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The estimation of non-uniform elongation in low-alloy steel weld deposits

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The plastic strain recorded during tensile testing of steel weld deposits has been factorized into a uniform and nonuniform component. It has been possible to express the nonuniform component in terms of the inclusion content of the weld deposits.

1. Introduction

The ductility of a metal is a measure of its ability to deform plastically without failure, and it is one of the most important parameters used to describe the mechanical behaviour of materials. In welding, it is conventional to specify minimum levels of required ductility for safe performance of the welded structure.

The ductility of a tensile specimen is conventionally measured in two ways; from the engineering strain at fracture, e_f, (usually called the elongation), and the reduction in area at fracture, q. However, a major problem in analysing these two parameters, as Dieter [1] pointed out, is that the occurrence of necking in the tension test makes any quantitative conversion between the two measures impossible. Separate treatments are, therefore, necessary; the present work focuses on the elongation property alone.

The detailed characteristics of ductile failure in steel welds are a consequence of many factors [2], such as the state of stress and strain, work hardening properties, and the presence of inclusions in the material. For weld deposits in particular, it is recognized that the presence of inclusions in weld metals is an important factor in determining their mechanical properties [3, 4]. Likewise, other details of the inclusion population are increasingly being highlighted as being influential on the mechanical properties of weld metals [5–7]. In the present work we examine whether, for a class of arc welds made of steel, the tensile ductility can be factorized into uniform and nonuniform components, on the hypothesis that the former component is largely dependent on material properties such as the strain hardening behaviour, whereas the nonuniform component depends on the details of the inclusion content of the weld. During the tensile deformation of a metal containing inclusions which are weakly bonded, voids grow at the inclusion/matrix interface at an early stage of plastic deformation. However, for weakly bonded inclusions, the deformation in the regions between the inclusions continues to be uniform, until those regions begin to locally neck [8]. For these circumstances, it is a good approximation that the localized necking corresponds to the macroscopically observed necking in the tensile test. Consequently, it may be possible to treat the uniform plastic strain prior to macroscopic necking as being controlled by factors which are not sensitive to the inclusion population. On the other hand, nonuniform plastic strain beyond necking would then depend very much on the distribution and volume fraction of the inclusions. A further approximation untilized in the present work is that for the specific welds considered, an increase in volume fraction of inclusions gives rise to a proportional increase in the number density of active inclusions.

2. Experimental method

Some of the variation in ductility of steel welds might be a consequence of differences in yield strength, although the role of yield stress on ductile fracture is not entirely clear [8]. If yield strength does influence ductility, it would be of use to know whether it is the uniform or the nonuniform component of the strain to failure that it affected most. An experiment was designed in order to see how ductility varies for weld metal with the same composition, and inclusion population, but with different matrix strength levels. To do this, tensile testing was carried out on a series of welds at a variety of temperatures, so that different strengths would be exhibited. In all cases, the fracture mode was found to be of a ductile 'cup and cone' type.

Five low-carbon manganese multipass welds were fabricated to give welds of approximately constant chemical composition. The joint geometry was in accordance with ISO 2560-1973 specifications. The number of weld runs was 23 or more, with three runs deposited per layer. The current and voltage used were 180 A and 23 V (d.c. positive) respectively. The net heat input was approximately 1.5 kJ mm^{-1}, and the maximum interpass temperature was 250° C. The nominal plate and deposit composition were Fe–0.12 C–0.55 Mn–0.25 Si wt %, and Fe–0.07 C–1.2 Mn–0.05 Si wt %, respectively. The number of beads per weld was usually 25, and not less than 23. The weld metal compositions are given in Table I.

