Bruscato factor in temper embrittlement of welds

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Published experimental data on the tendency for 2·25Cr–1Mo to undergo impurity induced temper embrittlement have been analysed quantitatively. The results indicate strong effects owing to phosphorus, silicon, manganese, and molybdenum concentrations, but the influence of tin, antimony, and arsenic cannot be perceived because of the overwhelming effects of the other elements. A computer model for the calculations is obtainable freely over the World Wide Web.

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INTRODUCTION

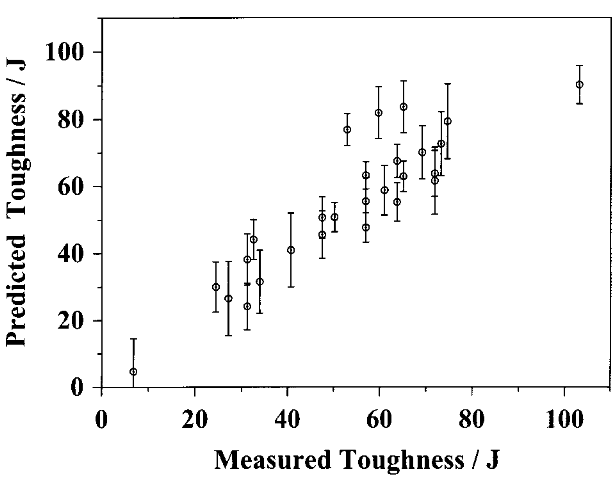
Welding alloys designed for creep resistant steels frequently have to be tempered in a temperature range where they are susceptible to embrittlement by impurity elements such as antimony or phosphorus. The segregation of these deleterious elements to the prior austenite grain boundaries leads to intergranular failure and consequently a reduction in toughness. Whereas this mechanism of embrittlement is well understood from a vast amount of research published over the last five decades, there are no quantitative methods capable of estimating the degree of embrittlement as a function of the chemical composition and heat treatment.

It was in this context that Bruscato[1] reported a large number of experiments, based on the classical 2·25Cr–1Mo composition, but with variations in the phosphorus, antimony, tin, and arsenic concentrations. There were also some variations in the concentrations of the major alloying additions, including carbon, manganese, silicon, chromium, and molybdenum. The tendency to embrittlement was monitored by comparing the impact toughness of both post-weld heat treated and step aged specimens. The latter heat treament exaggerates the extent of embrittlement.

Bruscato used an embrittlement factor to interpret his data, given by

$$\bar{X} = (10P + 5Sb + 4Sn + As)/100$$

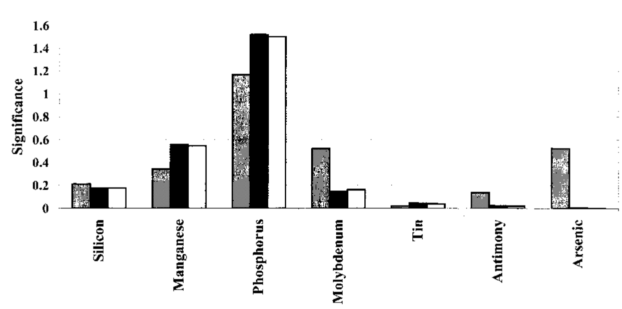
where the concentrations of the elements are in parts per million by weight. A large value of $\bar{X}$ implies a greater tendency towards temper embrittlement. This led Bruscato to conclude that the embrittlement of 2·25Cr–1Mo welds is directly related to the manganese, silicon, phosphorus, tin, arsenic, and antimony concentrations, with the first four being of greatest significance. The derivation of $\bar{X}$ was not presented in the original paper, although it is stated that the equation is based on data from chromium steels. The present work analyses Bruscato's original data using neural network analysis[2,3] and examines his conclusions in more detail. The neural network method has already been explained in previous publications[2,3] so is not reproduced here. Suffice it to say that neural networks are parameterised non-linear models used for regression or classification modelling. Their flexibility makes them useful for uncovering more complex relationships in data than traditional linear statistical models. The particular method used in the present work also has the advantage of indicating an error bar which depends on the position in the input space.



