Computer-Aided Design of Electrodes for Arc Welding Processes: Part II

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SUMMARY

This paper reports the continuing development of computer software based on the physical metallurgy of steel welds. The software enables the theoretical design of welding consumables and procedures for some arc welding processes, as a function of alloy chemistry, welding conditions and many other variables. New research has enabled the model to predict not only the primary microstructure of steel weld deposits, but also allows the effects of reheating in multirun welds to be estimated, together with the yield strength of such welds.

INTRODUCTION

In an earlier investigation (1) we reported the development of computer software for the theoretical estimation of the primary microstructure of manual metal arc, low-alloy steel weld deposits. The basis of the software lies in detailed phase transformation theory (2-8) which takes into account many variables including chemical composition (C, Si, Mn, Ni, Cr, Mo and V), welding current, voltage, arc transfer efficiency, interpass temperature, austenite grain structure, solidification sequence and alloying element segregation.

The initial work was confined to the primary microstructure of welds which is obtained as the weld cools from the liquid phase to ambient temperature. It consists of mixtures of allotriomorphic ferrite, Widmanstätten ferrite, acicular ferrite, martensite and other minor phases. While the ability to estimate the details of the primary microstructure is of considerable importance in the design of welding consumables, it does not represent the complete microstructure in multirun welds. In such welds, the metal deposited first is influenced significantly by additional thermal cycles arising during the deposition of any subsequent layers. Some regions of the original primary microstructure are thus reheated to temperatures high enough to cause reverse transformation into austenite, which during the cooling part of the thermal cycle retransforms into a variety of somewhat different transformation products. Other regions may simply be tempered by the deposition of subsequent runs. The microstructure of the reheated regions of the weld is henceforth referred to as the *secondary microstructure*. In a multirun weld, the volume fraction of the secondary microstructure (V_s) can vary widely depending on the exact welding conditions (9).

The ultimate goal of this project is to enable the microstructure and properties of arc welds to be estimated by calculation. Properties such as the macroscopic yield strength (σ_Y) which are of crucial importance in determining the toughness of weld deposits (10), cannot be estimated for multirun welds without a quantitative knowledge of how the volume fractions of the primary and secondary regions vary with welding conditions, alloy chemistry, etc. It is common practice to express the weld metal strength as an empirical function of the alloying elements present. This procedure is of limited use, as shown by the many different equations which exist for different sets of experiments (11,12). The method is also unsatisfactory since reheating causes a change in strength but not in chemical composition. In this work we attempt a different, less empirical approach to the problem of strength, which is shown to be applicable to a wide range of alloys and welding conditions. The aim of this paper is thus to present our recent attempts at establishing the relationship between the microstructure and properties of multirun weld deposits on a quantitative basis.

METHOD

Strength of the primary microstructure

Recent work (13) on a general method for the calculation of the strength of the primary microstructure can be summarised as follows:

In a multiphase system in which the amounts of the phases are do not differ widely, the overall strength will be strongly related to the strengths and volume fractions of the phases present. The simplest assumption from this would be that the mean strength of the weld should be related linearly to the strengths and abundances of the phases present (11). Consequently, the model (13) is based on the assumption that the strength can be factorised into components due to the intrinsic strength of pure annealed iron (σ_{Fe}), solid solution strengthening (σ_{SS}), and a contribution σ_{MICRO} from the three major phases (allotriomorphic ferrite, α, Widmanstätten ferrite, α_w and acicular ferrite, α_a) which constitute the microstructure:

$$\sigma_P = \sigma_{Fe} + \{\Sigma_i \ \sigma_{SS}\} + \sigma_{MICRO} \qquad [1]$$

where the subscript "i" identifies a particular alloying addition. We note that σ_{Fe} is a function of temperature and strain rate, and that the *solid solution* strengthening due to carbon will be negligible since most of the carbon is out of solution in ferrite at ambient or lower temperatures. At 25°C and a typical strain rate of 2.5×10^{-4}/s, σ_{Fe} is about 220 MPa; at 25°C the solid solution strengthening caused by 1 wt.% of Mn, Si, and N is 40, 106 and 4240 MPa respectively. The term σ_{MICRO} is for ambient temperatures, given by (13):

$$\sigma_{MICRO} = \sigma_\alpha V_\alpha + \sigma_a V_a + \sigma_w V_w \qquad [2]$$

where the coefficients σ_α, σ_a and σ_w are respectively, 27, 402 and 486 MPa and V_α, V_a and V_w are the volume fractions of α, α_a and α_w respectively. After combining with σ_{Fe} and σ_{SS} data obtained from many literature sources (listed in reference 13), eq.1 has been used to represent fairly accurately, the strength of the primary microstructures of many diverse steel welds and welding processes (13).

