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Effects of the variables of the double wire MIG/MAG process with insulated potentials on the weld bead geometry

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Introduction

The Double Wire MIG/MAG welding process with Insulated Potentials makes use of two electrically insulated electrodes which are fused on a single puddle. Because of the characteristic of providing a high rate of material deposition, the process was initially used to weld thick sheets.[1] However, it has been mainly applied in the welding of thin sheets at high speeds of over 2 m/min.[2–4]

The characteristic of providing a high material deposition rate encouraged the use of Double Wire at the beginning of this century, largely in automated applications. The persuasive promotional advertising, which credits the process with advantages such as greater productivity, a lower heat application of heat to the part, and consequently less distortion, among other things, is contributing to this growth. In many applications the results are highly satisfactory and indicate significant increases in welding speed, thereby reducing total operating time. On the other hand, there are few scientific works that demonstrate or investigate the information (advantages) announced, or which present studies of the process.

With regard to MIG/MAG welding with a wire, Double Wire welding involves greater operational complexity. Besides the large number of parameters to be set in double wire welding, the equipment manufacturers incorporate technological details which are described as being of greater relevance in terms of welding results but which increase the operational difficulty of the process. An example of this is the phase shift between the current pulses (time at which one of the wires is in the pulse cycle of the current and the other in the basic cycle). This technology is used for the purpose of reducing the electromagnetic interactions (magnetic blowout) between the arcs, giving them greater stability.[1,2,3,5,6]

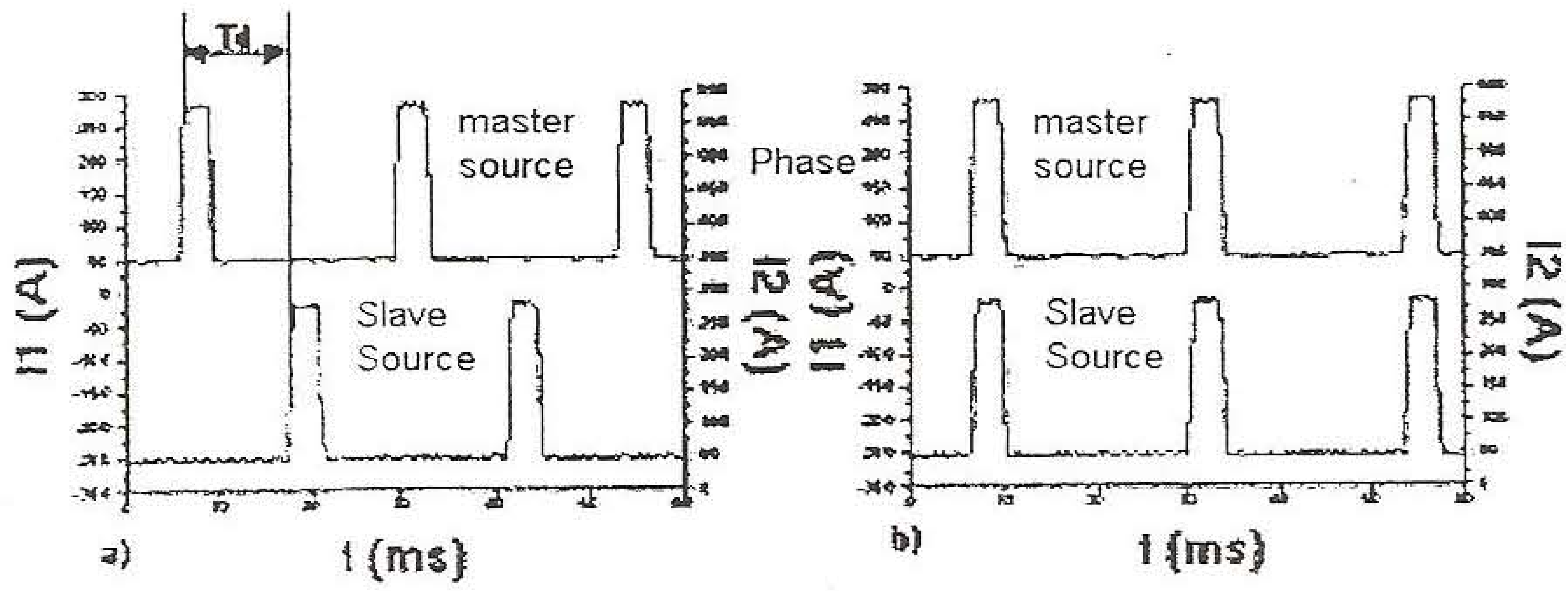
The greater operational complexity of Double Wire welding may result in failed applications of the process, causing irreparable losses. In Brazil, cases have been reported where users of the Double Wire have been obliged to shut down an entire production department because they did not achieve the claimed productivity with the process. Difficulties in obtaining stable voltaic arcs and with accessibility and positioning the torches on the joint limited the desired welding speeds or quality of the bead, causing a high part reject rate.

This work points to the need to conduct more detailed studies on Double Wire welding. The difficulties mentioned result from the lack of technical and scientific information on the process. Some statements made in the literature need to be carefully checked in terms of their accuracy with the aim of providing the user with better information. Important parameters, whose effects on the performance of the process are little known, such as the angle between torches, diameter of the electrodes, their position relative to the welding direction and arc length, need to be analysed in conjunction with the out-of-phase current pulses, in order to determine their influence on the weld beads, for example. The objective of this work is therefore to study the effects which these variables (phase shift between current pulses, mean current, positioning of the electrodes relative to the direction of welding displacement, length of the arcs, diameter of the electrodes) have on the geometric profile of the deposits, and to discuss the potential applications of the process.

Equipment, materials and experimental procedure

Equipment

All the welding operations in this work were carried out using two multi-process/multi-processed welding sources with a maximum current capacity of 450 A. The pulsed current with out-of-phase current pulses between the welding sources was used in all the tests. To promote this phase displacement, an electronic circuit was used in the welding sources for the purpose of controlling the pulsation times of the currents from each source. By means of this circuit the initiation of the pulsation of current from one of the sources (slave source) was controlled by the other (the master source). The out-of-phase time between the current pulses (time "Td" in



1 *Current oscillograms: a) Out-of-phase current pulses (Td – Out-of-phase time). b) Current pulses in ....*

Fig. 1) was specified by the user and corresponded to the time by which the slave source should delay the start of its pulsation relative to the initiation of the pulses from the master source. Besides the two welding sources, the test bench used consisted of: a) a system of linear displacement of the welding torches; b) two robot torches; c) two torches fixing supports; d) two wire speed measuring systems; e) a system for measuring the electrical values (voltage and current) and f) a data acquisition system.

Materials

All the welds were carried out on low class steel sheets of class ABNT 1010, which were cut to the dimensions of 12.5 x 100 x 200 mm and ground to remove the oxide layer. The electrode wires used were of class ER 70S-6, with diameters of 1.0 and were 1.2 mm thick. A mixture recommended by the manufacturer was used as the protective gas for welds with pulsed current, with 96% of Ar and 4% of CO_2 at a mean flow rate of 17 l/min.

