Appendix A

Estimation of Mechanical Properties of C–Mn Weld Metals, Avoiding Systematic Errors

In Chapters 4 and 5 essential mechanical properties of ferritic steel welds were modelled using neural network technique within a Bayesian framework. The data were collected from the published literature. As such the data originated from many different laboratories and possibly contained a variety of sources of experimental errors. By contrast, the data exploited here were on carbon–manganese and low–alloy steel welds from a single source (Evans [54]). It should therefore be possible to avoid unspecified systematic errors of the kind associated with a particular laboratory.

A.1 The Electrode Production

To study the effect of an element on the mechanical properties of weld metal requires high purity electrodes with accurate compositional control. It is very difficult to reproducibly maintain the transfer of alloying elements with conventional electrodes. The data used in the present work came from electrodes are specially manufactured with great care to detail. Rimmed steel with an average chemical composition shown in Table A.1 was selected as the core wire of an electrode. The flux contains 25% iron powder is selected and systematically mixed with other minerals to add microalloying elements which are to be studied and to keep some alloying elements such as Al, B, Nb, V and Ti below 0.0005 wt% in the final weld metal [2]. The multirun weld metal was made with three passes per layer, keeping dilution with the base metal to a minimum.

A.2 The Database

Around 720 individual experimental data of carbon–manganese multipass steel welds were compiled. The process used was shielded (manual) metal arc welding. The heat input was

Element	
Carbon (wt%)	0.07
Manganese (wt%)	0.50
Silicon (wt%)	0.008
Sulphur (wt%)	0.006
Phosphorus (wt%)	0.008
Titanium (p.p.m.)	4
Boron (p.p.m.)	2
Aluminum (p.p.m.)	15
Nitrogen (p.p.m.)	25
Oxygen (p.p.m.)	200
Chromium (wt%)	0.02
Nickel (wt%)	0.03
Molybdenum (wt%)	0.003
Vanadium (p.p.m.)	5
Copper (wt%)	0.02
Niobium (p.p.m.)	5

Table A.1: The average chemical composition of the core wire used to manufacture the electrode used in the present study. ‘p.p.m.’ corresponds to parts per million.

1.0 kJ mm^{-1} and the interpass temperature was 200 °C. With the exception of the Charpy impact toughness test samples, all of the other weld samples were given hydrogen removal heat treatments (200 °C for 14 h). All these experiments were done under identical conditions and data were measured by Evans [54]. The chosen input variables are tabulated in Table A.2; other variables such as heat input did not vary and hence were not included in the analysis. The input set was identical for all six models yield strength (YS), ultimate tensile strength (UTS), elongation, reduction in area and the Charpy impact toughness transition temperature at 100 J ($\mathrm{T}_{100\mathrm{J}}$) and 28 J ($\mathrm{T}_{28\mathrm{J}}$). Table A.2 shows the range, mean and standard deviation of all variables involved in model development.

The data distribution of each individual element with respect to yield strength are graphically represented in Figs A.1 and A.2. The output parameters UTS, elongation, reduction in area, $\mathrm{T}_{100\mathrm{J}}$ and $\mathrm{T}_{28\mathrm{J}}$ were plotted against YS in Fig. A.2. As discussed in Section 5.1.1, it was found that the difference in UTS and YS is constant. The higher strength welds will have a lower ductility. This can be found in elongation and reduction in area plots (Fig. A.2); it can be seen that the increase in yield strength leads to reduction in ductility.

Input element	Minimum	Maximum	Mean	Standard deviation
Carbon (wt%)	0.035	0.152	0.071	0.012
Manganese (wt%)	0.23	2.10	1.27	0.40
Silicon (wt%)	0.01	1.11	0.348	0.112
Sulphur (wt%)	0.003	0.046	0.0065	0.003
Phosphorus (wt%)	0.003	0.040	0.008	0.0027
Titanium (p.p.m.)	2.0	1000	105.7	142.62
Boron (p.p.m.)	1.0	200.0	16.5	39.4
Aluminum (p.p.m.)	1.0	680.0	38.7	108.0
Nitrogen (p.p.m.)	35.0	270.0	92.9	47.4
Oxygen (p.p.m.)	217.0	1180.0	398.1	90.1
Chromium (wt%)	0.03	3.5	0.166	0.50
Nickel (wt%)	0.03	5.48	0.34	1.05
Molybdenum (wt%)	0.005	1.16	0.068	0.228
Vanadium (p.p.m.)	3.0	2873.0	60.93	270.3
Copper (wt%)	0.02	2.04	0.076	0.251
Niobium (p.p.m.)	3.0	980.0	23.8	98.2
Yield strength (MPa)	350	1026	517.0	89.8
Ultimate tensile strength (MPa)	404	1123	588.9	90.0
Elongation (%)	10.5	35.8	25.6	3.9
Reduction in area (%)	21	87.8	75.3	5.3
Temperature (T_{100J}) at 100 J (°C)	-89	45	-42.0	23.3
Temperature (T_{28J}) at 28 J (°C)	-114	53	-67.3	20.9

Table A.2: The weld metal chemical composition used as input parameters and output variables to develop models. 'p.p.m.' corresponds to parts per million.

A.3 The Models

Six individual committee models for YS, UTS, elongation, reduction in area, T_{100J} and T_{28J} were developed. The committee model development procedure is similar for all these mechanical properties (Chapter 3). As the number of hidden units increases, the perceived level of noise σ_ν reduces, Fig A.3. It is interesting to note that the noise level is much lower than that of the levels found in the previously developed models (Chapter 4 and 5). This is because of the database comes from a single source. The other characteristics (log predictive error and test error) are shown in Fig. A.3. The details of the development of the neural network models are excluded for clarity, the procedure used is explained in Chapter 3.

A.4 The Analysis

The relevant input variables used to study the trends are shown in Table A.3. When the carbon concentration in weld metal is increased from 0.01 wt% to 0.07 wt%, there is an improvement

Input variable	
Carbon (wt%)	0.07
Manganese (wt%)	1.50
Silicon (wt%)	0.50
Sulphur (wt%)	0.006
Phosphorus (wt%)	0.008
Titanium (p.p.m.)	2.0
Boron (p.p.m.)	1.0
Aluminum (p.p.m.)	1.0
Nitrogen (p.p.m.)	80.0
Oxygen (p.p.m.)	300.0
Chromium (wt%)	0.03
Nickel (wt%)	0.03
Molybdenum (wt%)	0.005
Vanadium (p.p.m.)	3.0
Copper (wt%)	0.02
Niobium (p.p.m.)	3.0

Table A.3: Relevant inputs used to analyse mechanical properties of carbon–manganese weld metal. 'p.p.m.' corresponds to parts per million.

in mechanical properties, this is due to an initial improvement in microstructure [144]. In this range carbon promotes desirable acicular ferrite microstructure content at the expense of allotriomorphic ferrite and Widmanstätten ferrite. At higher carbon levels there is a decrease in toughness due to an increase in strength without improvement in microstructure. The effect of increasing carbon content is shown in Fig. A.13, as expected, carbon increases the strength and decreases the ductility of the weld metal. The amount of increase depends on other acicular ferrite promoting alloying elements such as manganese, molybdenum, nickel and chromium. Fig. A.14 shows that manganese improves toughness in the initial stages by decreasing the transition temperature, as well as increasing strength. The combined effects of carbon and manganese are shown in Fig. A.15. It is interesting to note that there is a gradual decrease in toughness and then an increase with increasing in carbon and manganese content. This is because, that at higher carbon and manganese levels, the acicular ferrite fraction increases, this is shown in Table A.4. These calculations were done using a published semi–empirical model [90], which enables us to calculate microstructural fractions in multirun welds. Here it can be noticed that the acicular ferrite and bainite microstructural fractions increased from 0.31 to 0.72 as the carbon content changed from 0.04 wt% to 0.14 wt% in 2.0 wt% manganese weld metal, even though there was an increase in strength. On the other hand, in 0.5 wt% manganese the amount of acicular ferrite and bainitic microstructure is less than in 2.0 wt% manganese.

Carbon (wt%)	Manganese (wt%)	Allotriomorphic ferrite	Widmanstätten ferrite	Acicular ferrite and Bainite	Yield strength (MPa)
0.04	0.5	0.73	0.19	0.08	397
0.14	0.5	0.30	0.11	0.52	440
0.04	2.0	0.41	0.27	0.31	523
0.14	2.0	0.14	0.03	0.72	587

Table A.4: The microstructural fractions in carbon–manganese weld metal calculated using physical model [90].

It is well known fact that nickel improves low temperature toughness by increasing the stacking fault energy and making flow of dislocations easier, thereby discouraging cleavage fracture. In Section 5.2 it was found that nickel improves low–temperature toughness at lower manganese concentrations only. This was predicted by this model, Fig. A.16 shows that at lower manganese levels both the strength and toughness are increasing. When comparing the effect of nickel in 0.5 wt% and 1.5 wt% manganese welds (Fig. A.17) at the same strength, an increase in nickel concentration causes deterioration in toughness at higher manganese contents, whereas at lower manganese content it improves toughness.

A comparative analysis was done between the predictions made by a previously Charpy impact toughness model (Section 5.2) and the present carbon–manganese models. Figs A.18 and A.19 show that at lower manganese contents nickel is effective in improving the low–temperature toughness. Here the error bars cannot be compared as their units are different. This has shown that even though the Charpy impact toughness model was developed on a wide variety of weld metals, it is able to fit a non–linear function for a particular system of weld metals without affecting predictions over other classes of weld metals.