1 Comparison of predicted and measured values of Charpy toughness: predictions made using committee of three models

DATA

Bruscato published results on 30 separate weld deposits; the range of parameters is listed in Table 1. The Charpy



2 Perceived significance σ_w values from three committee models for each input

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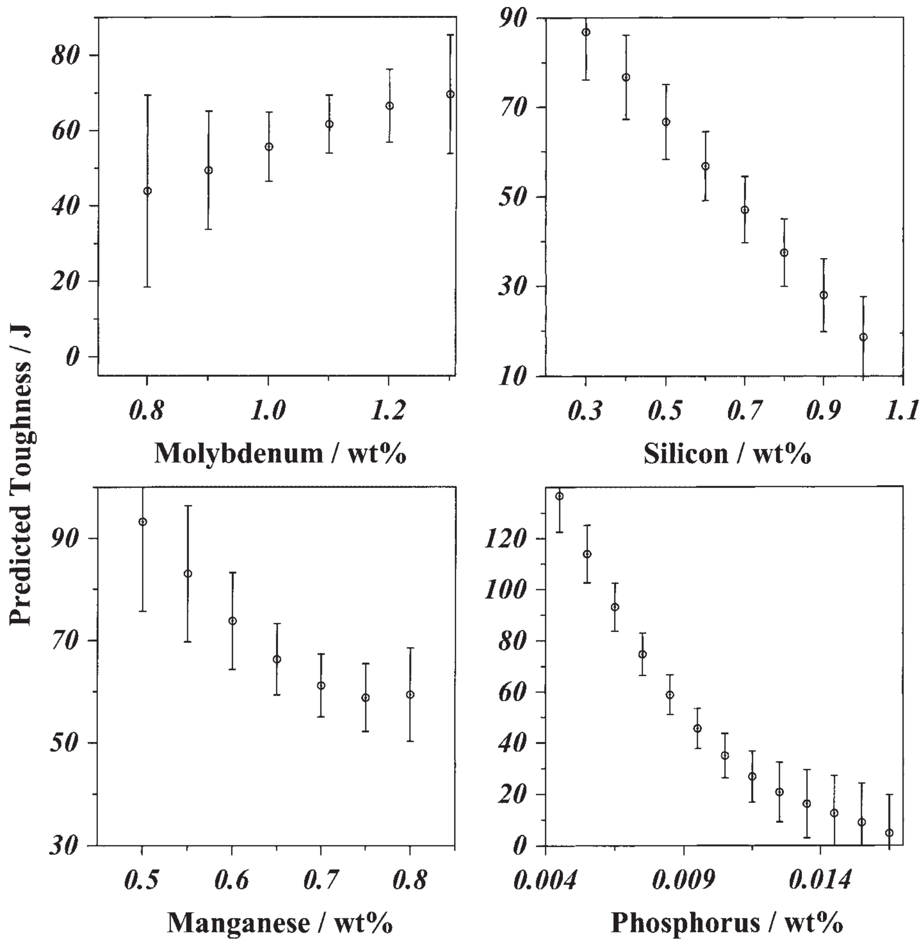


3 Effects of Mo, Si, Mn, and P on toughness after step aging

toughness of the step aged specimens represents the output to be modelled as a function of all the other variables listed in Table 1. All of the 30 welds had been given an identical heat treatment. For the purposes of the analysis, the data were all normalised in the range $\pm 0{\cdot}5$ in order to compare the significance of each of the input variables.

The data were divided at random into two parts, a training set and a test dataset. The neural network models were then created using just the training data.[3] The resulting models were assessed on their ability to generalise on the unseen test data. From the models created, a committee of three models was found to give the best generalisation on unseen data. These three models had 13, 11, and 11 hidden units with σ_v values of 0·083293, 0·083149, and 0·083118 respectively; σ_v is the perceived level of noise in the normalised output. An increase in the number of hidden units enables the network to recognise more complex relationships. Details of the network have been reported previously.[2,3] The committee members were finally optimised on the entire dataset. The performance of the committee is shown in Fig. 1.