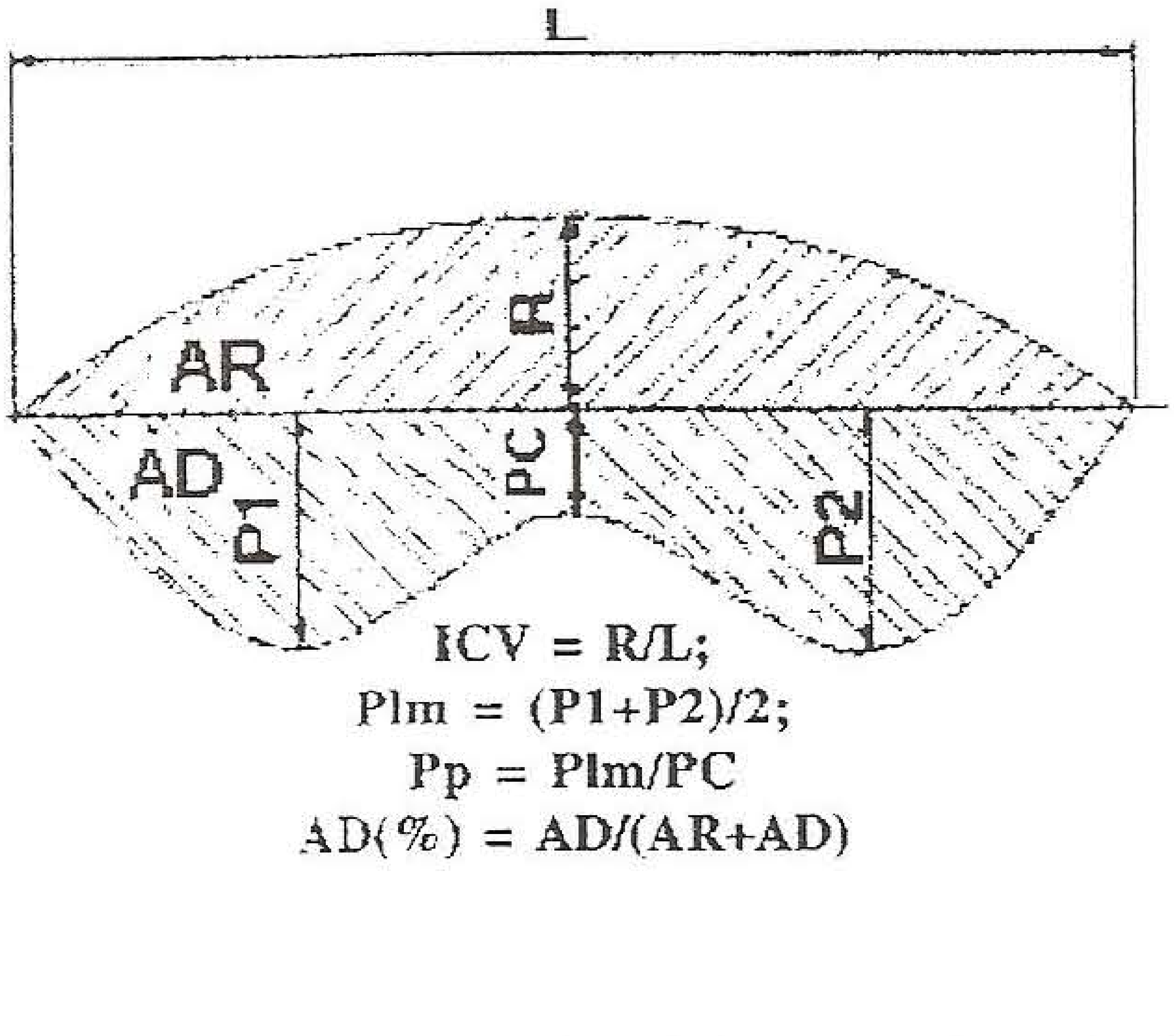
Experimental procedure

Due to the large number of variables to be analysed, the tests were divided into two stages. In the first stage only the effects of the angle between the electrodes on the variables of response of the experiments were analysed.

In the second phase the effects of the variables phase displacement between the current pulses, mean current, positioning of the electrodes relative to the direction of welding displacement and length of the arcs were analysed altogether.

The geometric characteristics of the bead profile were considered as response variables of the experiments (Fig. 2). These variables were: index of convexity* (ICV); mean penetration of the sides of the bead (Plm); penetration in the centre of the bead (PC); penetration profile** (Pp) and percentage of diluted area (AD). The selection of these variables relating to the profile of the weld bead, as experimental responses, is aimed at evaluating how the geometry of the weld changes with the process variables. The intention was to determine which was the most suitable profile for the main applications of the process, for example, coating welds, requiring long, flat beads (and therefore with a low ICV) and with low dilution.

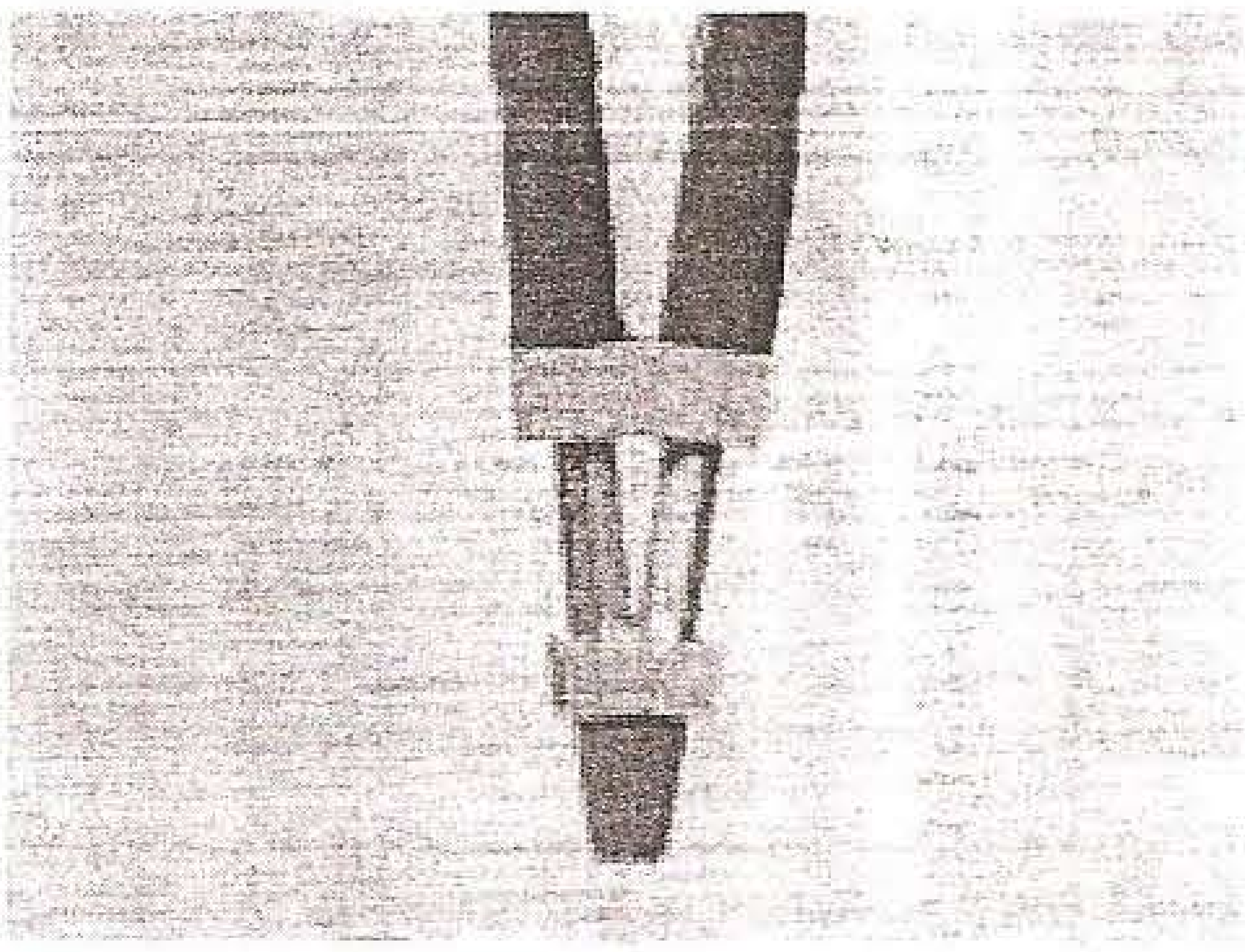
Each weld bead produced, approximately 150 mm in length, was cut in the transversal direction in two positions. Care was taken to maintain a distance of 30 mm between the start and end of the beads. This being so, two samples of transverse sections in each welding condition tested were prepared for the measurements. The samples were sanded (sand up to 600 mesh) and attacked with a solution of 3% nital to detect the penetration profiles, then photographed. The geometric characteristics shown in Figure 2 were measured by means of commercial software.



2 *Diagrammatic representation of the geometric profile of a weld bead. AR – area of reinforcement and AD (%) – diluted area.*

Stage 1 – Effect of the angle between the electrodes on the geometry of the weld bead