Approximate representation of the microstructure of multirun welds

As already noted, the microstructure of a multirun weld is complicated by the fact that each bead deposited causes the rest of the weld to experience a thermal cycle whose duration and peak temperature depends on the location with respect to the latest source of heat. The final microstructure is thus very complex and considerable simplification is necessary before its strength can be modelled; more detailed models will have to await detailed developments in phase transformation theory.

The following approximations are used for the present work:

(i) The primary microstructure is taken to include not only regions which are unaffected by thermal cycles due to subsequent runs, but also those regions which become fully reaustenitised as a consequence of reheating. These reheated regions will have a modified (equiaxed) austenite grain structure and in reality transform on cooling to somewhat different microstructures. As far as strength is concerned, it is mainly the effect of alloy chemistry on the thermodynamics and kinetics of transformations which determines microstructure. In essence, a hard as-deposited microstructure should on complete reaustenitisation and subsequent transformation yield a hard reheated microstructure.

(ii) The remainder of the microstructure, which consists of partially reaustenitised and significantly tempered regions is classified together as the secondary microstructure. This should be a good approximation these regions in general lose most of the microstructural strengthening present in the primary regions.

(iii) The steel becomes fully austenitic above Ac3. There is no method for calculating Ac3 for arbitrary steels and heat treatments; it is therefore approximated by the Ae3' paraequilibrium temperature (14). The use of an *equilibrium* temperature carries with it the unfortunate implication that the volume fraction of the secondary region is independent of cooling conditions; the results are thus valid only for manual metal arc welds.

Nitrogen

Although the concentration of nitrogen is generally rather low (≈ 40-120 p.p.m.) it is known to have a potent detrimental effect on the toughness of the weld. The mechanism of embrittlement is believed to be associated with strain hardening and solid solution hardening effects, both of which increase the yield stress of the weld, and consequently cause a decrease in the toughness. In many cases, nitrogen concentrations are not available, and it is in any case desirable to be able to calculate it for the purposes of strength prediction.

Nitrogen is a diatomic gas, so that its activity in liquid steel (a_N) varies with the square root of the partial pressure of nitrogen (p_N) in the gas which is in equilibrium with the liquid steel (15):

$$a_N = K\ p_N \qquad [3]$$

where K is a proportionality constant which depends on temperature. The concentration of nitrogen (x_N) is related to the activity by the relation:

$$a_N = f\ x_N \qquad [4]$$

where f is the activity coefficient given by:

$$\log_{10}\{f\} = \sum_i x_i\ e_i \qquad [5]$$

where x_i is the concentration in weight percent of an element "i" in the liquid steel, and e_i is the corresponding Wagner interaction parameter (15) between the element concerned and nitrogen, for dilute solutions. The activity coefficient thus represents the influence of other alloying additions on the solubility of nitrogen in dilute liquid steel. Values of interaction parameters for equilibrium between liquid steel and gaseous nitrogen at 1600^{O}C given by Pehlike and Elliott are used throughout this work (15).

If it is assumed that the amount of nitrogen found in the weld at ambient temperature is related directly to its solubility in liquid steel, then the above theory should provide a method of rationalising the nitrogen concentration of welds. Published data from some 79 manual metal arc welds (2, 7, 16-21) where the nitrogen concentrations, alloy chemistry and welding conditions were given, were collated and analysed by multiple regression to give (Fig. 1):

$$N\{p.p.m.\} = 240(1/f) + 10800(\text{heat input, J/mm}) - 0.132(T_{O}, {}^{O}C) - 147 \qquad [6]$$

where T_O is the interpass or preheat temperature. The standard error of the estimate using eq. 6 is 25p.p.m., and is not unexpectedly large since information on the core wire and coating nitrogen concentrations is not available. Equation 6 was used to estimate the nitrogen concentration for cases where the information was not found in published sources, but where the other data necessary for the strength analysis (presented below) were accessible.

