Table 1 Chemical composition of welding wire and base metal (wt pct)

	C	Si	Mn	P	S	Cr	Mo	Ni	Al	Co	Cu
316L steel	0.035	0.42	1.60	0.014	0.012	19.73	2.83	11.80	0.01	0.07	0.14
X65 steel	0.06	0.32	1.50	0.009	0.004	0.004	0.12	0.005	0.03	0.005	0.14
	Nb	Ti	V	W	Sn	B	As	Zr	Pb	Fe	
316L steel	0.48	0.005	0.08	0.03	–	–	–	–	–	balance	
X65 steel	0.05	0.02	0.04	<0.015	<0.002	–	0.005	0.003	–	balance	

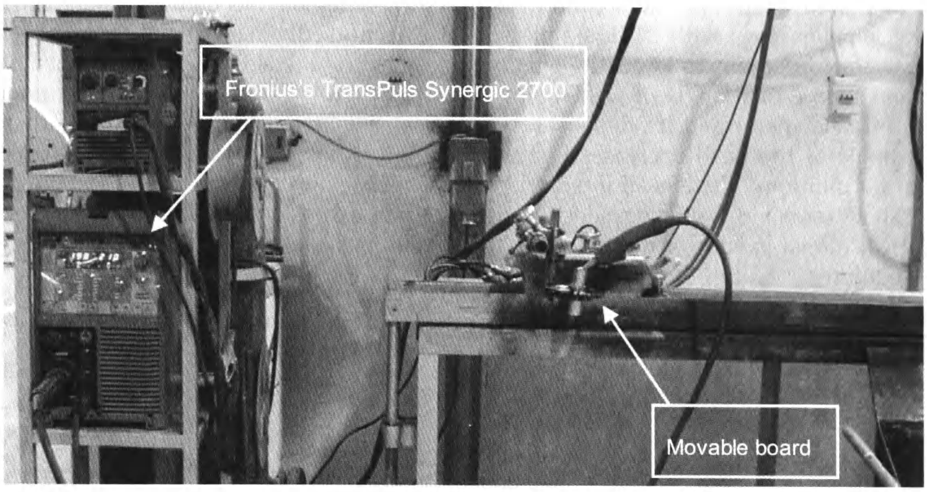

Fig.1 Experimental set-up used for cladding

Table 2 Welding parameters in blocks and their levels

Level	Wire feed rate/(m/min)	Travel speed/(cm/min)
1 (low)	4.5	30
2 (medium)	6.25	50
3 (high)	8	70

Table 3 Block parameters and their levels

Block	Distance between gas nozzle and plate/mm	Angle between gas nozzle and plate/deg.
1	10	0
2	5	0
3	10	20 (forehand)

Table 4 Measured values of bead dimension and dilution in block 1

No.	Feed rate(m/min)	Travel speed/(cm/min)	w/mm	h/mm	t/mm	D/%	Z/deg.
1	4.5	30	7.25	2.84	1.56	21.24	64
2	4.5	30	7.49	2.88	1.52	21.69	57
3	4.5	50	5.74	2.22	1.28	25.25	56
4	4.5	50	5.56	2.25	1.30	23.74	56
5	4.5	70	5.41	2.14	1.02	23.02	54
6	4.5	70	4.41	2.22	1.09	23.85	46
7	6.25	30	9.98	3.19	2.59	26.03	55
8	6.25	30	9.65	3.06	2.43	25.04	51
9	6.25	50	6.96	2.54	1.85	27.44	55
10	6.25	50	7.04	2.45	2.10	29.31	45
11	6.25	70	6.11	2.17	1.49	28.76	39
12	6.25	70	6.37	2.30	1.61	30.70	48
13	8	30	11.63	3.52	3.02	27.17	52
14	8	30	10.69	3.58	3.30	26.46	75
15	8	50	8.13	2.43	2.23	30.26	55
16	8	50	8.87	2.87	2.67	30.85	51
17	8	70	7.29	2.56	2.17	34.78	52
18	8	70	8.09	2.86	2.22	29.74	47