In weld metal, titanium forms oxides and protects boron (if added) from atmospheric oxygen [145, 95]. These oxides act as nucleation sites for the formation of acicular ferrite. Titanium being a strong carbide former, increases the strength by precipitation hardening. Fig. A.20 shows the expected trends, toughness was improved with initial small additions of titanium.

Oxygen forms oxide inclusions in weld metal, at low levels of oxygen in weld metal these inclusions are beneficial in promoting acicular ferrite in the presence of oxide forming elements such as titanium. At higher levels of oxygen, the increased density of oxides assists fast propagation of cracks, thereby reducing the overall ductility. Acicular ferrite microstructure offers more resistance to crack propagation, therefore the crack has to travel a greater distance before it reaches the critical length which leads to fracture. The effect of titanium in presence of varying amounts of oxygen is shown in Fig. A.21. Initial small additions of titanium promote acicular ferrite, thus increasing toughness.

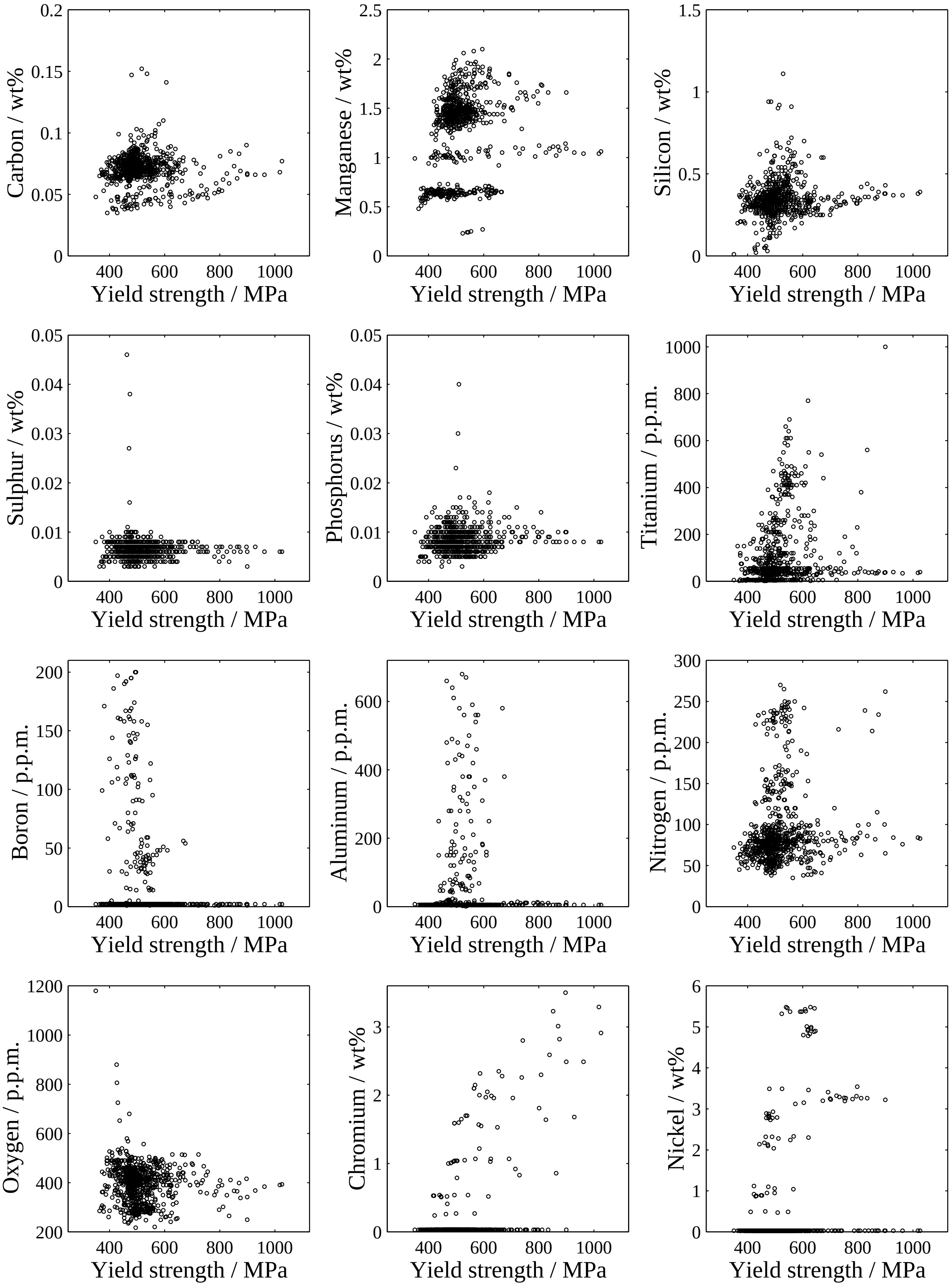

Figure A.1: The data distribution plotted against yield strength. 'p.p.m.' corresponds to parts per million by weight.

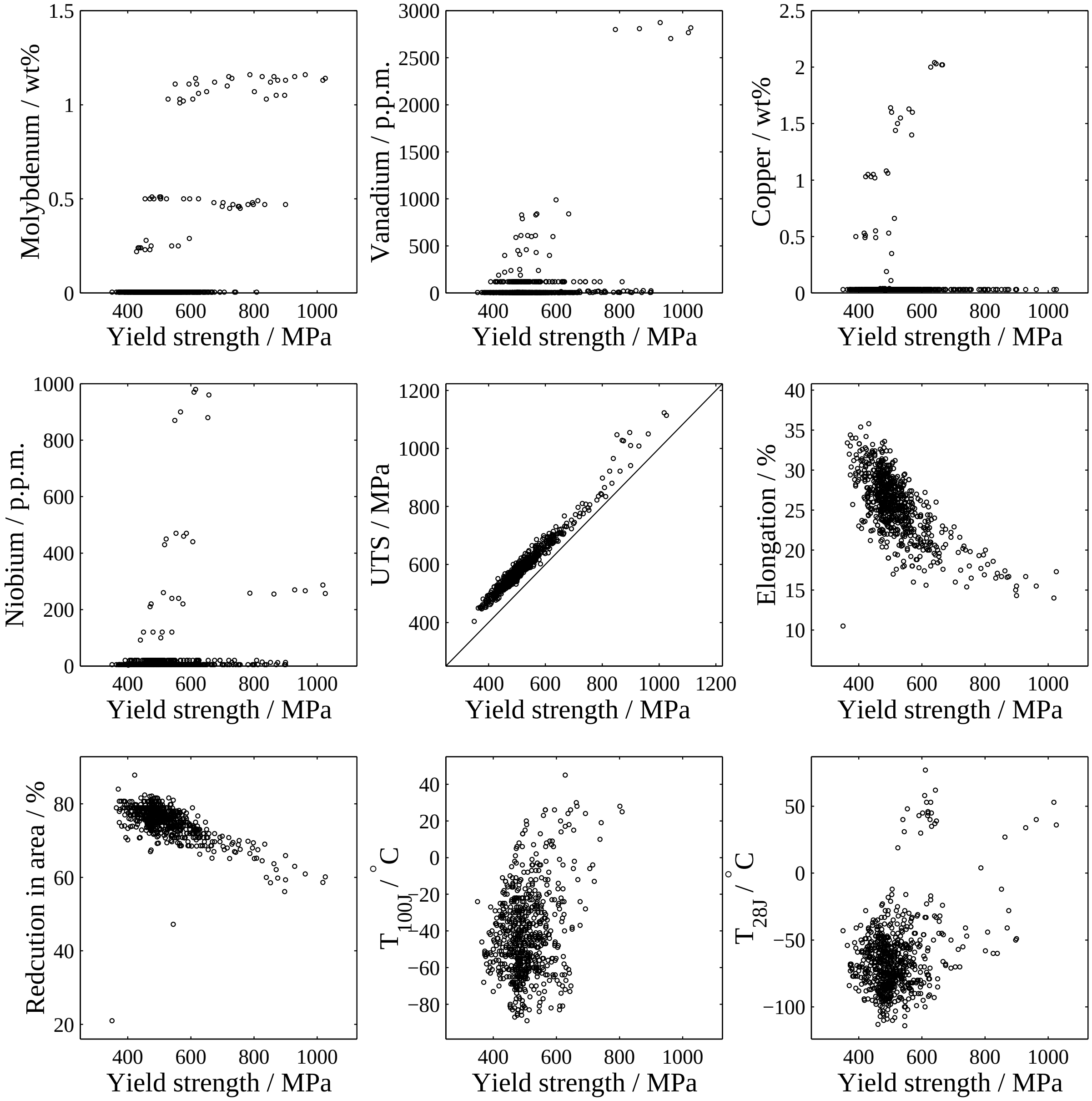

Figure A.2: Distribution of molybdenum, vanadium, copper, niobium against yield strength. The spread of UTS, elongation, reduction in area, T_{100J} and T_{28J} plotted against yield strength. 'p.p.m.' corresponds to parts per million by weight.

