details are not understood.

CONCLUSIONS

It is possible to create reasonable neural network models for the tensile elongation and Charpy impact energy properties of ferritic steel welds. The models take into account the chemical composition, heat treatment, and a number of welding parameters. The models are based on large experimental databases. However, significant deficiencies exist in the data, which are not uniformly distributed in the input space. Further work is needed to generate systematically new data for a future analysis.

The models used for these predictions can be obtained freely from http://www.msm.cam.ac.uk/map/map.html.

ACKNOWLEDGEMENTS

The authors are grateful to the Cambridge Commonwealth Trust for funding this work and to K. Mitchell of National Power for further financial support. They would also like to acknowledge Professor A. Windle of the University of Cambridge for the provision of laboratory facilities.

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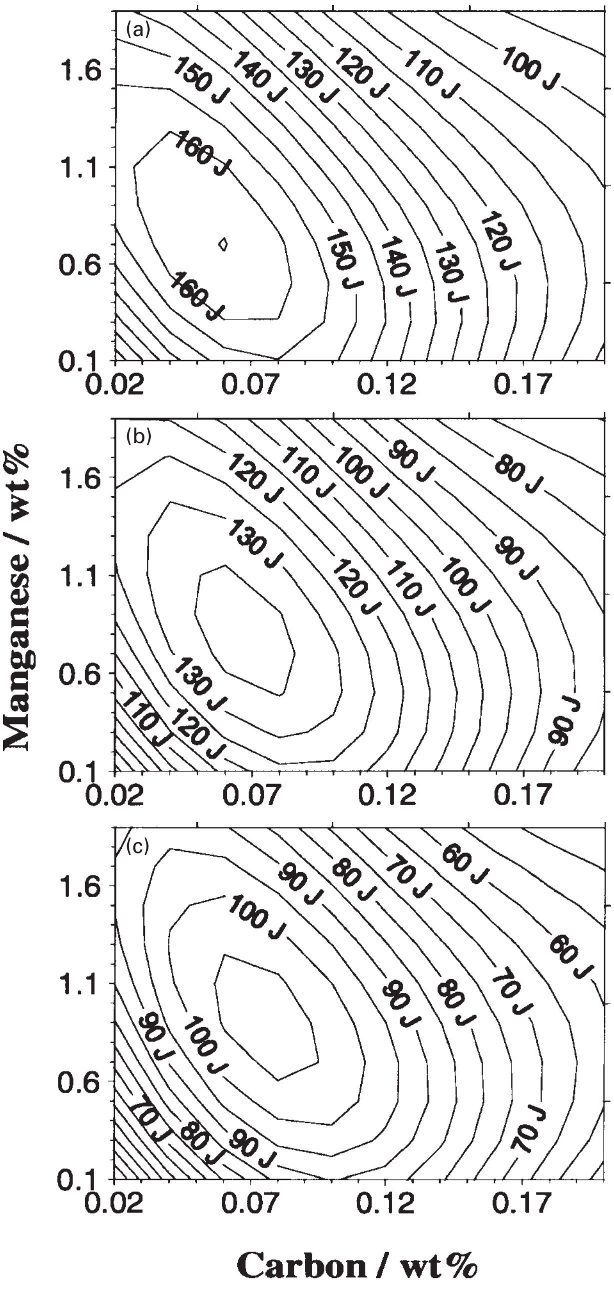
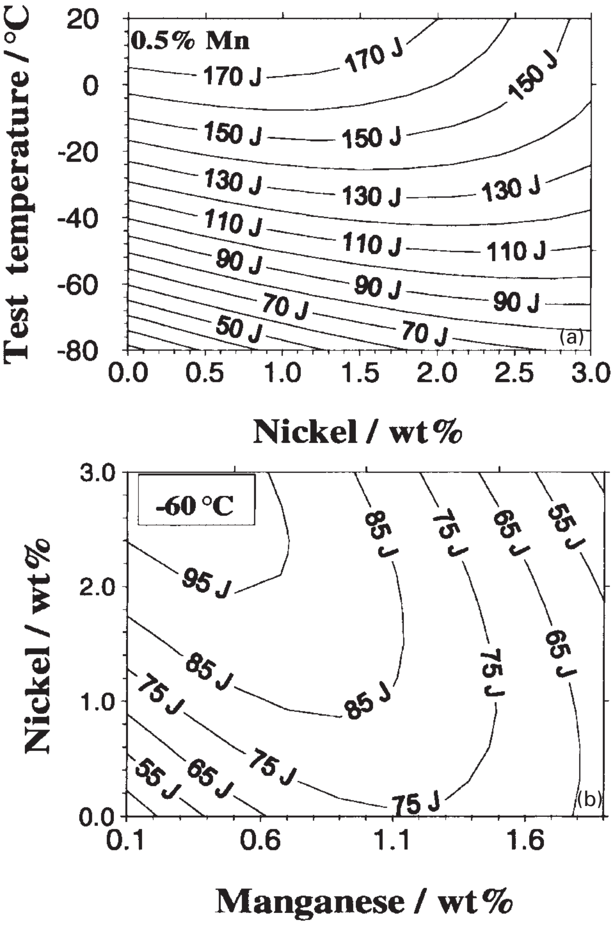