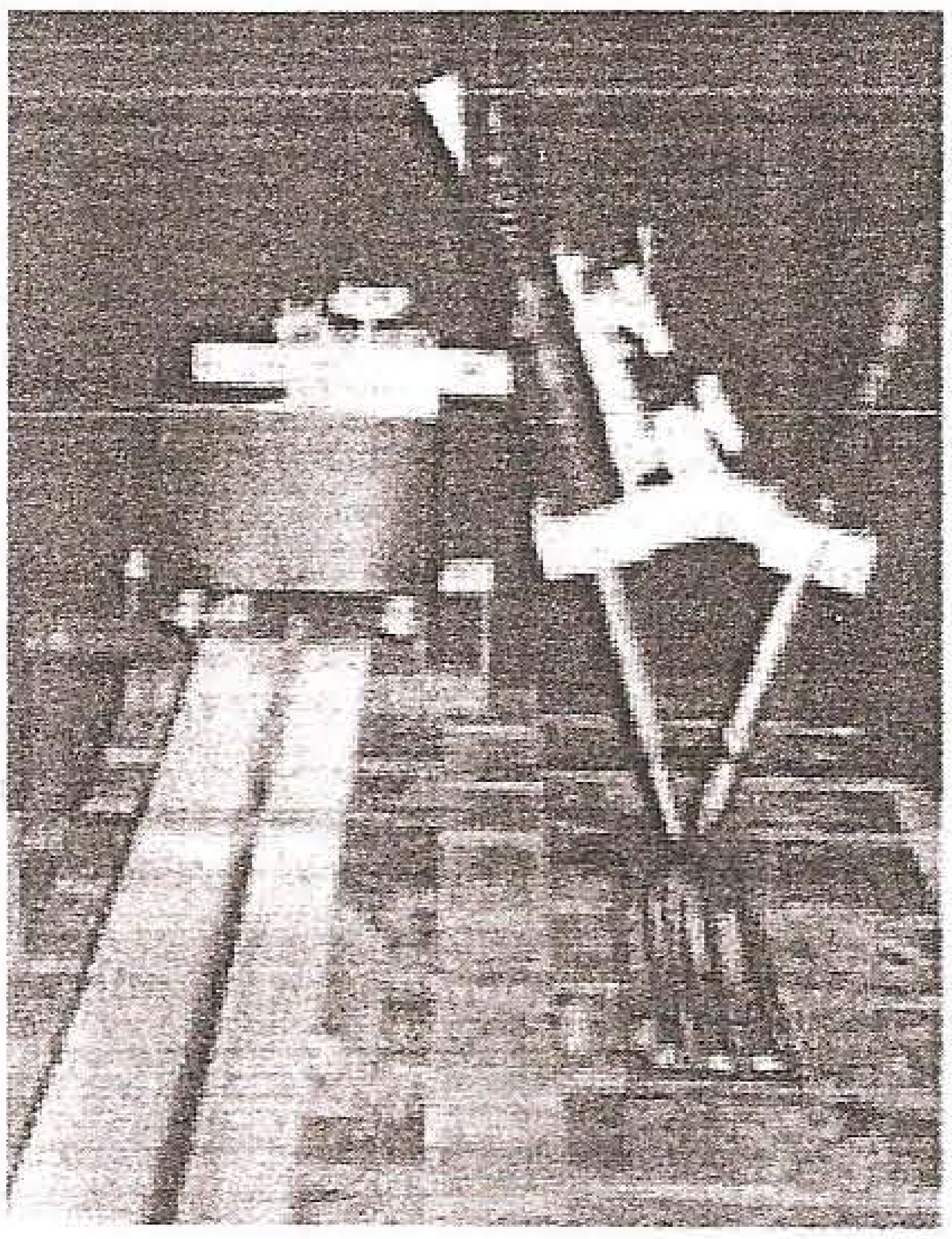
The purpose of the experimental tests carried out in this sub-item was to determine the effects of the angle between the electrodes on the geometric characteristics of the deposits. Two supports with different torch fixing angles were used to carry out the tests (Fig. 3). Because this is an investigative work, the supports were developed specifically for these tests. However, the authors of this work tried to design them with structural characteristics (angle between torches, distance between wires) similar to those observed in commercial available supports and torches for the double wire systems.



Support 1 – *angle between torches:13°*

Support 2 – *angle between torches: 30°*

3 *Torch fixing supports used in the tests.*



4 *"Side by side" positioning of the electrodes for carrying out the welding operations.*

The welding conditions in which these tests were carried out are shown in Table 1. The current pulsation parameters were set in the same way for both electrodes. The tests were carried out with the electrodes positioned one alongside the other relative to the direction of welding displacement ("side by side" position), and two beads were welded for each condition.

All the welds were carried out using pulsed current in both the electrodes, with mean values at two levels: 100 and 160 A/wire. The position of the electrodes (PE) relative to the welding displacement was analysed in two different situations: electrodes positioned one alongside the other "side by side" – LL) and electrodes positioned one in front of the other ("tandem" TD). The photo in Figure 4 shows the LL positioning of the electrodes for carrying out the tests.

As far as the phase displacement between the current pulses (DF) is concerned, this variable was analysed with the out-of-phase current pulses (Df) and with the in-phase pulses (F), in this case Td = 0 ms (Figs. 1a and 1b respectively). The arc lengths were included among the variables to be analysed to determine their effects on the profile and finish of the deposits, these fluctuating between tolerable values for the stabilities of the arcs (lengths ranging from approximately 5 to 8 mm).

The procedure used to carry out the tests was based on a factorial fractionated design of four factors at two levels, totalling 8 welding conditions. Since the tests were carried out in two blocks, one with the 1.0 mm electrode and the other with the 1.2 mm electrode, this totalled 16 tests.

The factorial fractionated design may be used in planning experiments which have a large number of factors to be investigated, the aim being to reduce the number of tests. According to Montgomery,[7] it is possible, using this technique, to analyse the effects of K factors at two levels each, in 2^{k-p} combinations of tests, only a part of the experiment being carried out without significantly compromising on the reliability of the conclusions obtained from analysing the results (for p=1 only half the experiments are carried out, for p=2 only ¼).

Table 2 shows the sequence of experiments carried out for the electrode of smaller diameter, and Table 3 shows that for the electrode of larger diameter. In each block of tests the welding speed was varied between the tests in order to keep approximately constant the volume of material deposited in the unit of time. This procedure guarantees that the energies imposed in all test

Table 1 Welding conditions in which the tests were carried out

Im (A/ar.)	Ip (A)	tp (ms)	Ib (A)	tb (ms)	Td (ms)	ϕ (°)	Vs (cm/min)	Da (mm)	Va1 (m/min)	Va2 (m/min)	ca (mm)	d_c (mm)
100	240	4.1	46	10.6	7.4	13	30	8	4.5	4.9	≈5	1.0
100	240	4.1	46	10.6	7.4	30	30	8	4.5	4.9	≈5	1.0

Notes: Im – mean current in each wire; Ip – pulsed current; tp – time and pulse; tb – basic current; sb = base time; f - angle between torches; Vs – welding speed; da – distance between wires; va1 – speed of wire 1; Va2 – speed of wire 2; ca – length of the arcs; d_3 – electrode diameter

Table 2 Sequence of the tests carried out for 1.0 mm wire

Sequen.	Im (A/ar.)	Ip (A)	tp (ms)	Ib (A)	tb (ms)	Td (ms)	PE.	ca (mm)	Vs (cm/min)	Va1 (m/min)	Va2 (m/min)
1	100	270	3.9	47	12.6	8.3	LL	5	22	4.1	4.8
2	100	270	3.9	47	12.6	0.0	LL	8	20	3.7	4.4
3	160	270	3.9	76	5.6	4.8	LL	8	34	6.1	7.4
4	160	270	3.9	76	5.6	0.0	LL	5	33	6.4	7.7
5	100	270	3.9	47	12.6	8.3	TD	8	22	3.5	4.2
6	100	270	3.9	47	12.6	0.0	TD	5	22	3.9	4.7
7	160	270	3.9	76	5.6	4.8	TD	5	33	6.3	7.6
8	160	270	3.9	76	5.6	0.0	TD	8	34	6.1	7.4

Table 3 Sequence of tests carried out for 1.2 mm wire

Sequen.	Im (A/ar.)	Ip (A)	tp (ms)	Ib (A)	tb (ms)	Td (ms)	PE.	ca (mm)	Vs (cm/min)	Va1 (m/min)	Va2 (m/min)
1	100	300	4.0	55	17.8	10.9	LL	8	22	2.5	2.4
2	100	300	4.0	55	17.8	0.0	LL	5	20	2.9	2.6
3	160	300	4.0	102	9.6	6.8	LL	5	34	4.3	4.4
4	160	300	4.0	102	9.6	0.0	LL	8	33	4.0	4.1
5	100	300	4.0	55	17.8	10.9	TD	5	22	2.4	2.4
6	100	300	4.0	55	17.8	0.0	TD	8	22	2.3	2.3
7	160	033	4.0	102	9.6	6.8	TD	8	33	3.9	3.9
8	160	300	4.0	102	9.6	0.0	TD	5	34	4.2	4.1

combinations are similar and that comparisons can be made between deposits welded with different levels of mean current.

In these tests the support with the angle between torches of 30° was used.

Experimental results and discussion

Stage 1 – Effects of the angle between the electrodes on geometry of the weld bead.

The results obtained from the tests in this stage may be visualised in Table 4, which shows the mean values of the geometric characteristics of the beads.

These results were subjected to variance analyses. The values of the significance levels "a" are shown in Table 5. With a reliability of 95%, the underlined values indicate statistically significant effects, i.e. they signify that there is a probability of error of less than 5%, allowing for the fact that the angle between torches factor influences the response variables analysed.

The significance levels listed in Table 5 indicate that the angle between torches has a significant influence on PC, Pp (Plm/PC) and AD (%). These effects can be seen in the graphs in Figs. 5, 6 and 7.