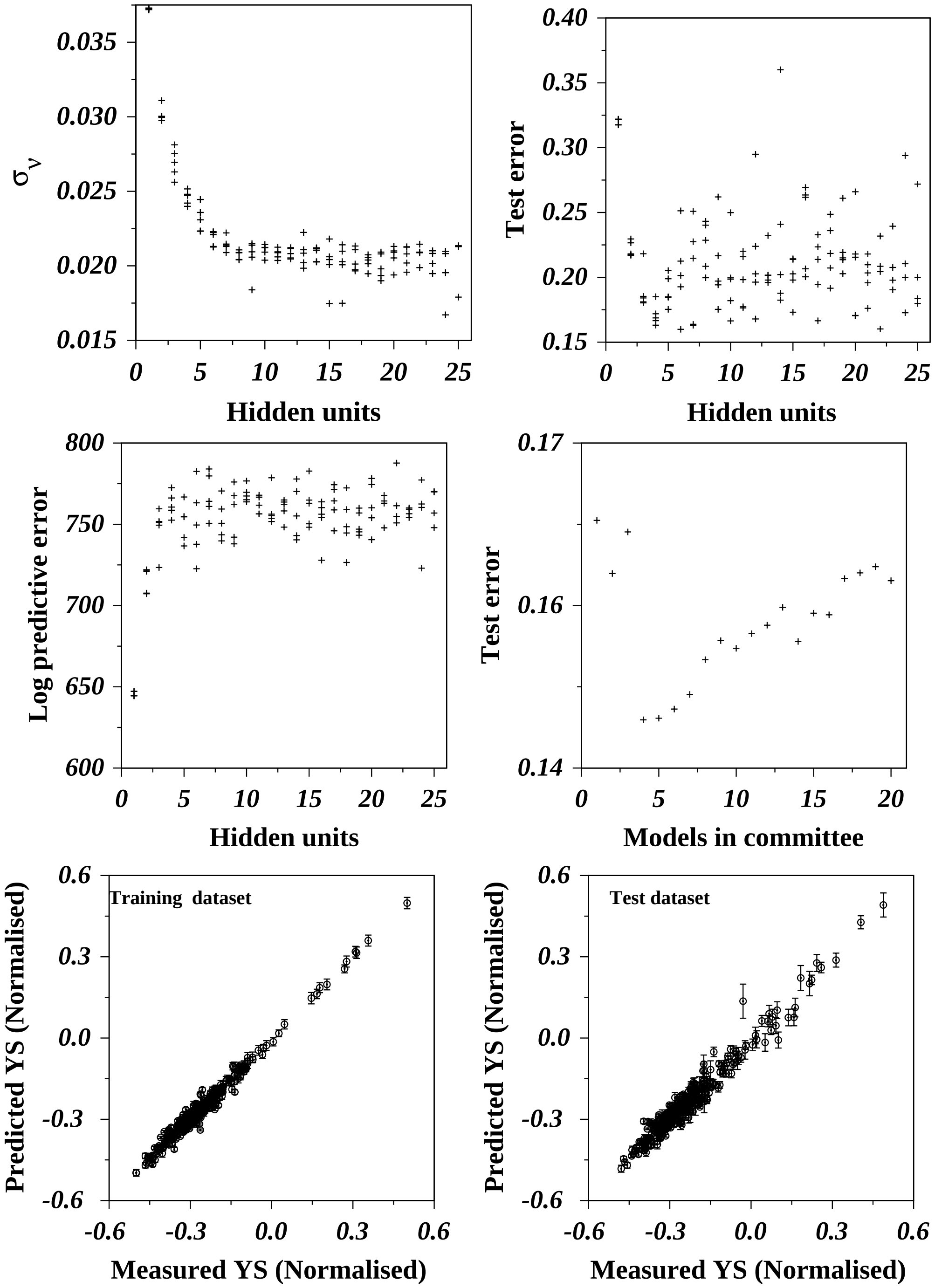

Figure A.3: Characteristics of the yield strength model.

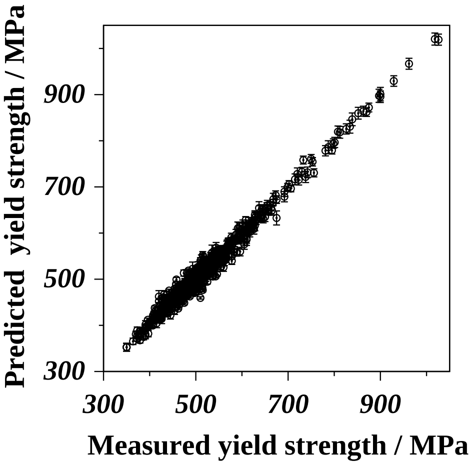

Figure A.4: Characteristics of the yield strength model.

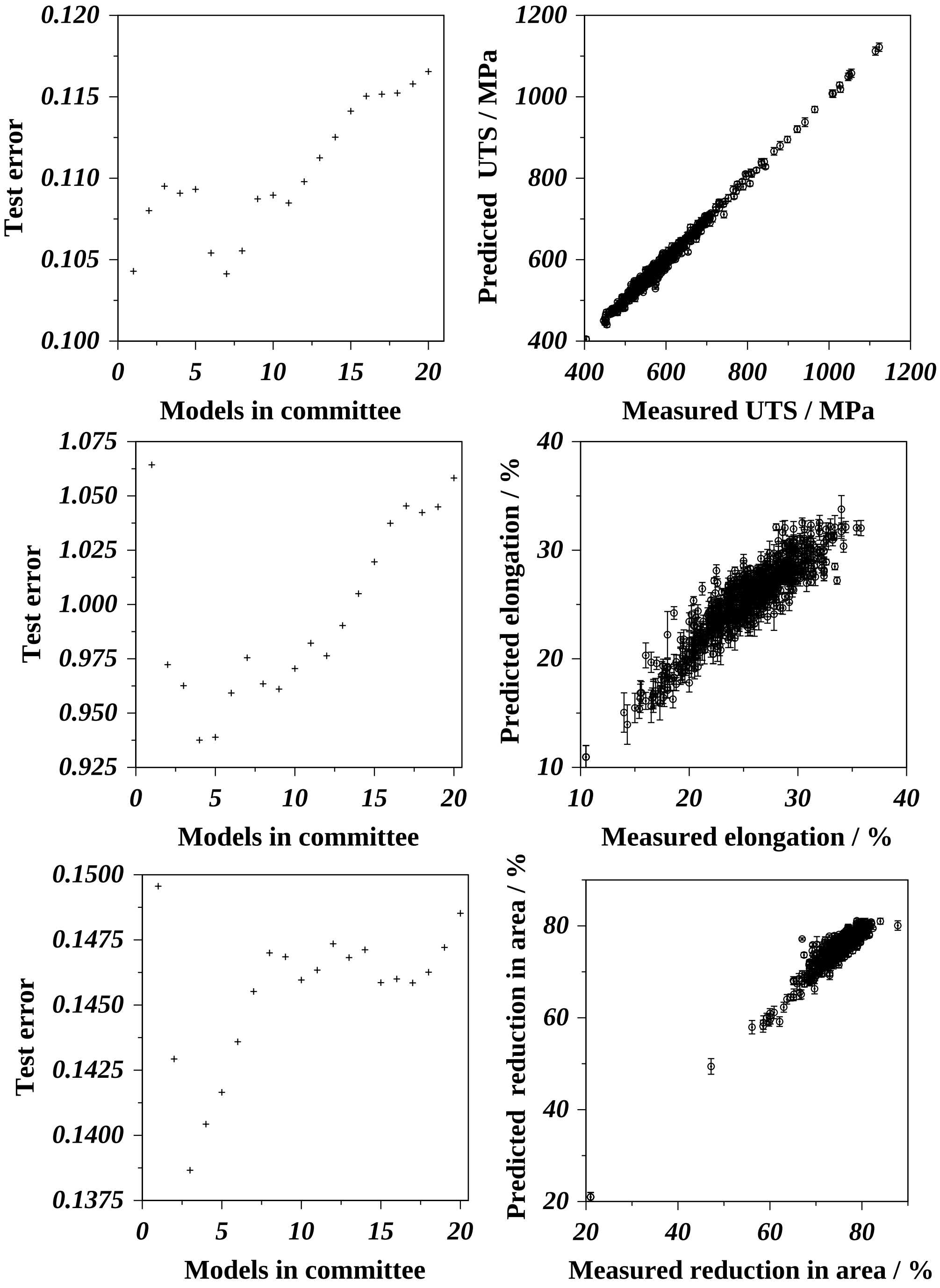

Figure A.5: Characteristics of the ultimate tensile strength, elongation and reduction in area models.

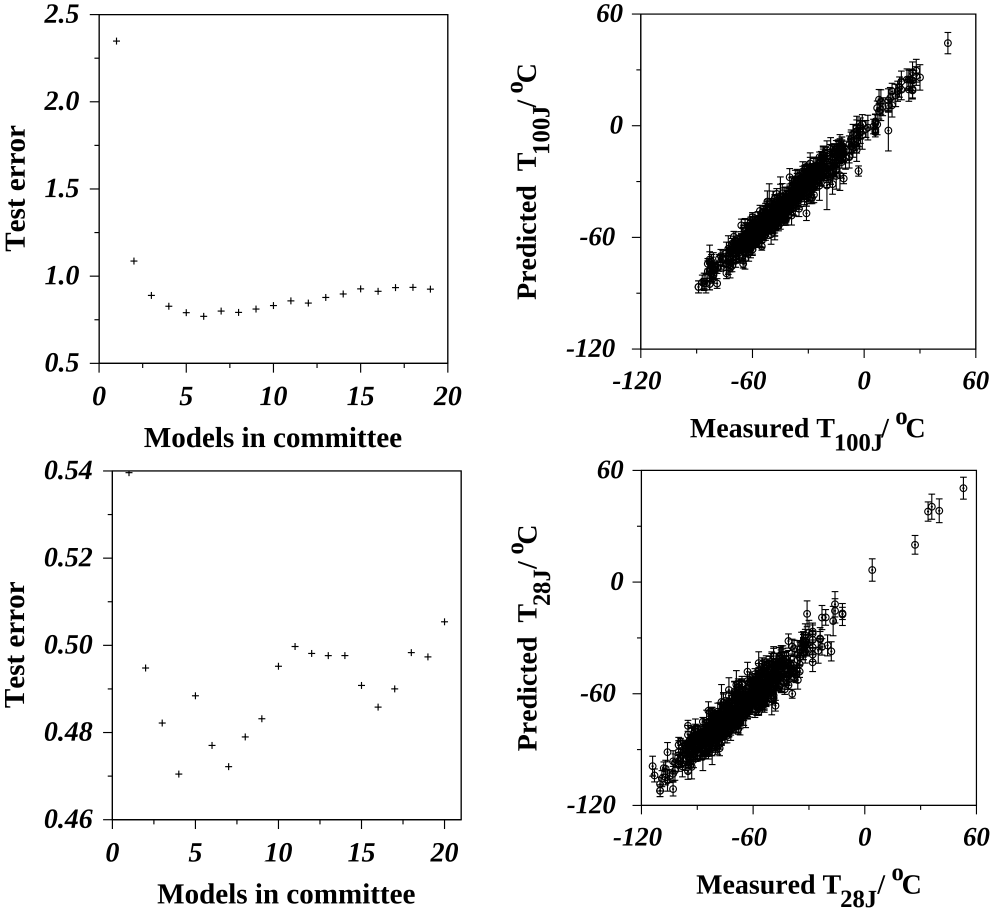

Figure A.6: Characteristics of toughness models, transition temperatures at 100J and 28J of Charpy toughness.