Table 5 Measured values of bead dimension and dilution in block 2

No.	Feed rate/(m/min)	Travel speed/(cm/min)	w/mm	h/mm	t/mm	D/%	Z/deg.
1	4.5	30	7.51	2.62	1.48	25.35	59
2	4.5	50	6.98	2.23	1.11	23.99	46
3	4.5	70	6.06	1.66	1.17	32.88	49
4	6.25	30	11.56	2.94	2.90	34.49	46
5	6.25	50	8.55	2.19	2.14	33.88	45
6	6.25	70	6.99	1.84	1.61	35.67	38
7	8	30	11.72	3.13	2.86	33.97	54
8	8	50	9.23	2.42	2.53	36.62	41
9	8	70	8.06	2.12	2.40	38.05	43

Table 6 Measured values of bead dimension and dilution in block 3

No.	Feed rate/(m/min)	Travel speed/(cm/min)	w/mm	h/mm	t/mm	D/%	Z/deg.
1	4.5	30	8.39	2.63	1.53	22.09	60
2	4.5	50	6.66	2.02	1.21	23.96	39
3	4.5	70	5.03	1.83	1.05	23.99	50
4	6.25	30	9.44	3.25	1.96	27.12	58
5	6.25	50	8.67	2.32	1.87	29.17	50
6	6.25	70	7.58	2.08	1.36	28.66	31
7	8	30	11.31	3.26	2.86	27.67	74
8	8	50	10.67	2.47	2.42	30.57	40
9	8	70	9.16	2.35	2.03	29.76	34

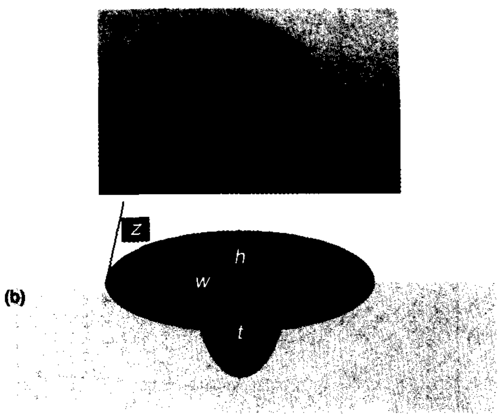

Fig.2 (a) Weld profile macrostructure of sample 18 in Table 4, (b) schematic illustration of bead geometry and dilution

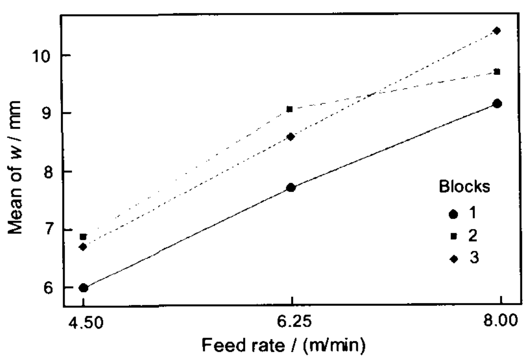

Fig.3 Effect of wire feed rate on means of w in 3 blocks

welding speed from 30 to 70 cm/min. Faster welding speed causes fewer melted wire deposited in the unit length and therefore smaller bead geometry. In both cases, width of bead increases with decreasing distance between gas nozzle and plate. The decrease in distance here means the decrease in electrode extension. This finding is in accordance with some previous studies[2,3,10]. Meantime, it is observed in the process that bead width increases in block 3 compared with block 1. In other words, forehand welding increases bead width.