Two *all-weld* metal tensile specimens, threaded at each end, with cylindrical gauge lengths were extracted longitudinally and machined from each weld in

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TABLE I Weld metal chemical analyses

Weld number	Composition (wt %)											Composition (p.p.m.)	
	C	Mn	Si	P	S	Cr	Ni	Mo	V	Ti	Al	N	O
1	0.058	1.28	0.44	0.019	0.008	0.05	0.05	0.01	0.008	0.009	0.005	85	316
2	0.060	1.31	0.44	0.018	0.008	0.06	0.06	0.01	0.006	0.008	0.014	97	352
3	0.054	1.33	0.45	0.017	0.008	0.03	0.03	0.01	0.002	0.008	0.004	79	293
4	0.053	1.30	0.44	0.018	0.008	0.02	0.03	0.01	0.003	0.008	0.003	92	305
5	0.056	1.36	0.46	0.018	0.008	0.03	0.03	0.01	0.005	0.008	0.004	85	345

TABLE II Welds 1-5: Results for mechanical testing results, carried out at temperature T

Weld number	T (K)	σ_y (MPa)	σ_{UTS} (MPa)	σ_y (σ_{UTS})	EL (%)		q (%)
					on 70 mm	on 55 mm	
1A	297	522	561	0.930	–	26.8	76
1B	296.5	512	550	0.931	28.8	–	76
2A	273	506	571	0.886	25.4	–	75
2B	273	528	566	0.933	–	27.8	76
3A	253	536	586	0.915	27.6	–	75
3B	253	535	586	0.913	29.6	–	75
4A	233	511	599	0.853	29.6	–	75
4B	233	533	608	0.877	–	29.9	75
5A	213	567	619	0.916	29.6	–	75
5B	213	571	619	0.922	–	30.8	76

accordance with SMS 674-10C50 specifications to give five pairs of tensile specimens in all, although, because of the limited amount of weld metal available, four of the specimens could only be made with a gauge length of 55 mm instead of the recommended 70 mm. The specimens were degassed for 16 h at 250° C to remove hydrogen prior to testing.

Tensile testing was carried out *in situ* at ambient temperature 0, −20, −40 and −60° C, the temperatures being achieved using mixtures of dry-ice and alcohol. The strain rate was approximately 2×10^{-4} sec^{-1}. The tensile specimens were threaded into place, and then a platinum thermocouple was taped to each specimen prior to testing to ensure that the appropriate temperature was attained, although during testing the temperature recorded unavoidably rose an average of 8.5° C as a consequence of deformation-induced heat evolution.

3. Results and discussion

Tensile testing results are given in Table II, σ_y is the yield strength and σ_{UTS} is the ultimate tensile strength. The elongation and reduction in area at fracture have been designated EL and q respectively.

The extension due to plastic deformation, Δl_p, is read directly from the load–extension curve; the

TABLE III The plastic strain for welds 1-5. l_0 and A_0 represent the gauge length and cross-sectional areas, respectively, and Δl_{u_p} and e_{u_p} represent the measured uniform plastic extension and uniform engineering plastic strain, respectively

Weld number	F_{UTS} (kN)	l_0 (mm)	A_0 (mm^2)	Δl_{u_p} (mm)	e_{u_p}
1A	43.3	69	78.7	10.3	0.149
1B	43.5	55	78.4	8.09	0.147
2A	44.5	70	78.1	9.33	0.133
2B	44.8	52	78.4	8.66	0.167
3A	46.4	73	78.5	10.9	0.149
3B	46.1	71	78.5	10.7	0.151
4A	48.1	71	78.5	12.5	0.177
4B	47.1	54	78.4	9.64	0.178
5A	47.6	70	78.5	12.4	0.177
5B	47.4	64	78.4	10.5	0.164