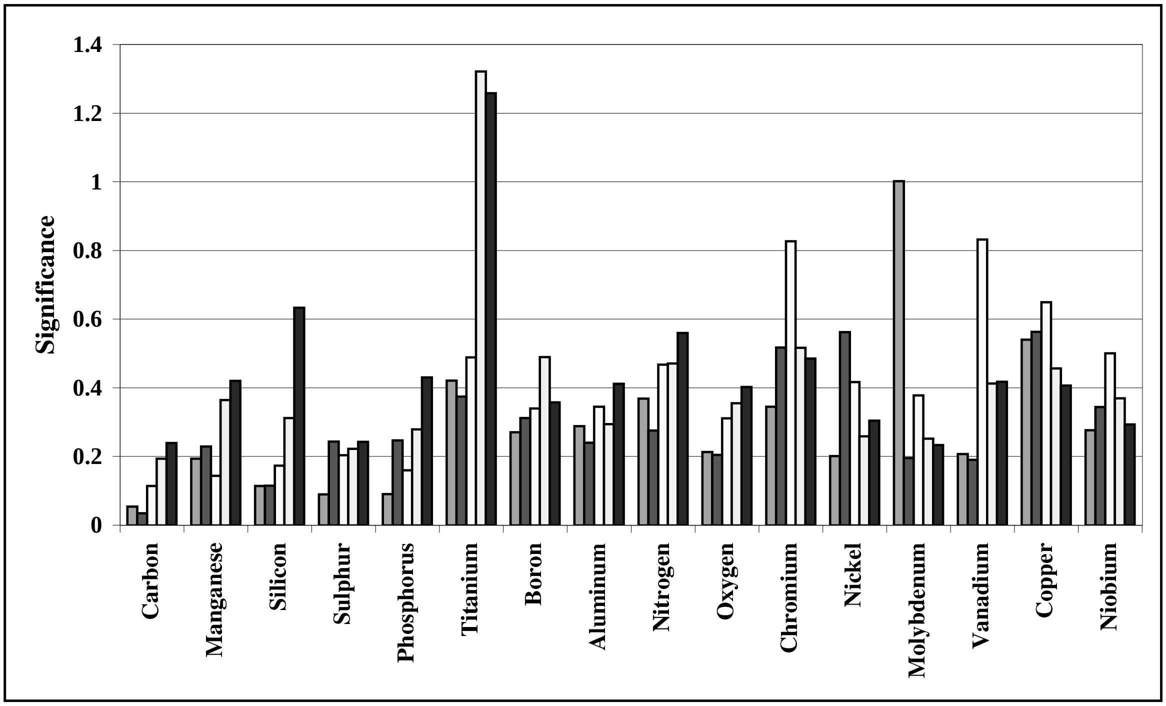

Figure A.7: The perceived significance σ_w values of yield strength committee models for each of the inputs.

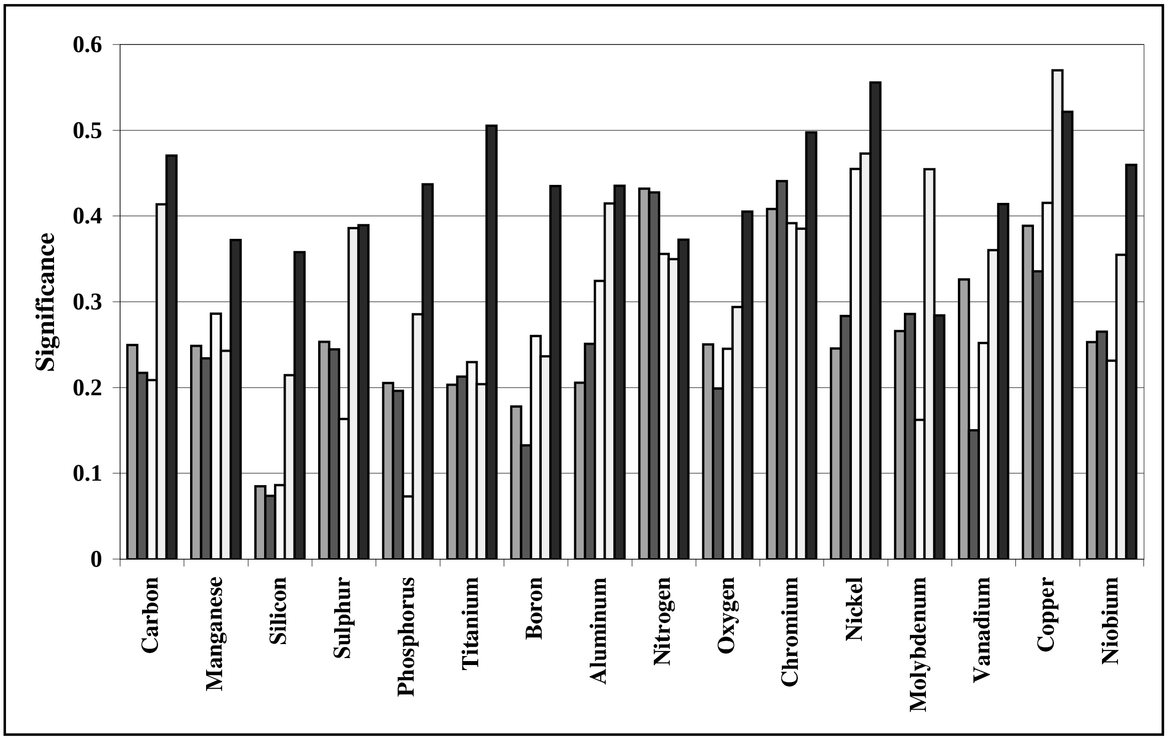

Figure A.8: The perceived significance σ_w values of ultimate tensile strength committee models for each of the inputs.

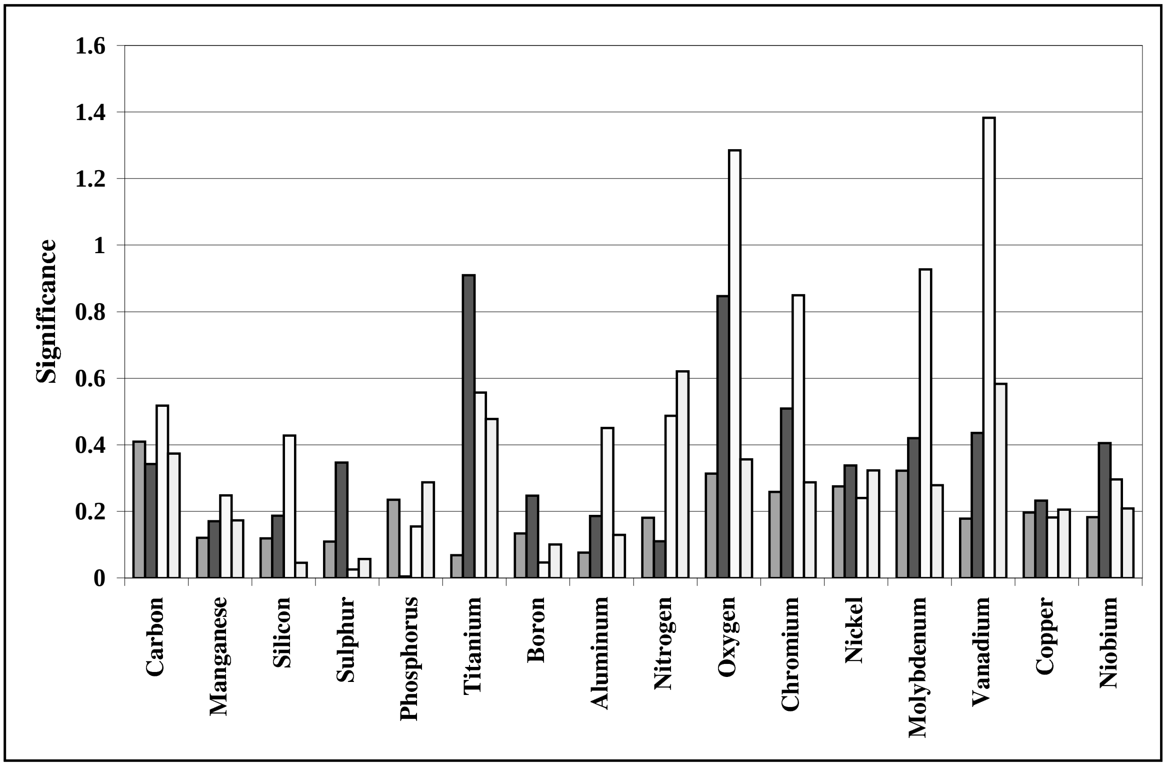

Figure A.9: The perceived significance σ_w values of elongation committee models for each of the inputs.