Strength of multirun weld deposits

The yield strength σ_Y as measured on large samples can be factorised as follows:

$$\sigma_Y = \sigma_P V_P + \sigma_S V_S. \qquad [7]$$

where σ_S is the strength of the secondary microstructure and we note that $V_S + V_P = 1$. It follows that:

$$V_P = 1 - V_S = (\sigma_Y - \sigma_S)/(\sigma_P - \sigma_S). \qquad [8]$$

σ_Y can be experimentally determined, σ_P can be calculated (13) and σ_S is given by:

$$\sigma_S = \sigma_{Fe} + \sigma_{SS} + \sigma_{MICRO\text{-}S} \qquad [9]$$

where all the terms other than the microstructural strengthening in the secondary regions (i.e., $\sigma_{MICRO\text{-}S}$) are known (13). Given that the secondary regions contain substantial amounts of heavily tempered steel, their $\sigma_{MICRO\text{-}S}$ was found to be 68 MPa from a measurement of the yield strength (409MPa) of an Fe-1.2Mn-0.3Si-0.1C wt.% weld which was annealed at 700^{O}C for 24 hrs. Having derived values of σ_S and σ_P, eq.5 can be used to deduce experimental values of V_S, and to correlate V_S against Ae3'. This was done using the experimental data and calculated Ae3' temperatures presented in Table 1:

$$(1 - V_S) = V_P = 3.313 - 0.0037(\text{Ae3'}, {}^{O}C) \qquad [10]$$

The statistically significant correlation coefficient for eq.10 was found to be -0.72, so that a large amount of the variation in the proportions of primary and secondary microstructures can be explained by the thermodynamic effects of alloying elements on transformations from austenite. The equation can now be used to estimate V_s for an arbitrary manual metal arc weld.

The comparison of experimental data versus calculations using equations 1-10 is presented in Fig. 2; it is seen that the agreement is very good, even at relatively high strengths where empirical equations usually fail.

CONCLUSIONS

The microstructure of a multirun weld deposit can, for the purposes of estimating strength, be divided into two essential types. The primary microstructure has a yield strength which is approximately the same as that of the microstructure which evolves from the liquid as it cools to ambient temperature. The secondary microstructure is that which originates from the primary regions which experience significant heat treatment as a consequence of the deposition of further weld metal, such that most of the microstructural component of strengthening is lost, the main contributions to strength being solid solution strengthening and the intrinsic strength of pure, annealed iron.

The strength of each region can be factorised into the strength of pure, annealed iron, solid solution strengthening and microstructural strengthening. The latter component can be very large for typical welds, and can be factorised further into components corresponding to each microstructural phase (α, α_w, α_a). The secondary regions however lose most of the microstructural component of strengthening as a consequence of heat-treatment after deposition.

It has proved possible to estimate the volume fractions of the primary and secondary regions of multirun welds as a function of the Ae3' temperature of the alloy concerned, although this is recognised to be an approximate procedure which will be refined with further research. Nevertheless, the yield strength can already be estimated to an accuracy comparable with the scatter typically observed in experimental data, and this for welds with widely differing chemical compositions and welding parameters.

Finally, an attempt has also been made to estimate the nitrogen concentration of manual metal arc welds; it is believed that the accuracy of estimation can be improved with more complete data on the nitrogen concentrations of the raw materials used in electrode manufacture.