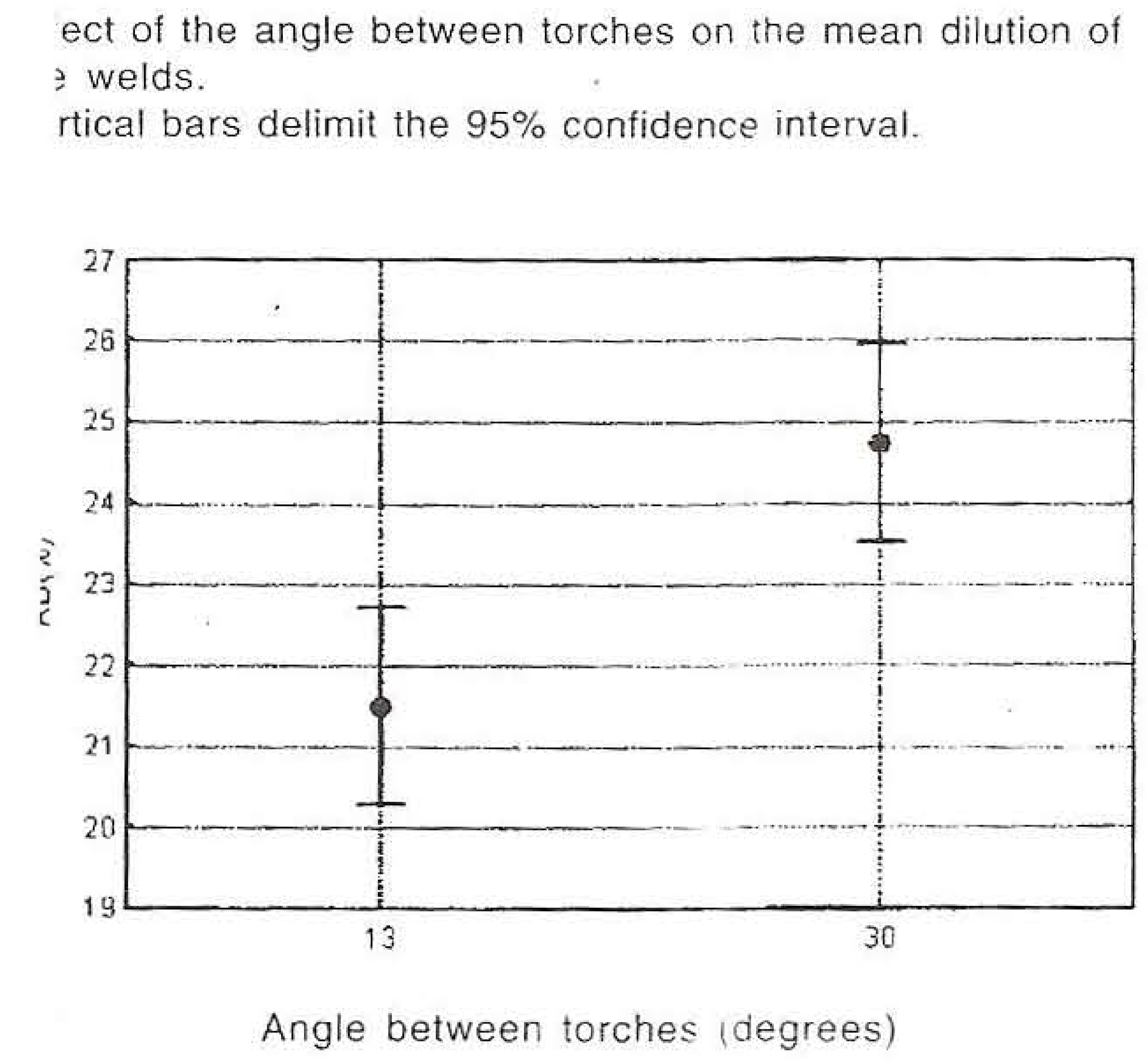
The three graphs show that torches separated by greater angles give rise to increases in the dilution of the welds and tend to increase the penetration in the centre of the beads, favouring the formation of more uniform profiles, because there is tendency toward a reduction in the difference in penetration between the centre of the bead and its ends. This profile described can be seen in the photo in Figure 8a. The photo in Figure 8b illustrates a penetration profile obtained with a smaller angle between torches (13°). The greater penetration is seen at the centre of the bead relative to the penetration on the sides.

Table 4 Geometric characteristics measured in the weld beads

Beads	ϕ(°)	L(mm)	R(mm)	PC(mm)	Plm(mm)	(Plm/PC)	AD(%)
Bead 1	13	14.39	2.57	0.046	1.61	35.0	21.34
Bead 2	13	14.85	2.66	0.06	1.68	28.0	21.67
Bead 1	30	14.34	2.63	0.16	1.69	10.6	24.37
Bead 2	30	13.72	2.69	0.15	1.82	12.1	25.10

Table 5 Levels of significance calculated for the effects of the torch angles on the response variables

Variables	L	R	PC	Plm	Plm/PC	AD(%)
"α"	0.266	0.493	**0.007**	0.274	**0.027**	**0.015**



Effect of variation of the angle between torches on penetration at the centre of the bead.

Stage 2 – Effects of the variables phase displacement between current pulses, mean current, positioning of the electrodes and length of the arcs on the profile of the beads

The measured values of the geometric characteristics of the deposits are shown in Table 6 for the tests carried out with the 1.0 and 1.2 mm electrodes.

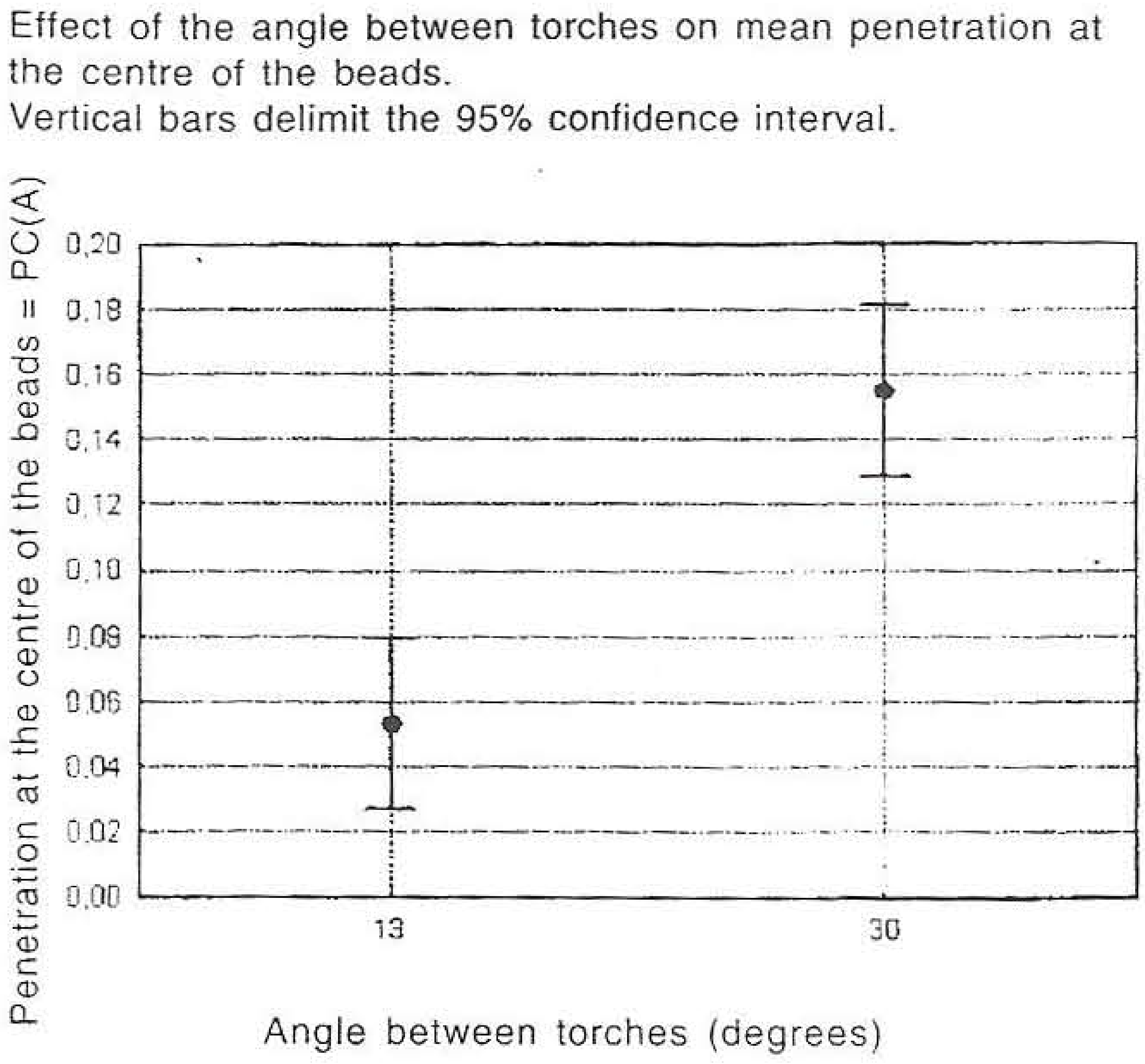
Correlation analyses were carried out to determine the degree of association between the variables analysed and the geometric characteristics measured. Table 7 shows the correlation coefficients and the respective levels of significance (values in brackets) for the tests carried out with the 1.0 and 1.2 mm wires. With 95% reliability, the significance levels less than 0.05 indicate a "non-zero correlation", i.e. the values are correlated statistically significantly (with a probability of error of less than 5%). The underlined indices indicate what the variables are.