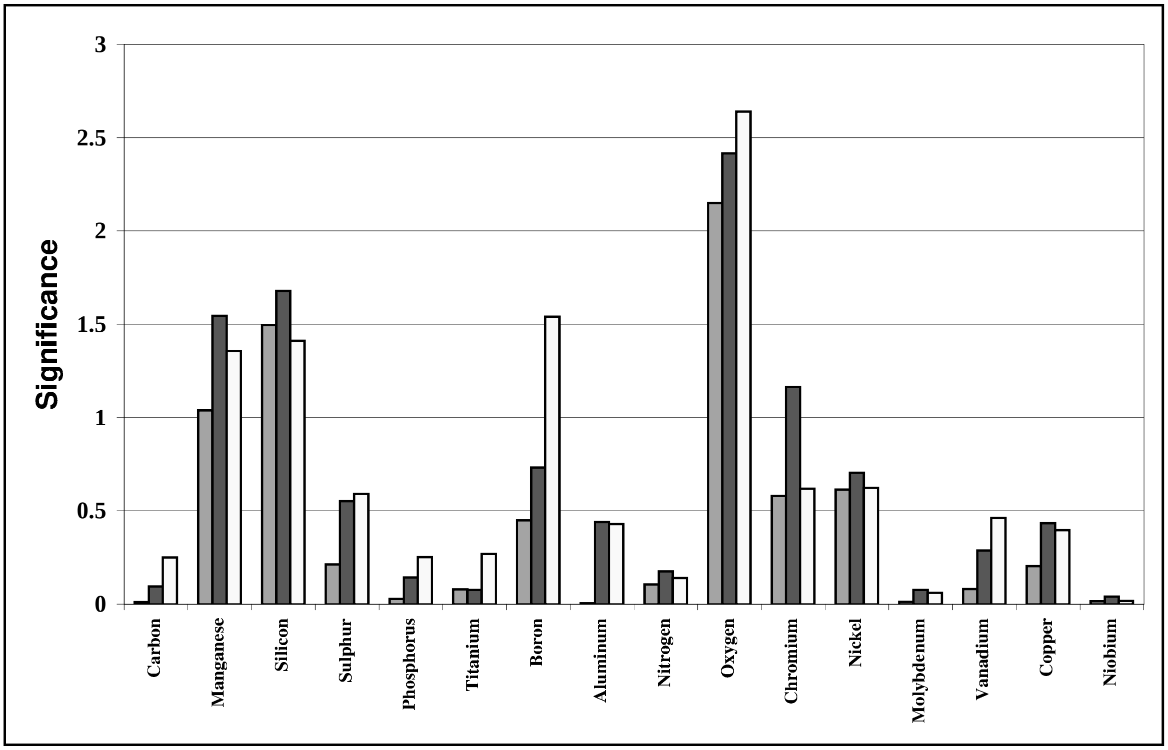

Figure A.10: The perceived significance σ_w values of reduction in area committee models for each of the inputs.

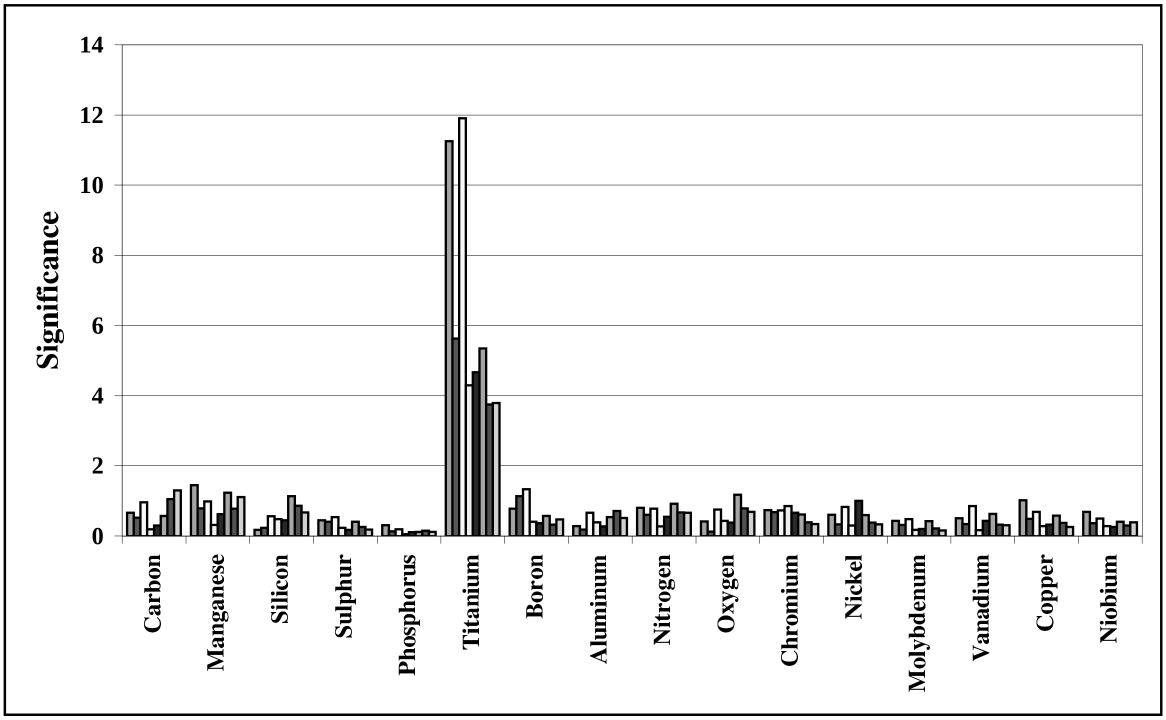

Figure A.11: The perceived significance σ_w values of T_{100J} committee models for each of the inputs.

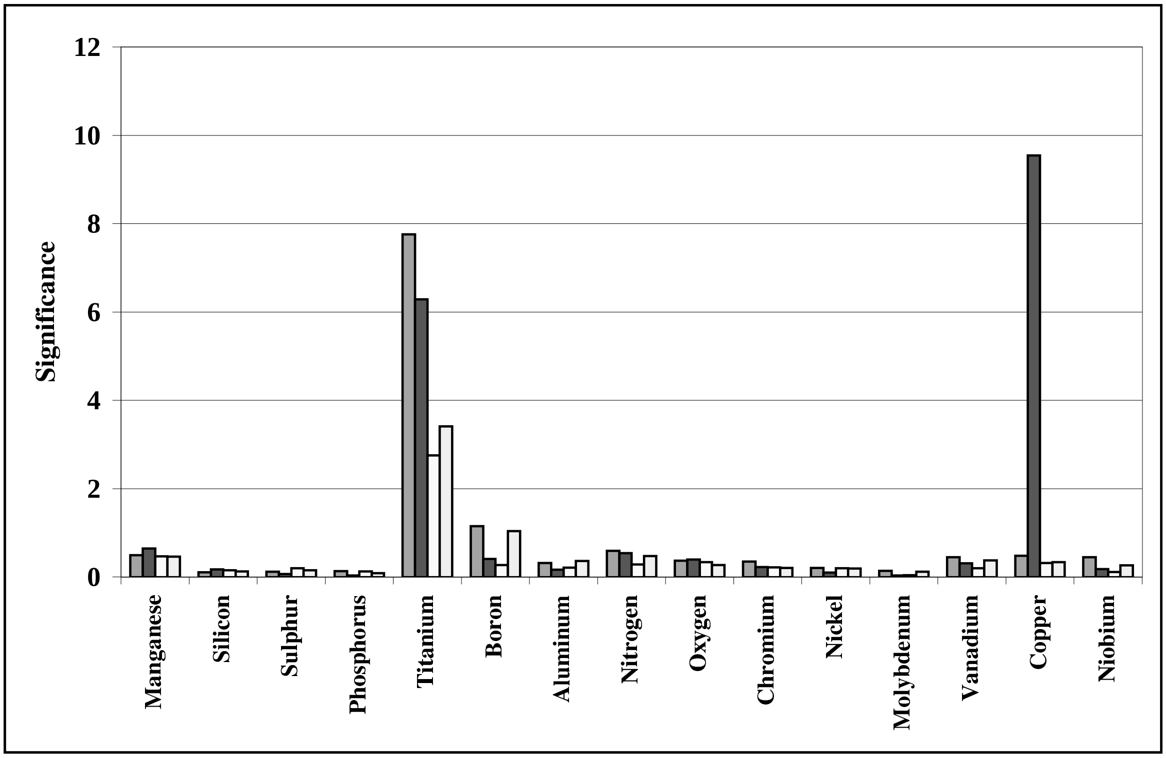

Figure A.12: The perceived significance σ_w values of T_{28J} committee models for each of the inputs.