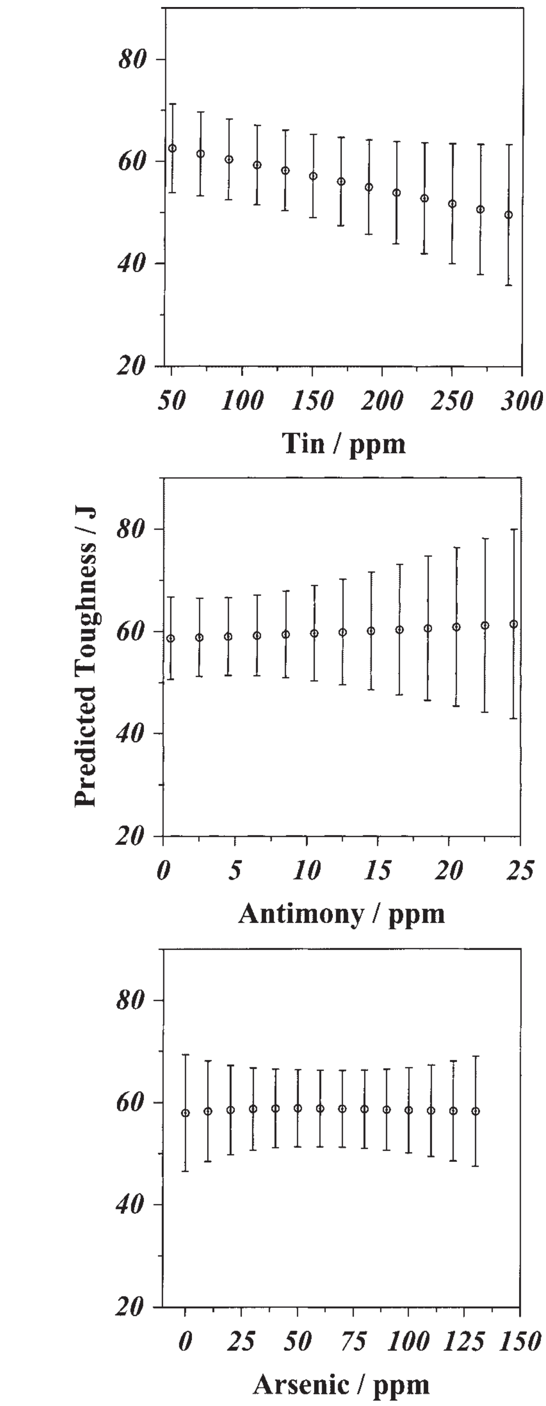
Figure 2 shows the significance σ_w of each of the input variables. The value of σ_w for a particular input variable indicates the ability of that input to explain variations in the output (Charpy toughness). Three σ_w values are presented for each input, corresponding to each of the three members of the committee of models. A consistent value of σ_w, for a given input, indicates that there exists a well defined relationship between that input and the output. Figure 2 shows that tin, antimony, and arsenic have very little effect on the embrittlement of the 2·25Cr–1Mo welds studied, whereas phosphorus has a very large effect.

These observations can be illustrated further by making predictions. Calculations were carried out using the base set of input values given in Table 2, while varying each input individually.

Figure 3 shows the effects of molybdenum, silicon, manganese, and phosphorus concentrations. As expected,

Table 1 Range of values reported by Bruscato and used in present work

Input element	Minimum	Maximum	Mean	Standard deviation
Si, wt-%	0·32	1·19	0·64	0·20
Mn, wt-%	0·54	0·79	0·69	0·06
P, wt-%	0·004	0·018	0·009	0·003
Mo, wt-%	0·9	1·27	1·10	0·10
Sn, wt-ppm	70	300	109	39
Sb, wt-ppm	0·9	22	5	4
As, wt-ppm	0·0	130	59	28
Charpy toughness after step aging, J	7	137	60	29



4 Effects of Sn, Sb, and As on toughness after step aging

phosphorus has a strong and very significant tendency to embrittle the weld metal; as stated above, the mechanism of phosphorus embrittlement is well understood, involving its segregation to prior austenite grain boundaries. Conversely, molybdenum actually improves the resistance to embrittlement. This is also expected, because molybdenum and phosphorus atoms tend to associate so that the latter is prevented from segregating to the prior austenite grain surfaces.[4]

Table 2 Base input values used in application of embrittlement model: values correspond to weld Q in Ref. 1

Si, wt-%	0·58
Mn, wt-%	0·78
P, wt-%	0·008
Mo, wt-%	1·05
Sn, wt-ppm	120
Sb, wt-ppm	1·6
As, wt-ppm	36

It is noteworthy that significant trends are recognised also for manganese and silicon. The manganese effect is consistent with work which suggests that it reduces the intergranular fracture strength.[5] Silicon is known to promote the segregation of phosphorus to the austenite grain boundaries.[6]

By contrast, there are no significant trends noticeable for arsenic, tin, or antimony (Fig. 4). Based on these observations, it is concluded that arsenic, tin, and antimony are not important contributors to embrittlement in the particular alloy system studied in the present work. It is possible that this result is a consequence of the fact that the welds all contain phosphorus in concentrations large enough to swamp the much smaller effects of arsenic, tin, and antimony. Thus, the mean phosphorus concentration is 90 wt-ppm, with a standard deviation of 30 wt-ppm.

CONCLUSIONS

It is found that phosphorus, silicon, and manganese all make 2·25Cr–1Mo welds susceptible to temper embrittlement, with the embrittling potency decreasing in that order. Molybdenum decreases the tendency to impurity induced embrittlement. These observations are all expected from published work. By contrast, arsenic, antimony, and tin have no perceptible effect on the welding alloys studied, probably because of the overwhelming influence of phosphorus. It follows that any attempt to reduce the effects of temper embrittlement should focus primarily on reduction in phosphorus. The computer model produced to make these predictions can be obtained from www.msm.cam.ac.uk/map/mapmain.html.

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