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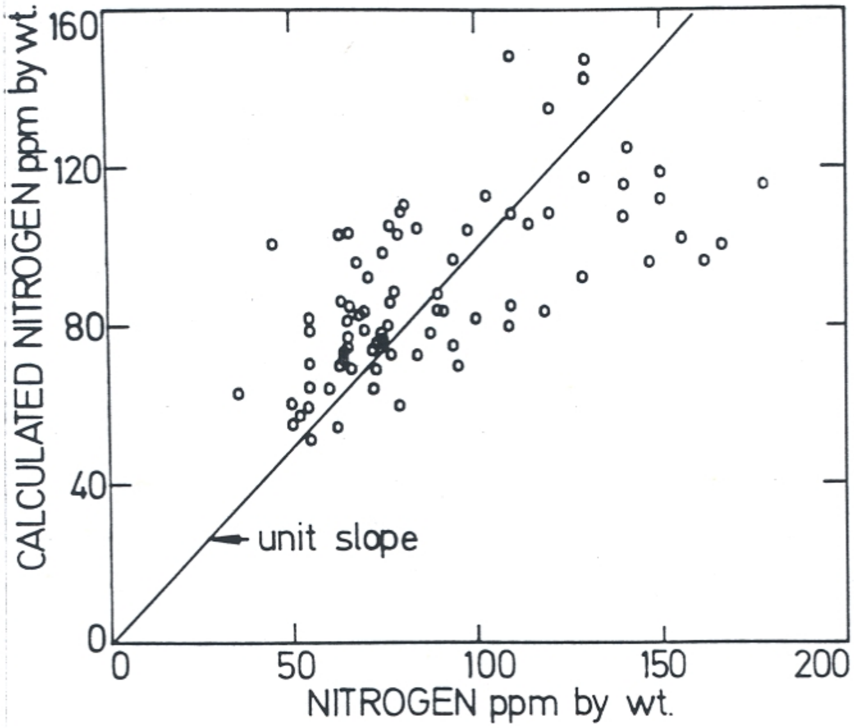
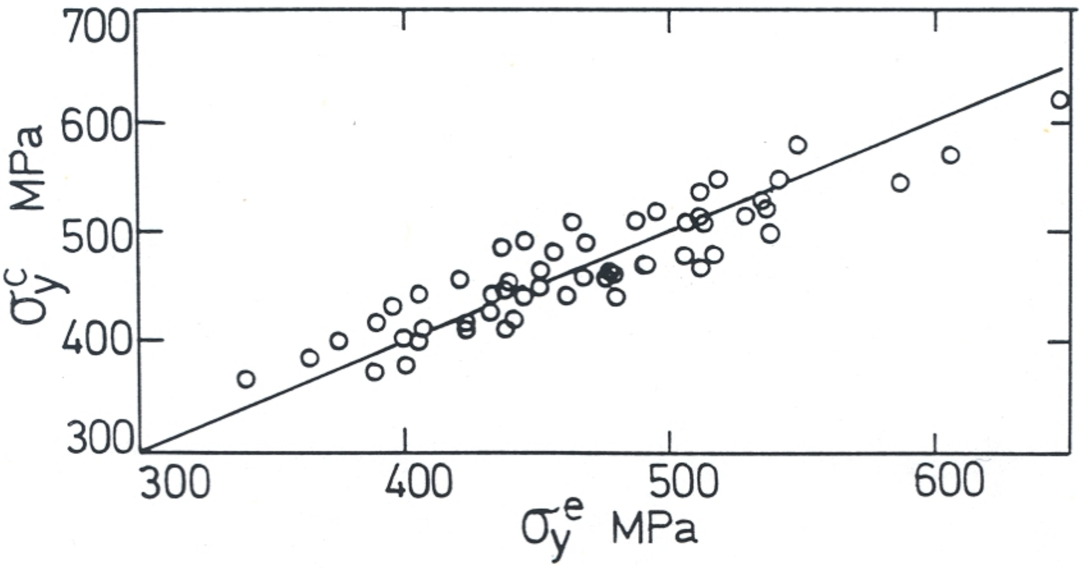


[1] Comparison of calculated (eq.6) and actual nitrogen concentrations of manual metal arc welds.



[2] Comparison of calculated and actual yield strengths of multirun manual metal arc weld deposits.