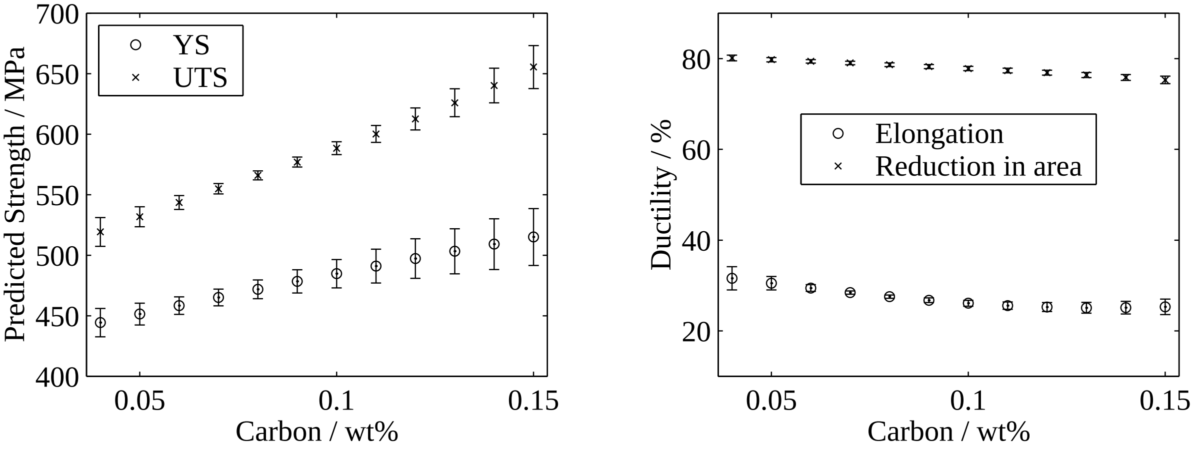

Figure A.13: The calculated effect of carbon on strength and ductility.

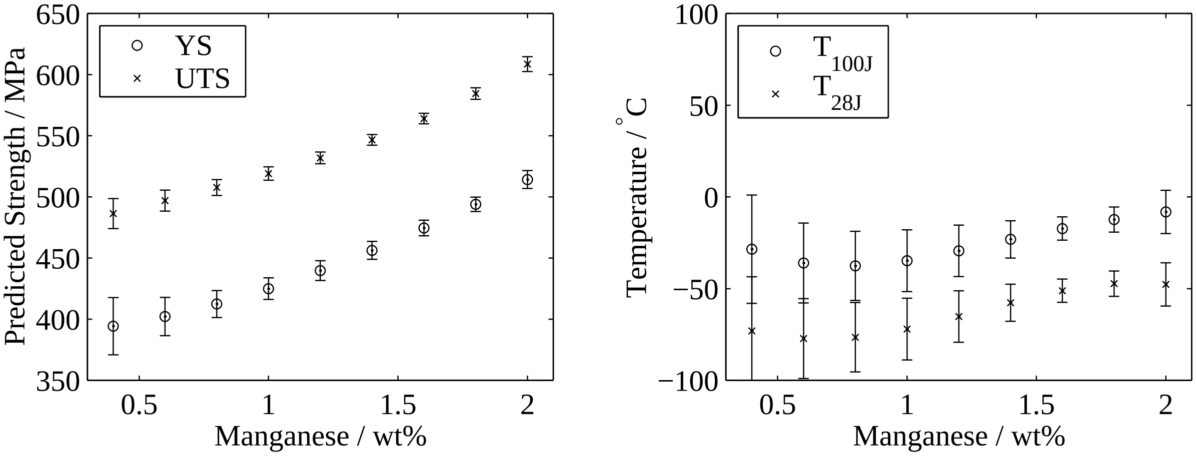

Figure A.14: The effect of manganese on strength and toughness.

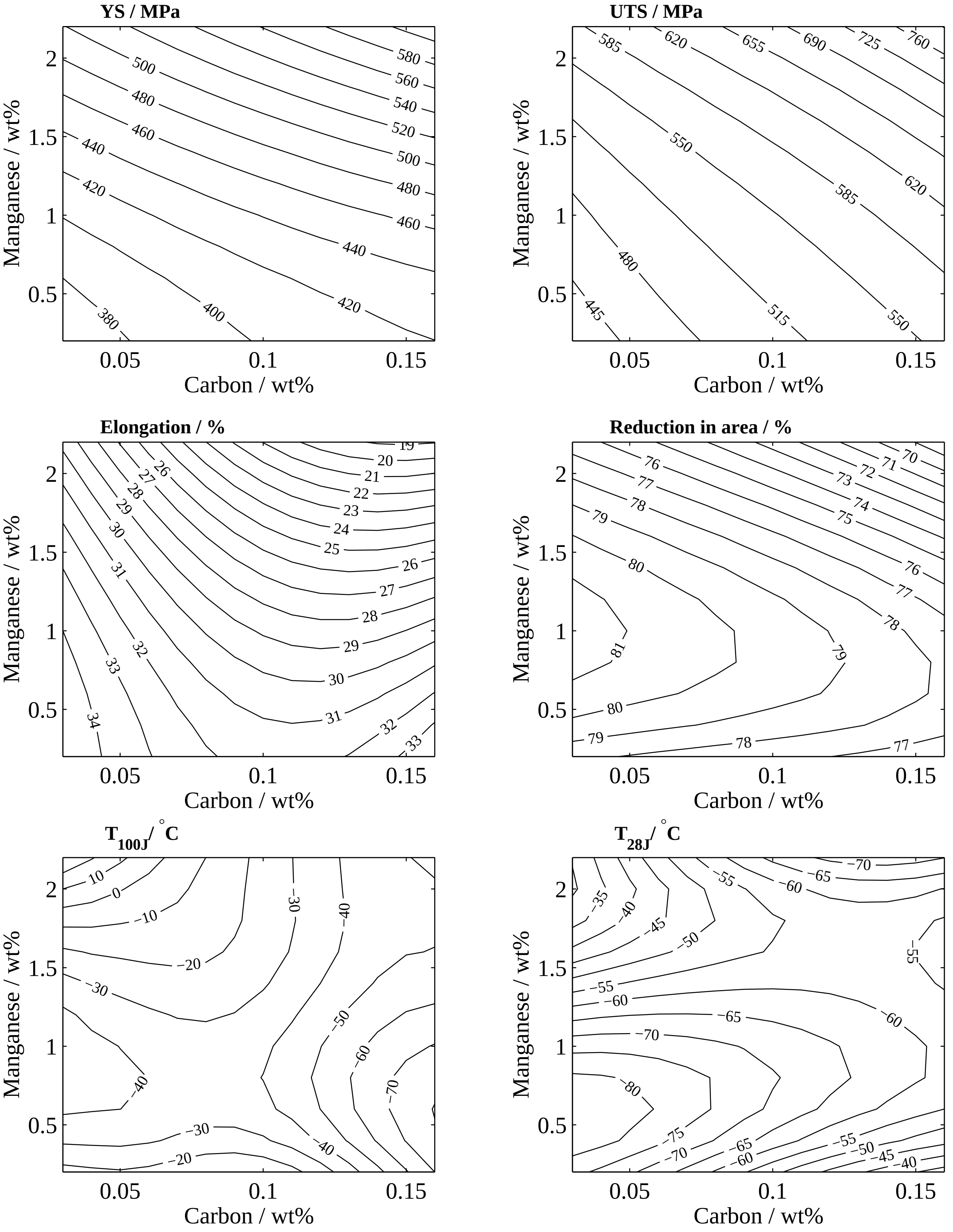

Figure A.15: The combined effect of carbon and manganese on mechanical properties of C–Mn weld metals.