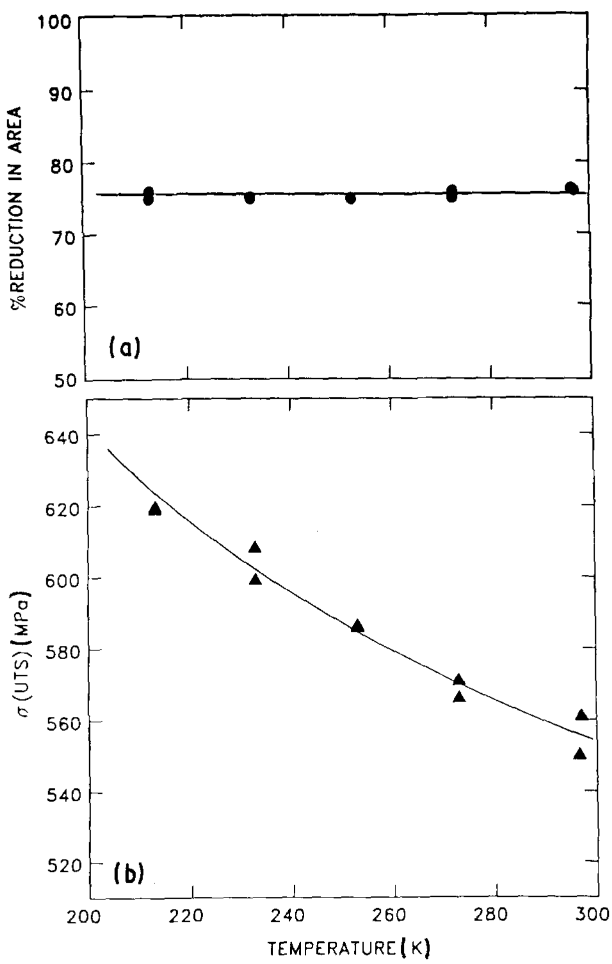

Figure 1 (a) Reduction in area, and (b) ultimate tensile strength as a function of temperature for the experimental welds.

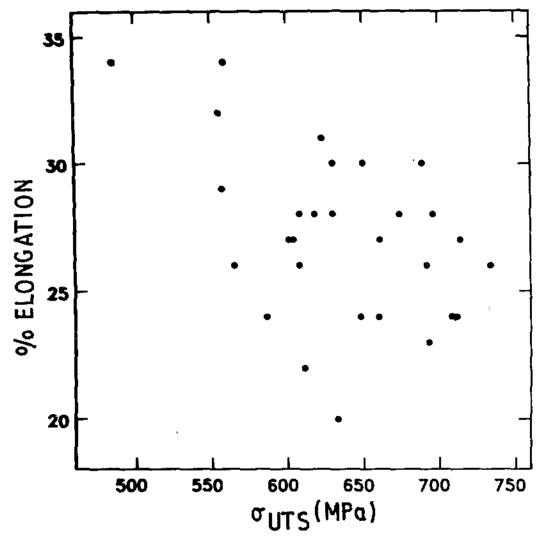

Figure 2 Showing the dependence of weld metal elongation on ultimate tensile strength (data due to Widgery [10]).

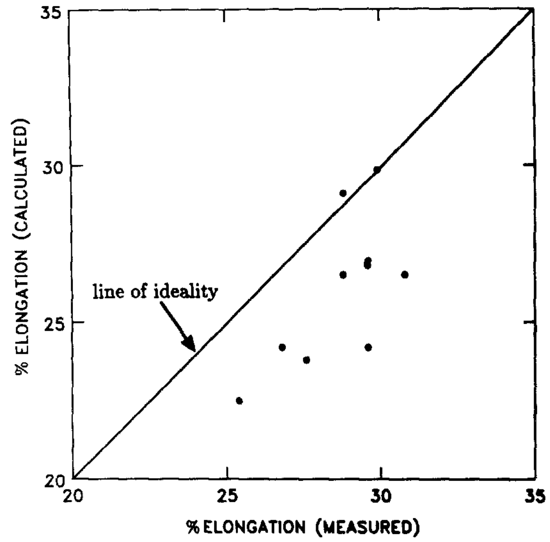

Figure 3 Calculated and measured values of per cent elongation for the experimental welds (see Table IV).

measured plastic strain experienced by the specimens during tensile testing are given in Table III. F_{UTS} is the applied load at the UTS, Δl_{u_p} is the plastic extension achieved during *uniform* elongation, and e_{u_p} is the value of the uniform plastic engineering strain for the welds tested. The total uniform plastic strain, e_{u_p}, corresponds, therefore, to the total strain up to the ultimate tensile strength, since the elastic component is relieved at fracture.