a 0°C; *b* −20°C; *c* −40°C

15 Predicted variations in Charpy toughness as function of C and Mn concentrations and test temperature: error bars have been omitted for clarity but range ±10–45 J



a Ni improves toughness at low temperatures; *b* optimum concentration of Ni depends on Mn concentration

16 Effect of Ni and Mn on Charpy toughness: error bars have been omitted for clarity but range ±10–25 J

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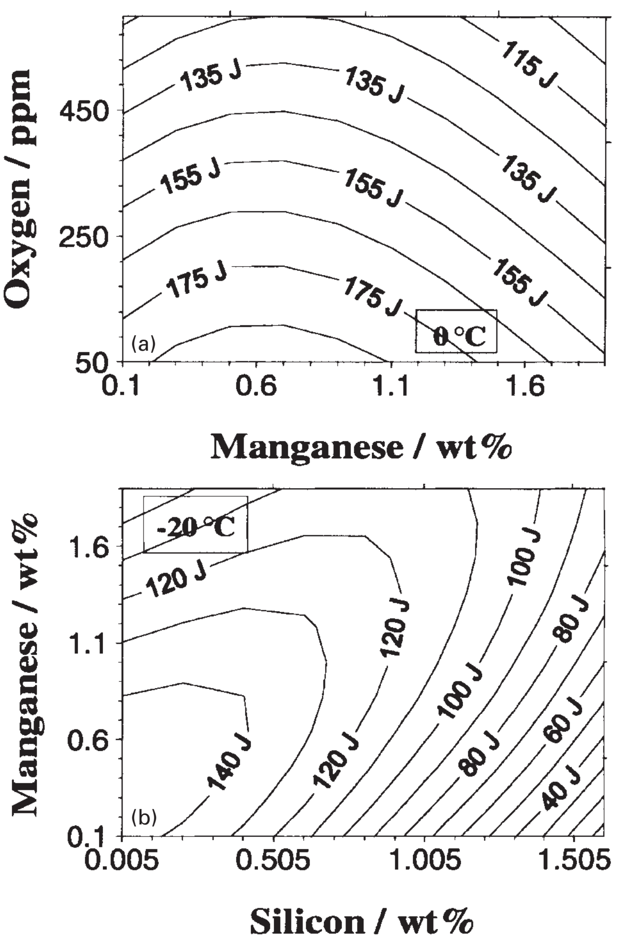

a Mn and O; *b* Mn and Si

17 Combined effects of given additions on toughness: error bars have been omitted for clarity but range ±10–60 J

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