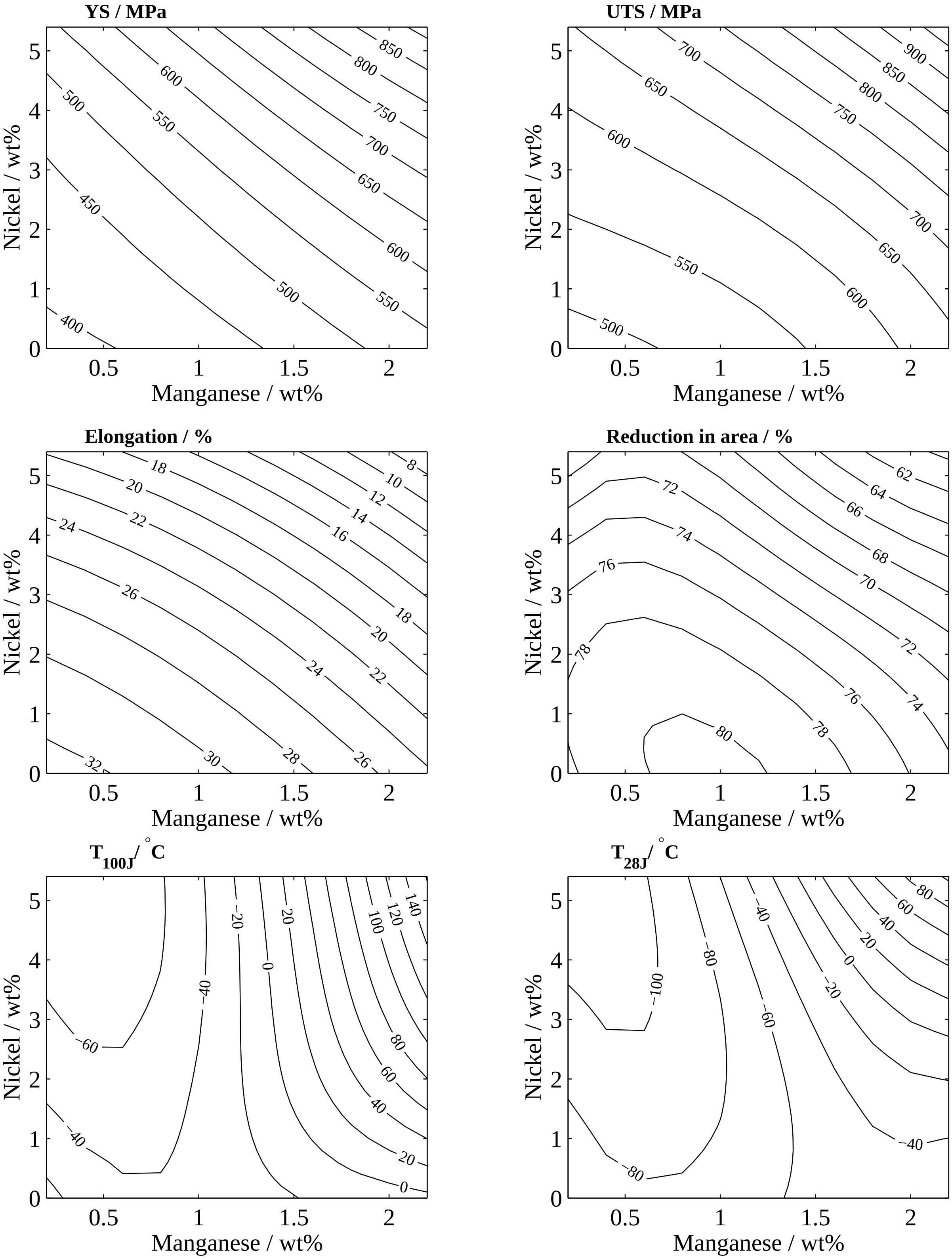

Figure A.16: Calculated mechanical properties of welds with respect to change in nickel and manganese.

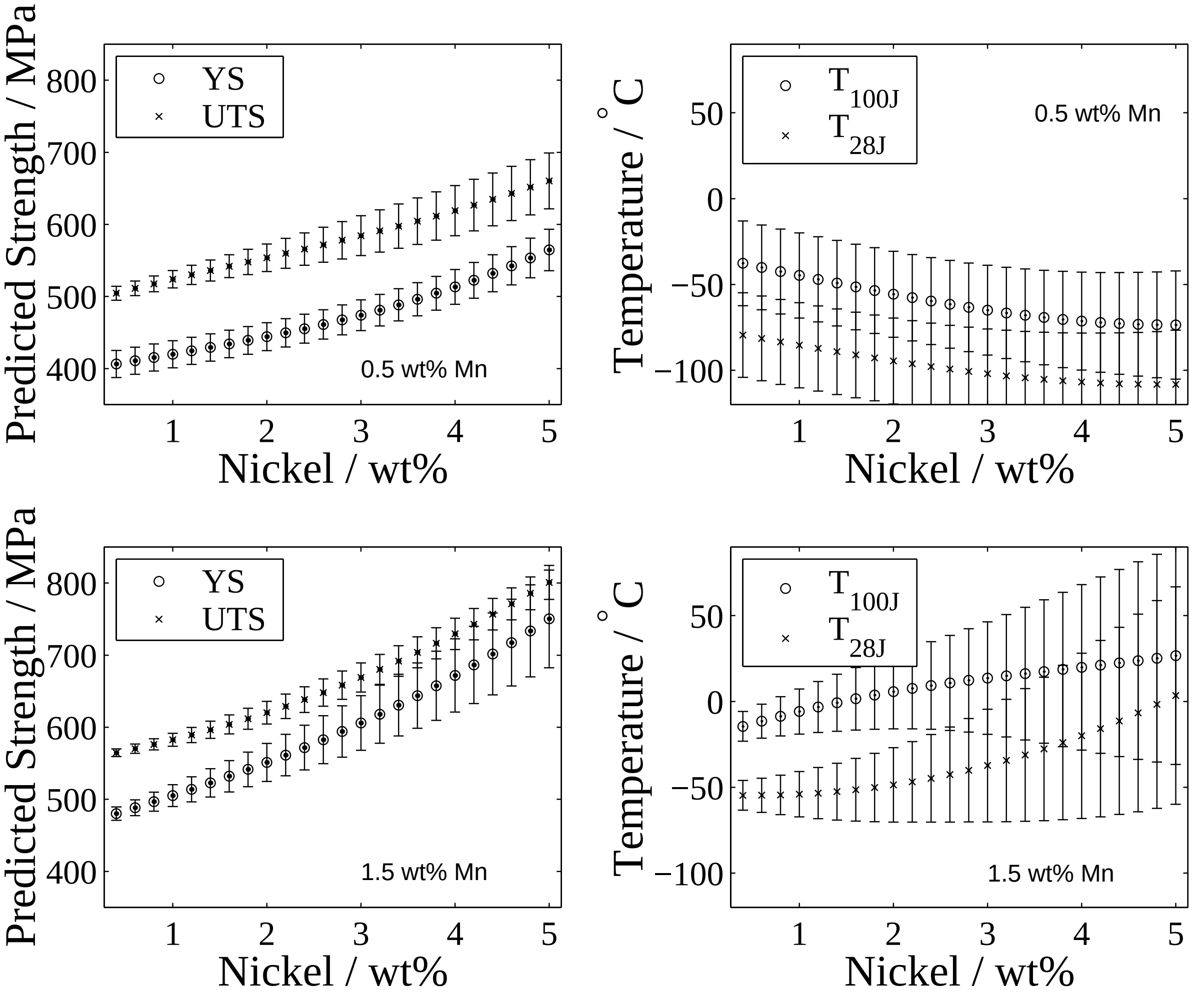

Figure A.17: Calculated strength and transition temperature in 0.5 wt% and 1.5 wt% manganese weld metal.

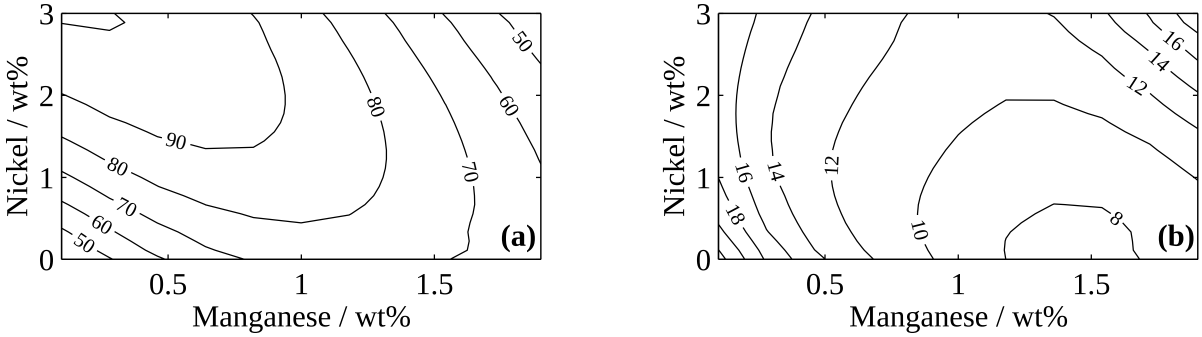

Figure A.18: Calculated Charpy impact toughness of welds with respect to change in nickel and manganese using Charpy impact toughness model (Section 5.2) a) Charpy toughness in Joule, b) the corresponding error bars in Joule.

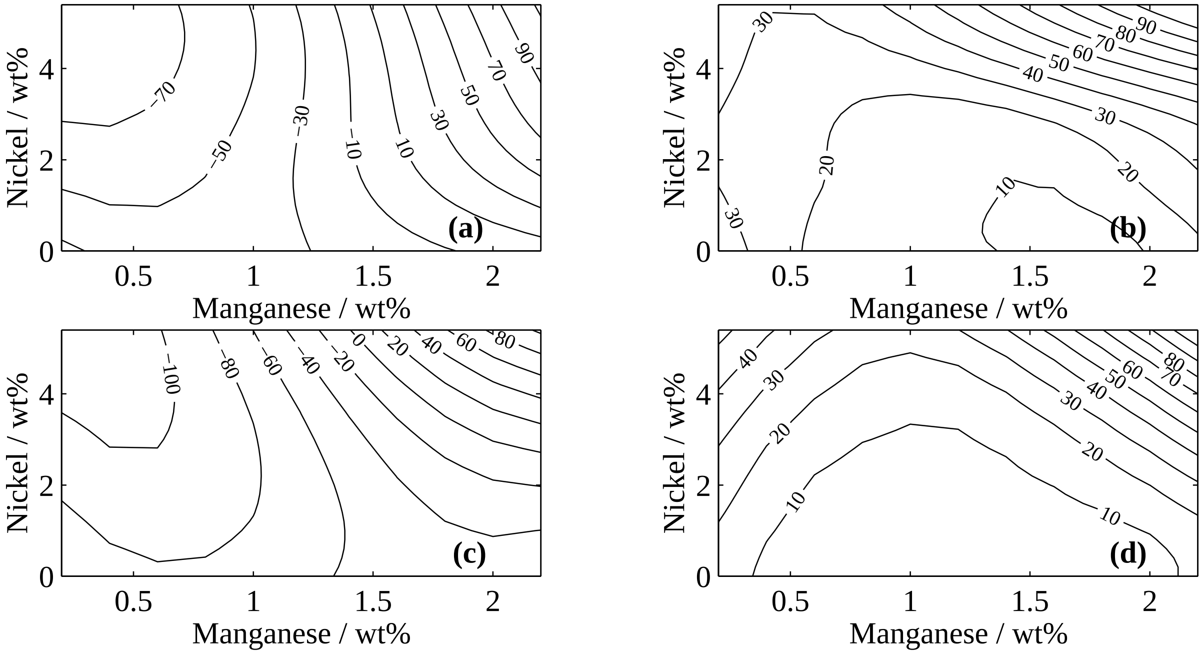

Figure A.19: Calculated Charpy impact toughness transition temperature of welds with respect to change in nickel and manganese using Carbon–Manganese weld metals model, a) transition temperature in °C at 100 J, b) the corresponding error bars in °C and c) transition temperature in °C at 28 J, d) the corresponding error bars in °C.