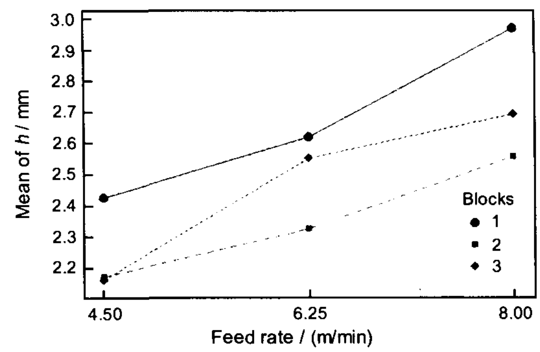

Fig.4 Effect of wire feed rate on means of h in 3 blocks

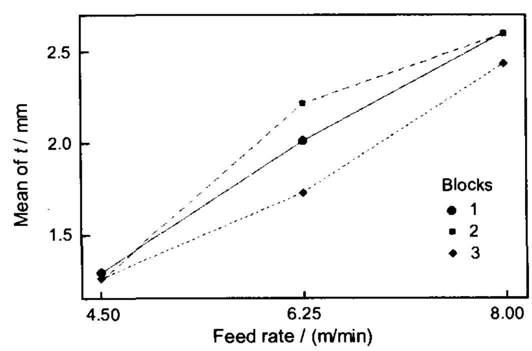

Fig.5 Effect of wire feed rate on means of t in 3 blocks

Figures 4 and 5 show the increase in bead height (h) and depth of penetration (t) in all 3 blocks, with the increase in wire feed rate from 4.5 to 8 m/min.