Although elongation varied slightly with temperature, Figs 1a and b show that for the temperature range investigated, reduction in area did not change. The results emphasize the different behaviours of these two measures of ductility. Widgery [9, 10] carried out mechanical tests on a large series of GMAW low-alloy steel welds. His work is of importance to the present study because the true maximum uniform strain achieved by each specimen in the course of tensile testing, ε_u, was also recorded. Figure 2 shows the relationship between measured elongation, *EL*, and ultimate tensile strength, σ_{UTS}, for Widgery's welds. The variation in strength levels is much larger and there is apparent, a trend showing a decrease in elongation as the strength increases. It can be seen that the recorded elongation decreases as the readiness of the weld metal to deform, as indicated by σ_{UTS}, increases. To examine whether the variations occur largely in the uniform component of the total elongation requires further analysis, which is presented below.

The plastic extension of a specimen at fracture can be factorized according to the expression [11, 12]:

$$e_f = \beta \frac{\sqrt{A_0}}{l_0} + e_u \qquad (1)$$

where β is a constant of proportionality (Unwin [12]), $\beta\sqrt{A_0}/l_0$ is the local necking strain and e_u is the uniform plastic strain of the specimen.

Equation 1 shows that the total elongation is a function of the specimen gauge length, and, therefore, to compare elongation measurements of different sized specimens the specimens must be geometrically similar, i.e. for round bars l_0/D_0 should be fixed. Since

$$e_u = \{\exp(\varepsilon_u) - 1\} \qquad (2)$$

it follows that

$$\begin{aligned} \%\mathit{Elongation} &= e_f \times 100 \\ &= \left\{\beta \frac{\sqrt{A_0}}{l_0} + \exp(\varepsilon_u) - 1\right\} \times 100 \end{aligned} \qquad (3)$$

and it is this equation which is used to analyse Widgery's data (Table IV).

It should be emphasized that the uniform plastic strain ε_u is expected to be very closely related to the

TABLE IV Measured and calculated values of per cent elongation for the weld metal tensile specimens. The calculated value of e_f is given by the sum of the measured uniform plastic strain and the calculated non-uniform plastic strain (assuming a value of $\beta = 0.73$)

Weld number	$\beta \frac{\sqrt{A_0}}{l_0}$	e_u (max)*	e_f (calculated)	*EL* (%) (measured)	*EL* (%) (calculated)
1A	0.0937	0.146	0.240	26.8	24.2
1B	0.118	0.147	0.265	28.8	26.5
2A	0.0922	0.133	0.225	25.4	22.5
2B	0.124	0.167	0.291	28.8	29.1
3A	0.0886	0.149	0.238	27.6	23.8
3B	0.0911	0.151	0.242	29.6	24.2
4A	0.0911	0.177	0.268	29.6	26.8
4B	0.120	0.178	0.299	29.9	29.9
5A	0.0924	0.177	0.269	29.6	26.9
5B	0.101	0.164	0.265	30.8	26.5

TABLE V Calculation of per cent elongation (data from [10])

Weld	Maximum uniform strain, ε_u	EL (%) (measured)	EL (%) (calculated)
A	0.115	26	30
B	0.105	24	29
C	0.10	24	29
D	0.13	28	32
E	0.10	23	29
F	0.095	22	28
G	0.09	20	28
H	0.11	24	30
J1	0.10	27	29
J2	0.12	28	31
J1R	0.11	24	30
J2R	0.13	27	32
J2RR	0.12	28	31
K	0.10	26	29
L	0.13	34	32
M	0.12	34	31
N	0.115	32	30
O	0.135	30	33
P	0.105	28	29
Q	0.07	24	26
R	0.115	30	30
S	0.11	26	30
T	0.125	29	32
U	0.12	27	31
W	0.08	24	27
X	0.13	30	32
Y	0.10	26	29
Z	0.13	31	32
Comm1	0.11	28	30
Comm2	0.10	27	29

work-hardening coefficient, n (see e.g. [13]). Widgery [9] found good correlation between these two quantities, with the best fit line: $n = 0.024 + 0.65\varepsilon_u$. The nonuniform plastic strain can be calculated from a knowledge of β, which is dependent upon alloy microstructure and composition, but for low-alloy steels, β has a characteristic value of 0.73 [14], and this was the value taken for the moment.