It will be noted that in both groups of experiments (tests with 1.0 and 1.2 mm wires) the correlations between the variables showed the same tendencies. For example, the width of the beads tends to increase and the convexity index tends to decrease (significantly for the two electrode diameters) as the mean current increases. The coefficients indicate that the arc length variable shows small correlations with the variables analysed. However, in comparing the electrodes, there is a reversal of the signs of the coefficients of correlation between the variables arc length (ca) and penetration profile (Pp = PLM/PC).

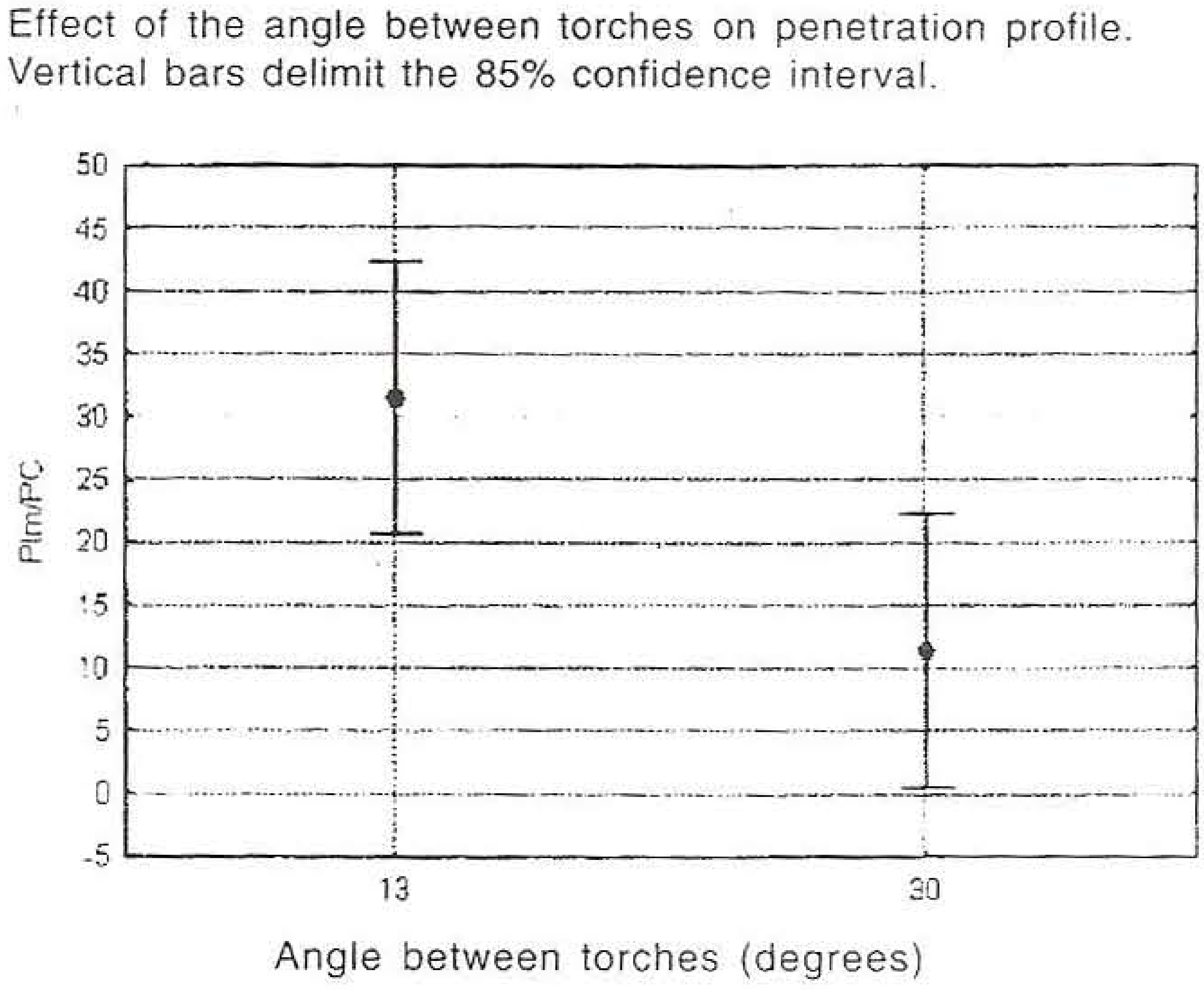
Partial correlation analysis

The partial correlation analysis provides a clearer idea of the individual effects of each independent variable on the response variable since it measures the correlation of two variables, all the others being kept constant. Table 8 shows the coefficients of the partial correlation analyses applied to the data in Table 6. It will be seen that there were no changes in the tendencies already observed in the correlation analysis in Table 7. However, some of the more significant correlations are shown. These are the correlations of the variables position of the electrodes (PE), phase displacement of the current pulses (DF) and length of the arcs (ca) with penetration in the centre of the bead (PC), and position of the electrodes (PE) with penetration profile (Pp = Plm/Pc) for the 1.2 mm electrode. Figures 11, 12 and 13 respectively show these tendencies.

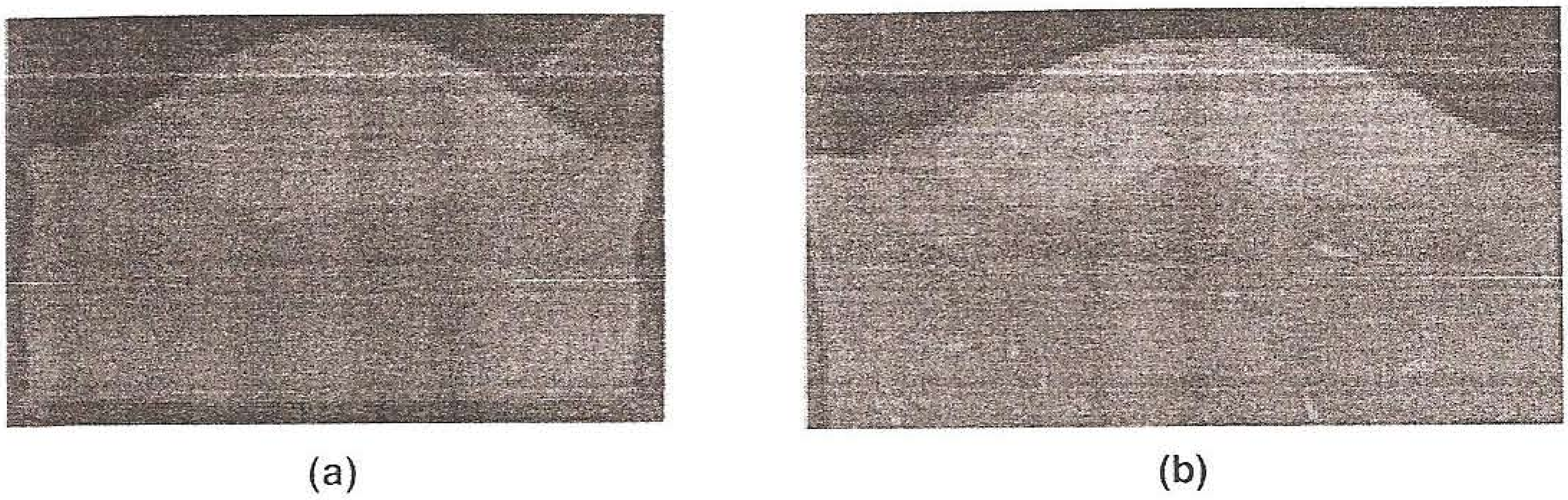
As with the correlation analysis in Table 7, it is noted in Table 8 that despite being low, the partial correlation coefficients of both electrodes indicated contrary effects between the variables arc length (ca) and penetration profile (Pp = Plm/PC). This result does not mean that the effects of the arc length variable (ca) on the variables mean penetration on the sides of the bead (Plm) and penetration in the centre of the bead (PC) are different for the two diameters analysed. It may be deduced from the coefficients in Table 8, for the two electrode diameters,