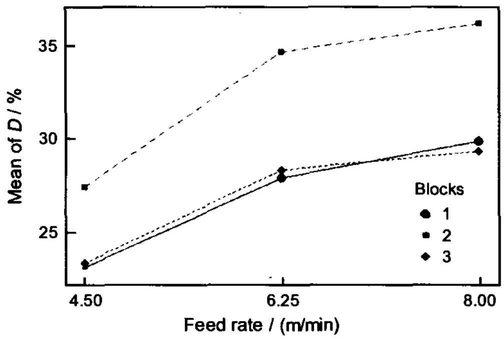

Fig.6 Effect of wire feed rate on means of D in 3 blocks

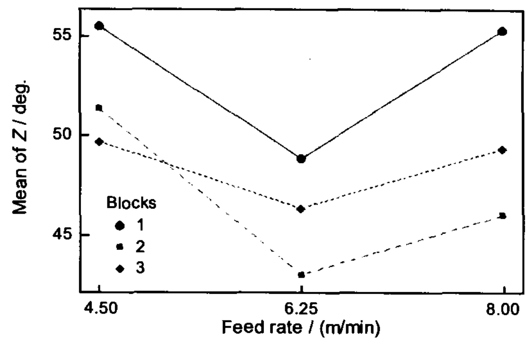

Fig.7 Effect of wire feed rate on means of Z in 3 blocks

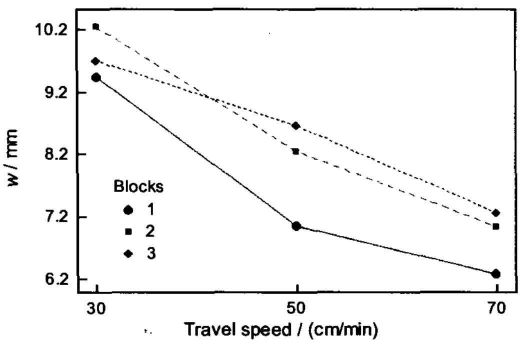

Fig.8 Effect of welding travel speed on means of w in 3 blocks

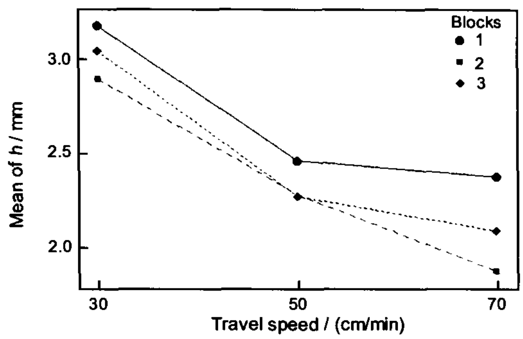

Fig.9 Effect of welding travel speed on means of h in 3 blocks

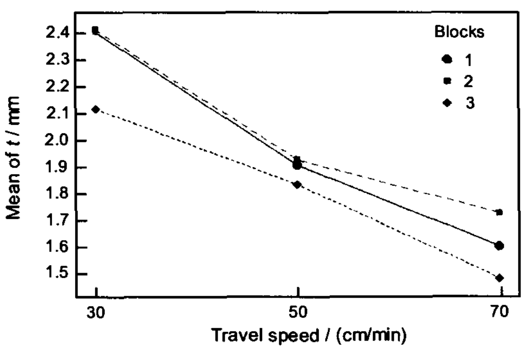

Fig.10 Effect of welding travel speed on means of t in 3 blocks

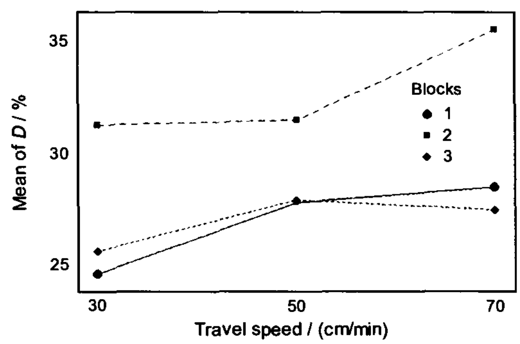

Fig.11 Effect of welding travel speed on means of D in 3 blocks

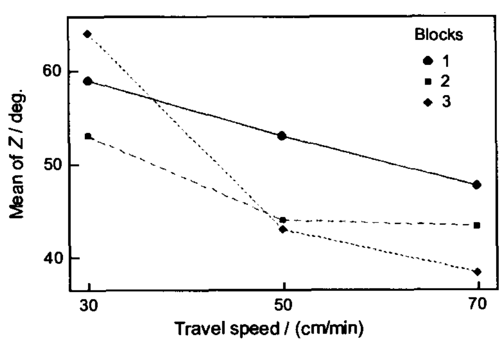

Fig.12 Effect of welding travel speed on means of Z in 3 blocks

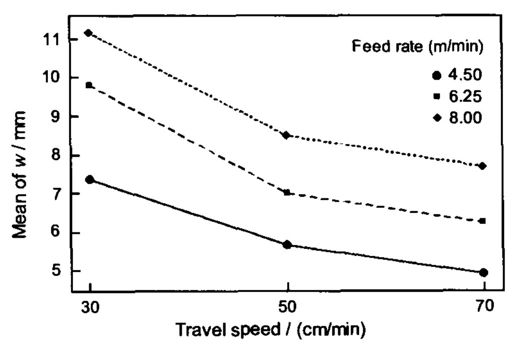

Fig.13 Interaction effect of wire feed rate and travel speed on w

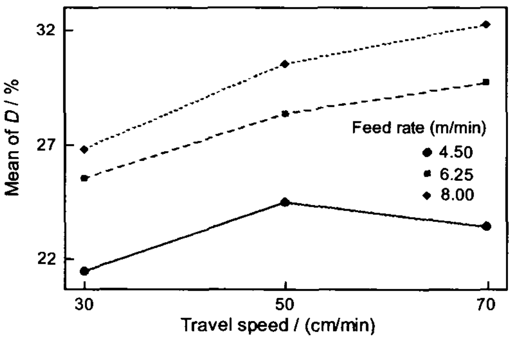

Fig.14 Interaction effect of wire feed rate and travel speed on D

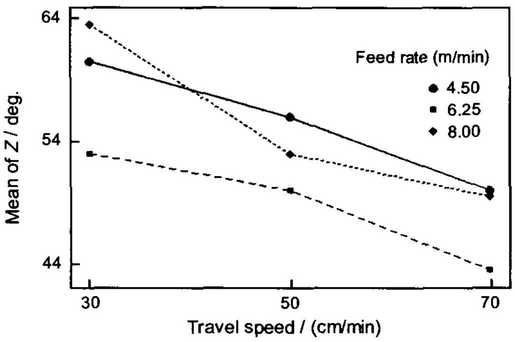

Fig.15 Interaction effect of wire feed rate and travel speed on Z

The behavior of h and t against welding travel speed is similar to w (see Figs.9 and 10). According to these figures, bead height decreases in block 2 and 3 compared with block 1. Therefore, it can be said that at a particular feed rate and travel speed, melting metal is constant in all 3 blocks and as such, width increases with decreasing the height. Meanwhile, the depth penetration behavior is different in all the blocks. The depth in block 2 is more than those of block 1 but at the same time block 3 has less depth. Thus, a forehand welding has a wider bead with less depth compared with block 1.

According to Figs.6 and 11, dilution (D) increases with increasing both wire feed rate and welding speed. In both situations, it seems that quantity of heat that affected the base metal or in the other words, arc power increases leading to the melting of more base metals. While comparing the variations of dilution in 3 experimental blocks, it is clear that blocks 1 and 3 roughly have the same dilution but dilution in block 2 encounters different situations. Welding specimens show that block 2 has more dilution than the other in average about 6%. However, electrode extension in this particular block is lesser than blocks 1 and 3.

Figures 7 and 12 indicate angle of contact (Z) that decreases with decreasing welding speed, but in feed rate, firstly it decreases to a minimum value and then increases once again. Comparisons of the two above cases show that specimens in block 1 have greater angle of contacts than those in blocks 2 and 3 in average about 7°.