Figure 3 shows a comparison between the calculated and measured values of per cent elongation for

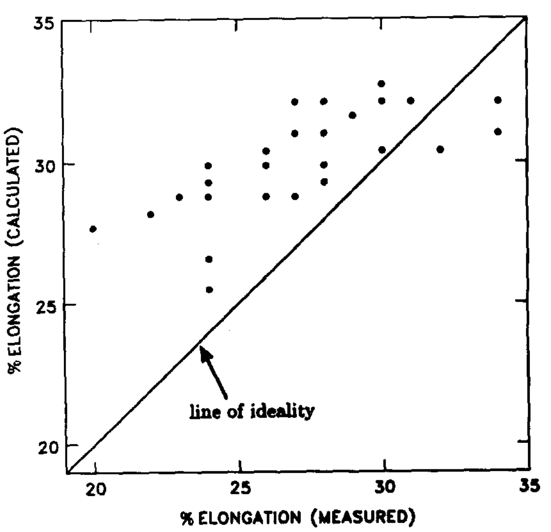

Figure 4 Measured elongations for 30 welds plotted against elongations calculated using Equation 3 (data due to Widgery [10]).

the experimental welds using data from Table IV. For Widgery's experiments, subsize specimens were used, but of recommended British standard dimensions [14]. The diameter and length were 6.41 mm and 22.7 mm respectively, ($l_0/D_0 = 3.54$).

Table V lists the maximum uniform strain achieved, together with measured and calculated values for elongation. Figure 4 shows calculated and measured values of per cent elongation for Widgery's welds. The fair correlation between theory and experiment implies the necking process contributes a fixed amount to the elongation. However, it can be seen that the behaviour of the data does not concur with those illustrated in Fig. 4, particularly with respect to the slope of the points relative to the line of ideality. The explanation for this is that $\beta = 0.73$ applies to low-alloy *wrought* steels. However, because weld metals contain inclusions, not only will β tend to be smaller (since the amount of elongation by the specimen after the UTS will be reduced), but the value of β should correlate with the volume fraction of inclusions. The inclusion fraction, I, in vol %, may be evaluated using the approximate relationship [15–17]:

$$I \approx 5.5(\text{wt}\,\%[\text{O}] + \text{wt}\,\%[\text{S}]) \qquad (4)$$

The best value for β was found to be

$$\begin{aligned} \beta &= 1.239 - 1.704 \times I \\ &= 1.239 - 9.372 \times (\text{wt}\,\%[\text{O}] + \text{wt}\,\%[\text{S}]) \quad (5) \end{aligned}$$

For example, $I = 0.30$ vol % gives $\beta = 0.73$. However, for a larger volume fraction of 0.50 vol %, β drops to 0.39. The values of elongation, calculated using the new expression for β (Equation 5) together with Equation 3 are given in Table VI. Calculated and measured values of percent elongation, EL, are plotted in Fig. 5 for the experimental welds and for the data due to Widgery [10]. It can be seen that the differences in behaviour with respect to the lines of ideality, observed in Figs 3 and 4 have disappeared, and that general agreement is much better. It is concluded therefore, that for the weld deposits studied here, variations in nonuniform plastic strain are largely due to variations in inclusion content; furthermore, it also follows that the dependence of ductility on strength is mainly via the uniform component of strain.

4. Summary

The factors controlling tensile ductility in low-alloy steel manual metal arc weld deposits have been examined. It seems that the tensile ductility can to a good approximation be divided into two main components whose magnitudes can be assumed to be controlled by different physical processes. These components are the uniform plastic strain, as recorded prior to the onset of macroscopic necking in the tensile specimen, and the nonuniform component which is the remainder of the plastic strain.