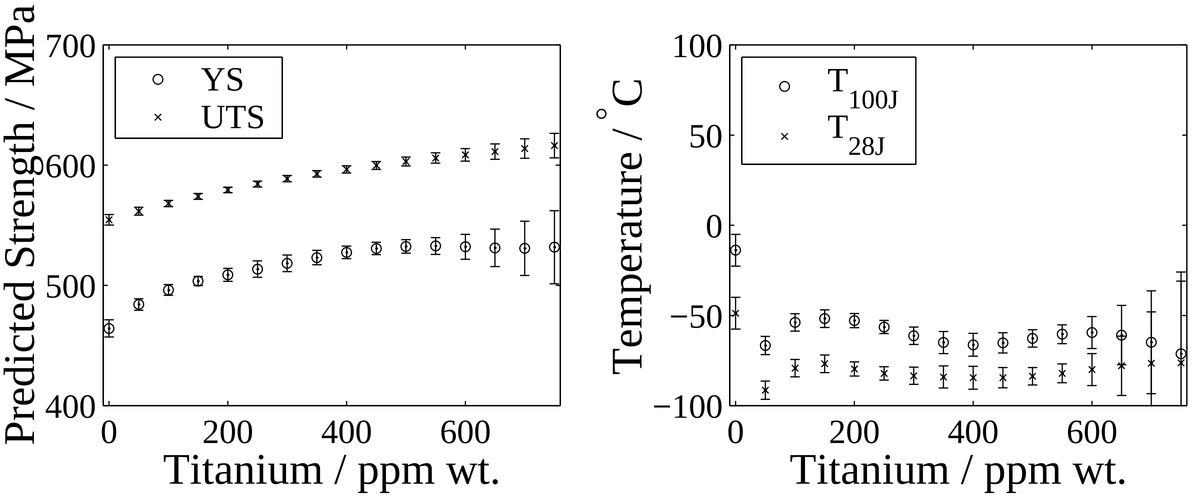

Figure A.20: Calculated mechanical properties of welds with respect to change in titanium content in weld metal.The contour plot curves represents impact toughness in J.

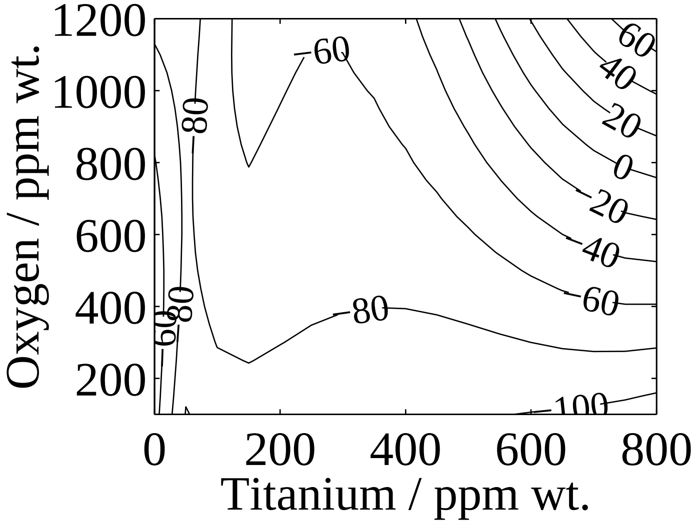

Figure A.21: Combined effect of oxygen and titanium on transition temperature at Charpy impact toughness of 28 J. The contour plot curves represents temperature in °C.

Appendix B

Design of Novel Weld Metals

A variety of commercial and experimental weld metals have been designed using the models developed in the present work. This appendix shows two examples of alloys developed using the models described in the thesis.

B.1 New Weld Design in Nippon Steel

The Nippon Steel Welding Company was able to develop novel high strength welding alloys in response to customer demands, by calculating the effect of molybdenum on the strength of welds and without doing any prior experiments. Kazutoshi Ichikawa (Nippon Steel, Japan) had the task to develop weld metal for the manual metal arc welding (MMAW) and submerged arc welding (SAW) processes for thick plates (upto 80 mm).

He demonstrated first that the models could predict the ultimate tensile strength of existing alloys already marketed by his company to great accuracy, Fig. B.1. He needed to raise the UTS to around 750 MPa so he chose to increase the molybdenum to 0.6 wt%. When the actual weld was made, (Table B.1) and the results matched predictions. Thus Nippon Steel Welding Products and Engineering Co. Ltd. was then able to commercialise and patent the new electrode.

B.2 Further Applications

Scientists at ESAB AB (Sweden) have been searching for strong and tough weld metals for submarine applications. Marimuthu [146] had designed welds for this purpose using the models described in this thesis. The expected and actual results are tabulated in Table B.2. It is heartening to find that the models are able to extrapolate to 9 wt% nickel even though the maximum nickel concentration in the database used to create the models is 4.8 wt% (Table 4.1).

As a result of this work, an interaction has been discovered between manganese and nickel which leads to a remarkable improvement in toughness. This has been demonstrated experi-

Input variable	**MMAW**
C (wt%)	0.078
Si (wt%)	0.38
Mn (wt%)	1.37
S (wt%)	0.003
P (wt%)	0.011
Ni (wt%)	0.64
Cr (wt%)	0.03
Mo (wt%)	0.57
V (wt%)	0.004
Cu (wt%)	0.012
Co (wt%)	0.0
W (wt%)	0.0
O (p.p.m.)	247
Ti (wt%)	150
B (p.p.m.)	$\leq$3
Nb (p.p.m.)	30
Heat input(kJ mm^{-1})	1.85
Interpass temperature (°C)	100
Tempering temperature (°C)	20
Tempering time (h)	0.0
Predicted UTS(MPa)	760
Measured UTS (MPa)	771

Table B.1: Comparison between the designed and experimental results of new weld metal designed for Nippon Steels, Japan.

mentally but the details cannot be described here for commercial reasons.

B.3 Software

All the models and programs developed can be accessed on the world wide web;

YS and UTS models:

http://www.msm.cam.ac.uk/map/neural/programs/weldmetalyu-b.html

Elongation and Charpy impact toughness models:

http://www.msm.cam.ac.uk/map/neural/programs/weldmetalec.html

27 J Charpy toughness transition temperature model:

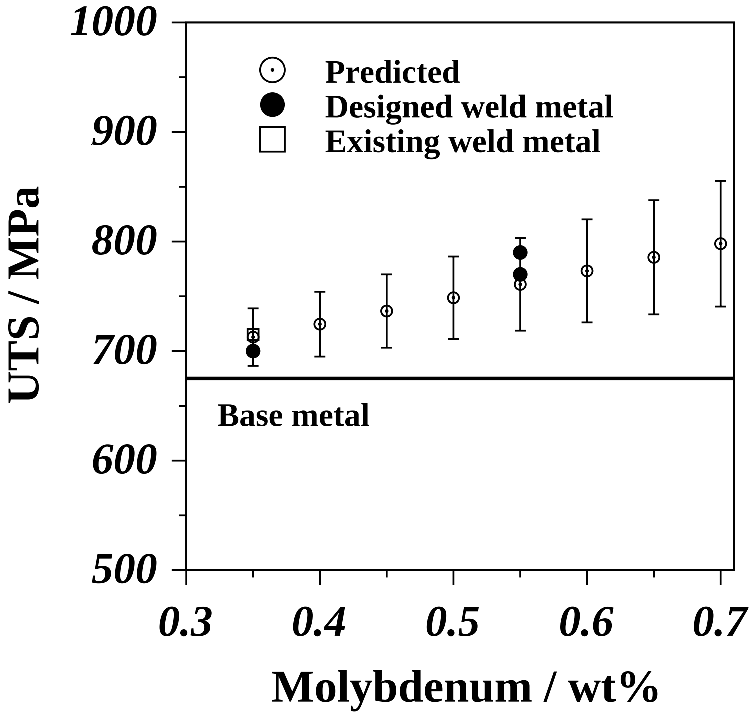

Figure B.1: Effect of molybdenum on ultimate tensile strength.

http://www.msm.cam.ac.uk/map/neural/programs/weldmetalT27J.html

Temper embrittlement model:

http://www.msm.cam.ac.uk/map/neural/programs/weldmetalEmb.html

Analysis of electron diffraction patterns program:

http://www.msm.cam.ac.uk/map/crystal/programs/crystal2.html

Input variable	Proposed	Actual
C (wt%)	0.030	0.030
Si (wt%)	0.29	0.35
Mn (wt%)	2.09	2.18
S (wt%)	0.012	0.007
P (wt%)	0.005	0.010
Ni (wt%)	7	7.2
Cr (wt%)	0.43	0.34
Mo (wt%)	0.59	0.63
V (wt%)	0.019	0.13
Cu (wt%)	0.03	0.03
Co (wt%)	0.0	0.009
W (wt%)	0.0	0.004
O (p.p.m.)	267	370
Ti (wt%)	0.014	0.013
B (p.p.m.)	0.0005	0.0006
Nb (p.p.m.)	0.0	10
Heat input(kJ mm^{-1})	1.0	1.14
Interpass temperature (°C)	200	200
Tempering temperature (°C)	250	250
Tempering time (h)	14	14
YS (MPa)	814 ± 179	789

Table B.2: Comparison between the proposed and actual properties of C–Mn–Ni weld metal. ‘p.p.m.’ corresponds to parts per million by weight.

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