Figures 13, 14 and 15 show the interaction effects of welding parameters on w, dilution and angle of contact. In Fig.13, it is clear that width has the same trends by changes in welding speed in different levels of feed rate. In the other words, all three lines have approximately similar shape. Also, distance between two lines is almost constant in the course of the length. Therefore, no interaction effects are seen between welding parameters, in the case of width. Figure 14 indicates that interaction effects on D. In this graph, the three rows are approximately similar and therefore, there seem no interaction effects in this situation either. Meanwhile, there appear to be different levels of feed rate in Fig.15, and thus, Z has different trends with increasing welding speed. It is evident that three graph lines have different trends and distance between each of two lines is up-and-down at different points.

Each of the weld bead parameters (w, h, t, Z and D) can be expressed as an mathematical function of f (wire feed rate) and s (welding speed)[3,10–12]:

$$y = \theta(f, s)$$

For this purpose, the quadratic regression model was used. They can be expressed thus:

$$Y = \beta_0 + \beta_1 f + \beta_2 s + \beta_{11} f^2 + \beta_{22} s^2 + \beta_{12} f s$$

where β_0 is a free term of the regression equation, β_1 and β_2 are linear term, β_{11} and β_{22} are the quadratic terms and, β_{12} is the interaction term.

The measured values of weld bead parameters are listed in Tables 4–6. From these tables, mathematical models were developed for three blocks through computer calculation as follows:

Block 1:

$$w = 5.48 + 0.90f - 0.08s - 0.14(0.57f - 3.57)^2 + 0.81\left(\frac{s}{20} - \frac{5}{2}\right)^2 - 0.25(0.57f - 3.57)\left(\frac{s}{20} - \frac{5}{2}\right)$$

$$h = 2.44 + 0.16f - 0.02s + 0.08(0.57f - 3.57)^2 + 0.32\left(\frac{s}{20} - \frac{5}{2}\right)^2 - 0.04(0.57f - 3.57)\left(\frac{s}{20} - \frac{5}{2}\right)$$

$$t = 0.63 + 0.37f - 0.02s - 0.06(0.57f - 3.57)^2 + 0.10\left(\frac{s}{20} - \frac{5}{2}\right)^2 - 0.12(0.57f - 3.57)\left(\frac{s}{20} - \frac{5}{2}\right)$$

$$D = 11.81 + 1.92f + 0.10s - 1.38(0.57f - 3.57)^2 - 1.27\left(\frac{s}{20} - \frac{5}{2}\right)^2 + 0.87(0.57f - 3.57)\left(\frac{s}{20} - \frac{5}{2}\right)$$

$$Z = 63.06 + 0.04f - 0.28s + 6.58(0.57f - 3.57)^2 + 0.33\left(\frac{s}{20} - \frac{5}{2}\right)^2 - 0.88(0.57f - 3.57)\left(\frac{s}{20} - \frac{5}{2}\right)$$