By factorizing the ductility into these components, it was possible to express the nonuniform component in terms of the inclusion content of the weld deposits, after taking into account variations in specimen cross-sectional areas and gauge lengths. On this basis, it

TABLE VI Recalculation of per cent elongation for welds given in Tables IV and V

Weld number	[O] (wt %)	[S] (wt %)	e_u	e_f	*EL* (%) (measured)	*EL* (%) (calculated)
1A	0.032	0.008	0.149	0.268	26.8	25.8
1B	0.032	0.008	0.147	0.288	28.8	27.7
2A	0.035	0.008	0.133	0.254	25.4	23.8
2B	0.035	0.008	0.167	0.288	28.8	30.9
3A	0.029	0.008	0.149	0.276	27.6	25.7
3B	0.029	0.008	0.151	0.296	29.6	26.2
4A	0.031	0.008	0.177	0.296	29.6	28.7
4B	0.031	0.008	0.178	0.299	29.9	32.2
5A	0.034	0.008	0.177	0.296	29.6	28.3
5B	0.034	0.008	0.164	0.308	30.8	28.0
A	0.055	0.017	0.122	0.26	26.0	26.3
B	0.055	0.017	0.111	0.24	24.0	25.2
C	0.048	0.012	0.105	0.24	24.0	27.4
D	0.055	0.013	0.139	0.28	28.0	29.0
E	0.047	0.014	0.105	0.23	23.0	27.2
F	0.067	0.012	0.010	0.22	22.0	22.5
G	0.058	0.011	0.094	0.20	20.0	24.2
H	0.057	0.013	0.116	0.24	24.0	26.2
J1	0.060	0.010	0.105	0.27	27.0	25.1
J2	0.056	0.012	0.128	0.28	28.0	27.9
J1R	0.054	0.007	0.116	0.24	24.0	28.3
J2R	0.063	0.011	0.139	0.27	27.0	27.6
J2RR	0.063	0.013	0.128	0.28	28.0	26.0
K	0.064	0.008	0.105	0.26	26.0	24.6
L	0.063	0.007	0.139	0.34	34.0	28.5
M	0.048	0.009	0.128	0.34	34.0	30.3
N	0.053	0.007	0.122	0.32	32.0	29.1
O	0.045	0.009	0.145	0.30	30.0	32.8
P	0.048	0.011	0.111	0.28	28.0	28.3
Q	0.042	0.008	0.073	0.24	24.0	26.6
R	0.047	0.008	0.122	0.30	30.0	30.3
S	0.040	0.008	0.116	0.26	26.0	31.3
T	0.052	0.011	0.133	0.29	29.0	29.5
U	0.043	0.012	0.128	0.27	27.0	30.9
W	0.049	0.010	0.083	0.24	24.0	25.5
X	0.041	0.010	0.139	0.30	30.0	32.9
Y	0.046	0.010	0.105	0.26	26.0	28.4
Z	0.029	0.013	0.105	0.31	31.0	35.4
Comm1	0.034	0.011	0.116	0.28	28.0	32.3
Comm2	0.036	0.013	0.139	0.27	27.0	30.4

seems probable that it is the uniform component of plastic strain which reflects any influence of yield strength on tensile ductility. More work is needed to model the uniform component of plastic strain.

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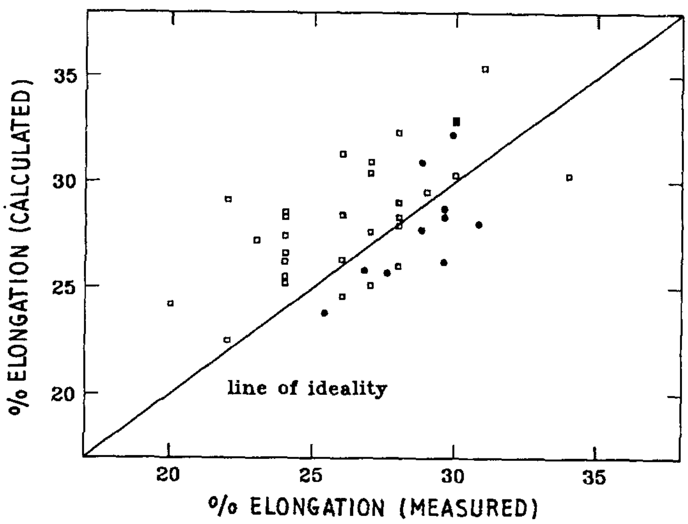

Figure 5 Recalculated and measured values for per cent elongation for this work and for Widgery [10] taking into account the inclusion content.

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