6 *Effect of the variation of the angle between torches on the penetration profile Pp (Plm/PC).*



7 *Effect of variation of the angle between torches on dilution.*



8 *a) – More uniform penetration profile. Im = 100A/wire, f = 30°; 8*
b) Less uniform profile with double penetration characteristics. Im = 100A/wire, f = 13°.

that both PC and Plm tend to decrease with the increase in the arc lengths. The reversal of signs of the coefficients means that the penetration profiles of the beads welded with the 1.2 mm electrodes and high voltaic arcs showed clearer double penetration characteristics (less uniform) than the profiles welded under the same conditions with the 1.0 mm electrodes. This is because the welding operations with the higher diameter electrode and high arcs showed a low penetration in the centre of the beads. (The high coefficient of partial correlation between the variables arc length (ca) and penetration in the centre of the bead (PC) confirms this result). These results coincide with those observed by Ecer [8], who studied the effects of an external magnetic field parallel with the direction of welding, on the behaviour of voltaic arcs in the TIG process. The author claimed that arcs formed from electrodes of greater diameter deflect less, but that they are colder than those formed from electrodes of smaller diameters; long arcs, despite being deflected more easily, show a lower current density adjacent to the cast puddle.

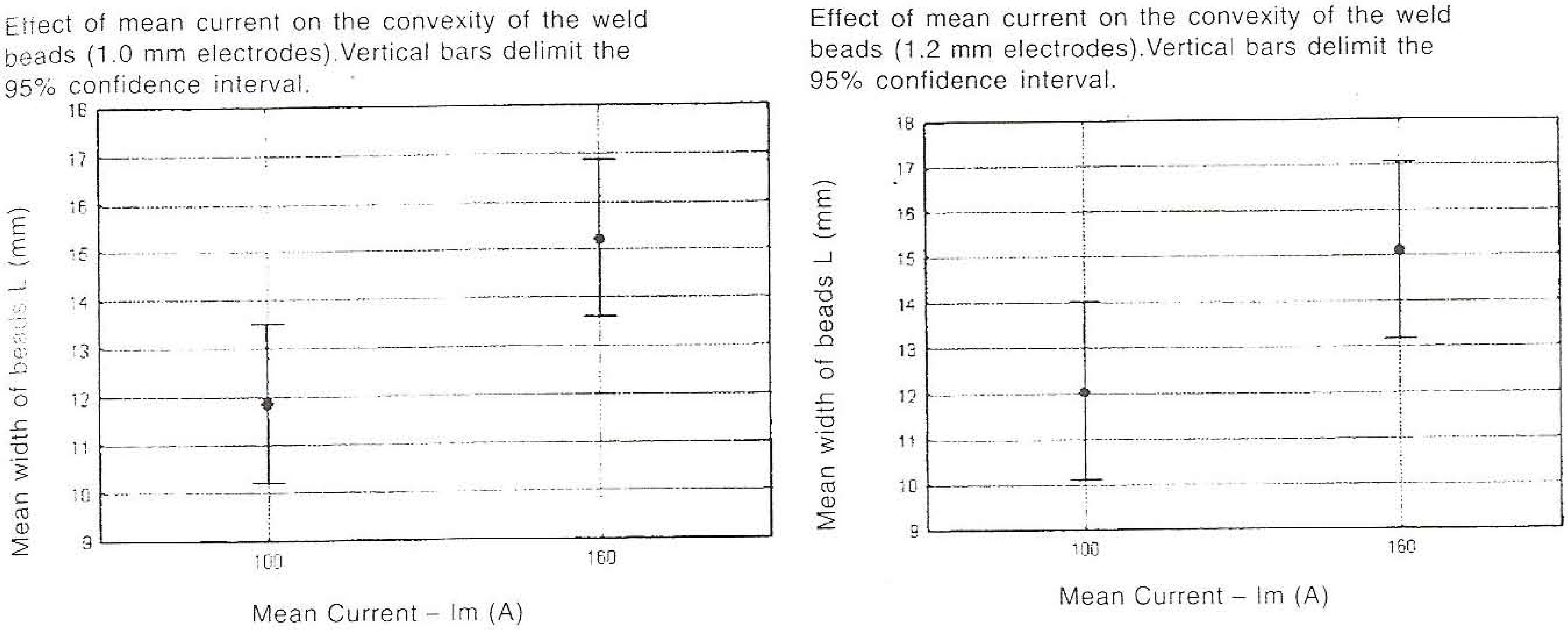
Table 6 Geometric characteristics measured in the welded beads with 1.0 and 1.2 mm electrodes

Sequence	d_e (mm)	L(mm)	ICV	PC(mm)	Plm (mm)	P_r	AD(5)
1	1.0	14.47	0.22	0.20	1.55	7.75	24.33
	1.2	13.6	0.20	0.23	1.00	6 93	25.67
2	1.0	11.20	0.32	1.53	0.50	0.34	22.00
	1.2	13.23	0.23	1.07	0.52	0.48	24.00
3	1.0	15.83	0.18	0.83	1.93	2.53	37.33
	1.2	16.77	0.14	0.63	1.38	2.53	36.00
4	1.0	15.63	0.20	1.43	0.77	0.54	29.67
	1.2	14.23	0.21	1.00	0.70	0.71	26.00
5	1.0	9.97	0.35	1.23	0.40	0.31	18.00
	1.2	10.47	0.30	1.40	0.38	0.28	22.00
6	1.0	11.77	0.30	1.63	0.60	0.38	24.67
	1.2	10.90	0.27	1.33	0.27	0.20	22.00
7	1.0	15.03	0.23	2.13	0.70	0.32	34.00
	1.2	14.27	0.18	1.03	0.48	0.47	25.67
8	1.0	14.40	0.20	1.60	0.55	0.35	28.33
	1.2	15.17	0.18	1.70	0.57	0.34	30.00

Table 7 Correlations between the input variables and the experimental responses. Coefficients and levels of significance (values in brackets)

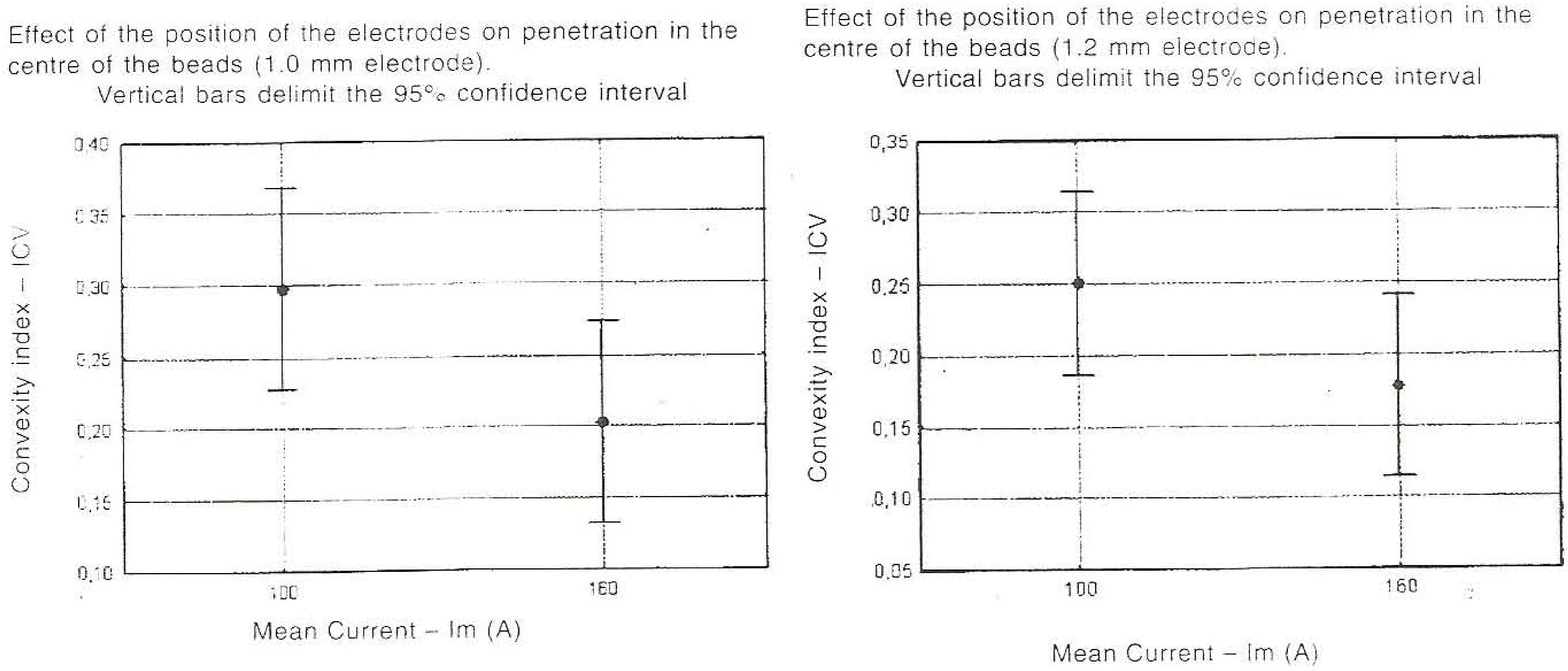
Variable	d_e (mm)	L	CV	PC	Plm	P_r(Plm/PC)	AD(5)
PE LL=>TD	1.0	−0.357 (0.385)	0.310 (0.455)	0.594 (0.121)	−0.601 (0.115)	−0.502 (0.205)	−0.175 (0.678)
	1.2	−0.450 (0.264)	0.398 (0.329)	**0.739** **(0.036)**	−0.696 (0.055)	−0.525 (0.182)	−0.346 (0.402_
Im	1.0	**0.808** **(0.015)**	**−0.805** **(0.016)**	0.319 (0.440)	0.216 (0.607)	−0.258 (0.538)	**0.848** **(0.008)**
	1.2	**0.782** **(0.022)**	**−0.729** **(0.04)**	0.097 (0.819)	0.354 (0.39)	−0.239 (0.568)	0.691 (0.058)
DF Df=>F	1.0	−0.138 (0.745)	0.092 (0.829)	0.411 (0.311)	−0.521 (0.186)	−0.476 (0.233)	−0.189 (0.653)
	1.2	−0.100 (0.813)	0.176 (0.676)	0.525 (0.181)	−0.439 (0.276)	−0.474 (0.235)	−0.211 (0.616)
Ca	1.0	−0.330 (0.426)	0.250 (0.558)	−0.050 (0.914)	−0.060 (0.895)	−0.280 (0.502)	−0.150 (0.728)
	1.2	−0.168 (0.690)	0.060 (0.887)	−0.350 (0.395)	−0.147 (0.729)	0.288 (0.489)	−0.365 (0.374)