Table 1: Data (16, 18, 19) used in the strength analysis

No.	C wt.%	Si wt.%	Mn wt.%	V_a	V_α	V_w	Ae3' °C	σ_Y MPa	N p.p.m.
1	0.045	0.30	0.65	0.12	0.24	0.64	865	406	68
2	0.044	0.32	0.98	0.39	0.30	0.31	845	432	71
3	0.044	0.32	1.32	0.56	0.20	0.24	825	451	75
4	0.045	0.30	1.72	0.68	0.13	0.19	805	488	80
5	0.059	0.33	0.60	0.03	0.25	0.72	850	407	65
6	0.063	0.35	1.00	0.48	0.22	0.30	830	451	68
7	0.066	0.37	1.35	0.66	0.13	0.21	810	469	71
8	0.070	0.33	1.77	0.74	0.10	0.16	790	511	76
9	0.099	0.35	0.65	0.11	0.15	0.74	830	433	59
10	0.098	0.32	1.05	0.37	0.17	0.46	820	477	64
11	0.096	0.30	1.29	0.64	0.16	0.20	810	506	68
12	0.093	0.33	1.65	0.76	0.11	0.13	790	535	71
13	0.147	0.40	0.63	0.18	0.18	0.64	830	480	52
14	0.152	0.41	1.00	0.34	0.15	0.51	810	517	55
15	0.148	0.38	1.40	0.72	0.09	0.19	790	536	60
16	0.141	0.36	1.76	0.79	0.05	0.16	770	606	65
17	0.044	0.32	0.62	0.31	0.56	0.13	865	445	67
18	0.046	0.31	0.96	0.51	0.38	0.11	845	479	71
19	0.050	0.38	1.42	0.69	0.26	0.05	825	511	73
20	0.055	0.35	1.93	0.77	0.19	0.04	790	587	79
21	0.037	0.29	0.60	0.26	0.60	0.14	870	401	69
22	0.039	0.29	0.94	0.49	0.40	0.11	850	438	72
23	0.048	0.35	1.41	0.64	0.30	0.06	825	479	74
24	0.051	0.32	1.80	0.73	0.21	0.06	800	507	79
25	0.038	0.24	0.55	0.23	0.64	0.13	870	389	69
26	0.036	0.24	0.89	0.48	0.41	0.11	850	400	73
27	0.042	0.28	1.37	0.60	0.34	0.06	830	438	77
28	0.045	0.26	1.69	0.69	0.25	0.06	810	456	80
29	0.043	0.20	0.52	0.17	0.67	0.16	870	341	69
30	0.042	0.20	0.93	0.40	0.45	0.15	850	376	74
31	0.043	0.24	1.37	0.57	0.37	0.06	825	405	77
32	0.047	0.25	1.73	0.67	0.27	0.06	805	437	81
33	0.060	0.20	0.60	0.28	0.32	0.40	855	365	55
34	0.070	0.38	0.66	0.45	0.22	0.33	850	390	63
35	0.065	0.61	0.65	0.39	0.24	0.37	860	396	57
36	0.070	0.95	0.64	0.52	0.30	0.18	870	439	55
37	0.064	0.20	1.40	0.69	0.23	0.08	810	421	55
38	0.066	0.36	1.41	0.72	0.13	0.15	810	446	72
39	0.073	0.62	1.44	0.70	0.20	0.10	810	463	64
40	0.063	0.93	1.38	0.72	0.18	0.10	830	495	50
41	0.032	0.44	0.78	0.11	0.56	0.27	865	423	95
42	0.030	0.44	1.27	0.44	0.35	0.21	840	467	94
43	0.030	0.42	1.71	0.65	0.24	0.11	810	511	109
44	0.030	0.45	2.05	0.71	0.22	0.77	800	518	119
45	0.060	0.35	0.77	0.25	0.40	0.35	850	423	66
46	0.060	0.34	1.09	0.34	0.31	0.35	830	445	64
47	0.060	0.30	1.44	0.48	0.29	0.23	810	491	65
48	0.060	0.34	1.83	0.63	0.27	0.10	790	528	76
49	0.090	0.40	0.78	0.33	0.35	0.32	830	441	36
50	0.090	0.36	1.18	0.38	0.35	0.27	810	478	73
51	0.090	0.38	1.59	0.54	0.23	0.23	800	513	77
52	0.090	0.39	2.25	0.68	0.19	0.13	770	548	88
53	0.120	0.44	0.86	0.49	0.29	0.22	825	461	54
54	0.120	0.46	1.35	0.67	0.20	0.13	800	538	55
55	0.120	0.38	1.83	0.63	0.21	0.16	770	541	63
56	0.120	0.35	2.18	0.66	0.16	0.18	740	646	74