Block 2:

$$w = 4.24 + 0.80f + 0.03s - 0.77(0.57f - 3.57)^2 - 2.62\left(\frac{s}{20} - \frac{5}{2}\right)^2 + 0.06(0.57f - 3.57)\left(\frac{s}{20} - \frac{5}{2}\right)$$

$$h = 1.67 + 0.11f + 0.01s + 0.04(0.57f - 3.57)^2 - 0.82\left(\frac{s}{20} - \frac{5}{2}\right)^2 - 0.07(0.57f - 3.57)\left(\frac{s}{20} - \frac{5}{2}\right)$$

$$t = -0.04 + 0.38f + 0.005s - 0.29(0.57f - 3.57)^2 - 0.59\left(\frac{s}{20} - \frac{5}{2}\right)^2 + 0.05(0.57f - 3.57)\left(\frac{s}{20} - \frac{5}{2}\right)$$

$$D = 22.53 + 2.51f - 0.10s - 2.87(0.57f - 3.57)^2 + 2.24\left(\frac{s}{20} - \frac{5}{2}\right)^2 + 1.87(0.57f - 3.57)\left(\frac{s}{20} - \frac{5}{2}\right)$$

$$Z = 57.91 - 1.52f + 0.02s + 5.67(0.57f - 3.57)^2 - 9.33\left(\frac{s}{20} - \frac{5}{2}\right)^2 + 0.25(0.57f - 3.57)\left(\frac{s}{20} - \frac{5}{2}\right)$$

Block 3:

$$w = 5.18 + 1.05f - 0.06s - 0.03(0.57f - 3.57)^2 - 0.18\left(\frac{s}{20} - \frac{5}{2}\right)^2 + 0.30(0.57f - 3.57)\left(\frac{s}{20} - \frac{5}{2}\right)$$

$$h = 2.60 + 0.15f - 0.02s - 0.12(0.57f - 3.57)^2 + 0.30\left(\frac{s}{20} - \frac{5}{2}\right)^2 - 0.03(0.57f - 3.57)\left(\frac{s}{20} - \frac{5}{2}\right)$$

$$t = 0.45 + 0.33f - 0.01s + 0.12(0.57f - 3.57)^2 - 0.03\left(\frac{s}{20} - \frac{5}{2}\right)^2 - 0.09(0.57f - 3.57)\left(\frac{s}{20} - \frac{5}{2}\right)$$

$$D = 16.21 + 1.71f + 0.05s - 1.98(0.57f - 3.57)^2 - 1.35\left(\frac{s}{20} - \frac{5}{2}\right)^2 + 0.05(0.57f - 3.57)\left(\frac{s}{20} - \frac{5}{2}\right)$$

$$Z = 73.51 - 0.10f - 0.64s + 3.17(0.57f - 3.57)^2 + 8.17\left(\frac{s}{20} - \frac{5}{2}\right)^2 - 7.5(0.57f - 3.57)\left(\frac{s}{20} - \frac{5}{2}\right)$$

4. Conclusions

(1) Width, height, depth and dilution of weld metal increase with increasing the wire feed rate from 4.5 to 8 m/min, but the contact angle decreases first and again increases after reaching a minimum value.

(2) Width, height, depth and the contact angle of weld metal decrease with increasing welding speed from 30 to 70 cm/min, but dilution increases.

(3) Wire feed rate and welding speed appear to be have interaction effects on the angle of contact.

(4) Dilution increases in average about 6% and angle of contact decreases in average about 7° with decreasing the electrode extension. It seems that forehand welding has no apparent effect on dilution but reduces the angle of contact in average about 6°.

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