Note: LL => TD represents the transfer of the variable PE from level LL to level TD.
Df => F represents the transfer of the variable DF from the out-of-phase to the phase level.



(a) (b)

9 *Effect of current on the width of the weld beads. A) 1.0 mm wire and b) 1.2 mm wire.*



(a) (b)

10 *Effect of current on the convexity index. A) 1.0 mm wire and b) 1.2 mm wire*

It is not sufficient to melt the material in the region. The reduction in penetration in the centre of the beads (more evident for the 1.2 mm wire) may be explained by the results obtained by Ecer.[8]

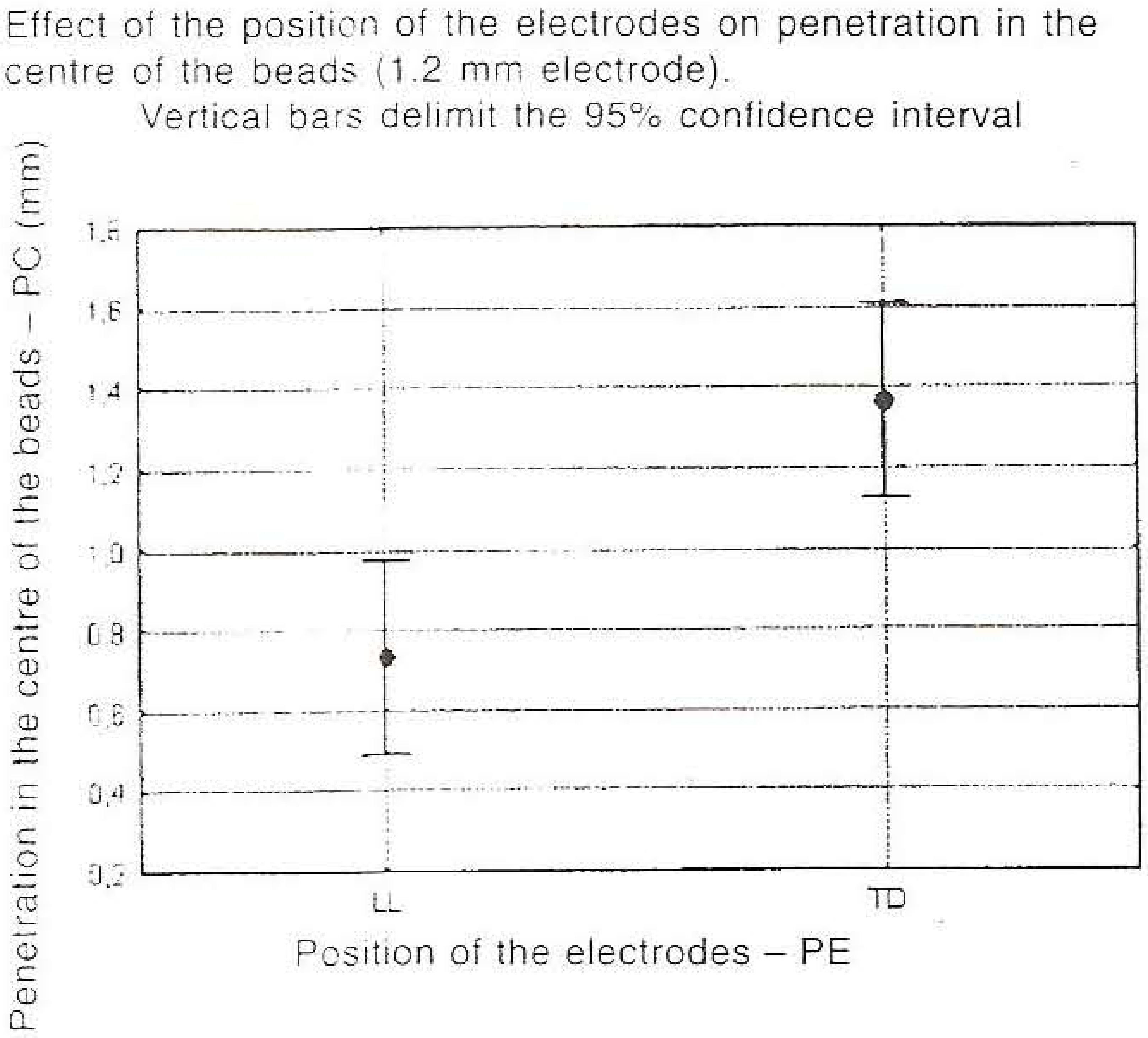
In analysing the results of this work it may be ascertained that a larger angle between torches tends to provide the beds with a more uniform penetration profile and greater dilution.

Generally speaking, the variables relating to the penetrations of the beads (PC, Plm and %AD) are more likely to increase with the increase in mean current. The penetration in the centre of the beads tends to increase, and that on the sides decrease when the positioning of the electrodes changes from "side by side" to "tandem" (geometric characteristic of the bead similar to the profile shown in Figure 8a). This same tendency is observed with a change in the condition from out-of-phase pulses to in-phase pulses.

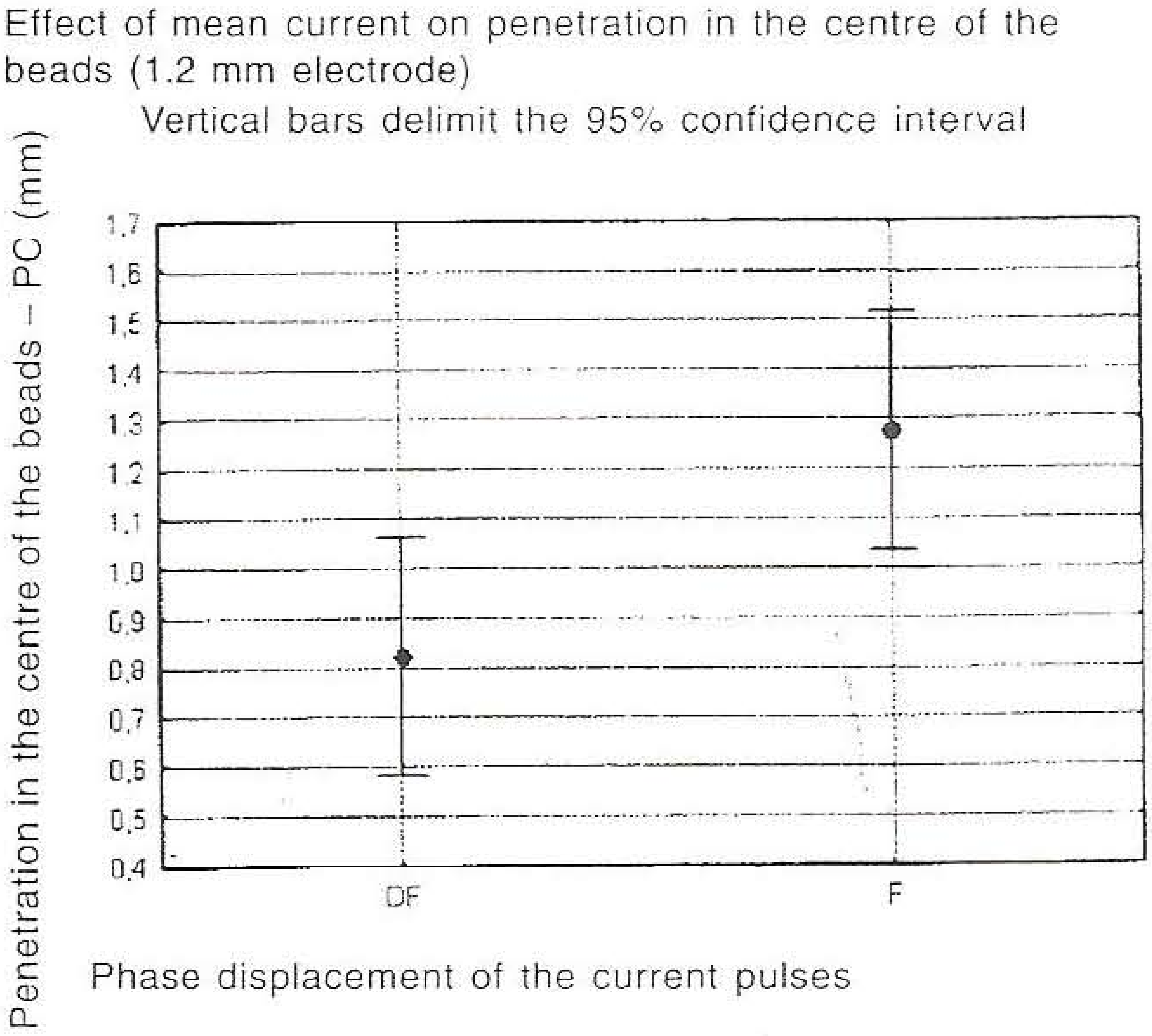
The possibility of working with these variables, and consequently changing the geometric characteristics of the beads, demonstrates the flexibility of the process. According to the application, if a user of the process wishes to apply the double wire in coating operations (low penetration and flatter bead), he must use low mean current levels in each arc, electrodes positioned "side by side" and out-phase current pulses. However, if he wants to weld in joints, and even with side by side electrodes, he must adjust the higher mean current levels in each arc and the in-phase current pulses, since these conditions provide a bead of greater regularity (Pp close to the value 1) and greater penetration in the centre of the bead. It must be emphasised that since the welds were produced from simple depositions (closer to the coating reality), these tendencies must be treated with reservation for welds in a chamfered joint.

Table 8 Coefficients of partial correlation between the input variables and the experimental responses

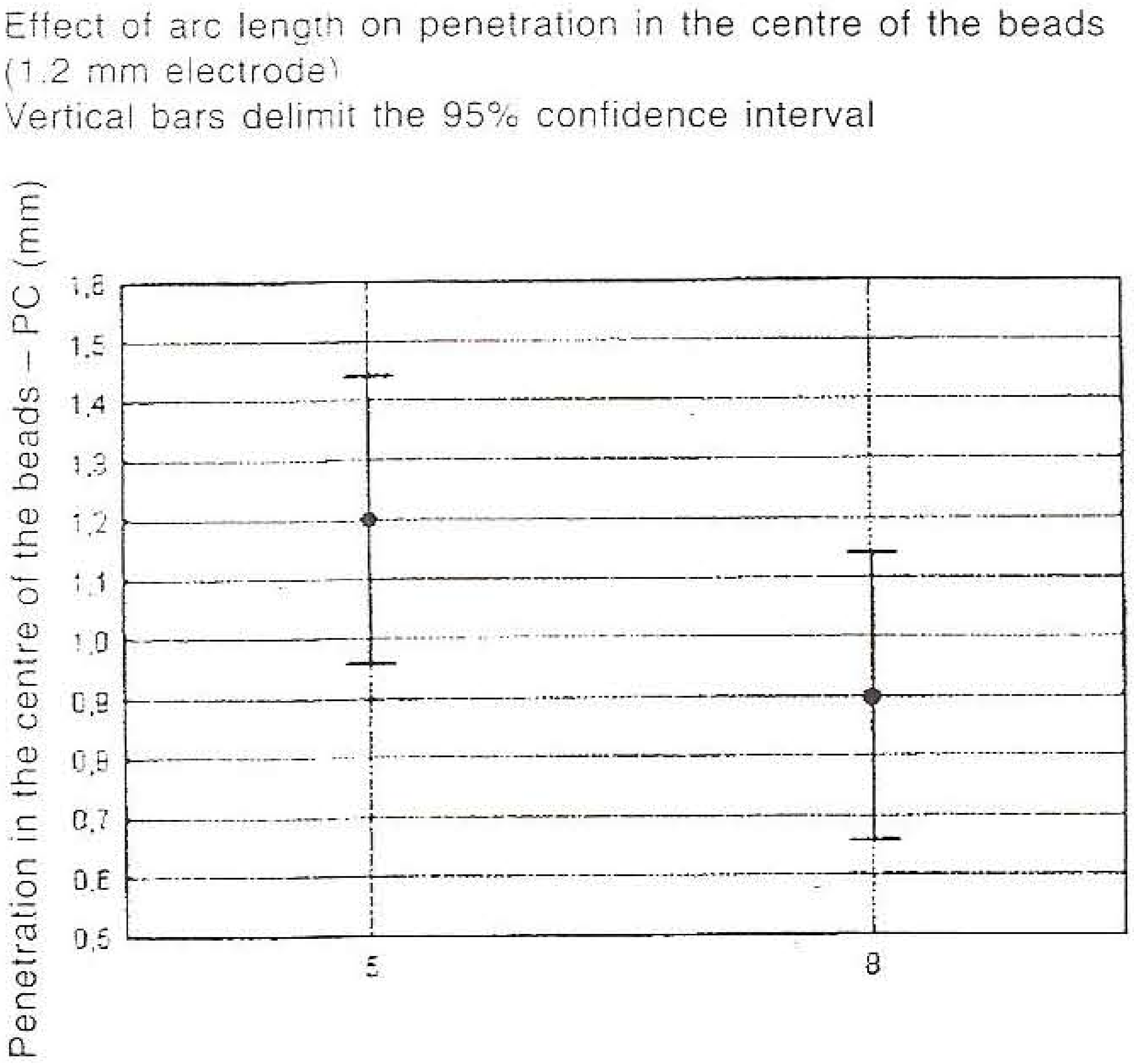
Variable	d_e (mm)	L	CV	PC	Plm	P_p(Plm/PC)	AD(5)
PE LL=>TD	1.0	–0.763	0.581	0.697	–0.729	–0.633	–0.371
	1.2	–0.761	0.604	**0.960**	**–0.856**	–0.658)	–0.588
Im	1.0	**0.937**	**–0.881**	0.464	0.358	–0.387	**0.888**
	1.2	**0.898**	**–0.811**	0.412	0.645	–0.370	**0.824**
DF Df=>F	1.0	–0.415	0.207	0.558	–0.678	–0.613	–0.397
	1.2	–0.253	0.318	**0.926**	–0.723	–0.620	–0.406
Ca	1.0	–0.734	0.493	–0.075	–0.099	–0.415)	–0.318
	1.2	–0.402	0.114	**–0.852**	–0.330	0.433	–0.609



11 *Effect of variation in the position of the electrodes on penetration in the centre of the beads.*



12 *Effect of phase displacement between the current pulses on penetration in the centre of the beads.*



13 *Effect of arc length on penetration in the centre of the beads.*

Conclusions

The results obtained in this work for carbon steel welding enable the following conclusions to be drawn:

- A greater angle between the electrodes resulted in increases in penetration in the centre of the beads and in dilution, and tends to provide welds with more uniform penetration.
- The change in positioning of the electrodes from "side by side" to "tandem" increases the penetration in the centre of the beads and tends to provide welds with more uniform penetration.
- Increases in mean current tend to increase the penetration, dilution and width of the beds, causing them to be flatter.
- In keeping all the other variables constant, increases in the length of the arcs results in a reduction in the penetration in the centre and in the sides of the beads.

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