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Assessment of the Use of Negative Polarity in Double-Wire MIG/MAG-Welding Filling Passes

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Abstract: The aim of this work was to evaluate the use of negative polarity in the trail wire in double-wire MIG/MAG-welding filling passes. A comparative study of the conventional technique (two wires working with pulsed DCEP) and the proposed combinations of pulsed DCEP in the lead wire with pulsed DCEN in the trail wire and pulsed DCEP in the lead wire with controlled short-circuit CSC(-) in the trail wire was carried out. The mean current in each wire and the ratio of travel speed to wire feed rate (for the same bead volume per unit weld length), as well as wire type and size, shielding gas composition and joint type (a butt joint in a flat position), were kept constant. Bead surface finish and geometry, deposition efficiency and maximum travel speed for each combination were evaluated. In conclusion, the use of negative polarity in the trail wire increased the deposition rate (higher travel speeds for the same bead) compared with the use of pulsed DCEP in both wires but at the cost of reduced operational robustness, as the conventional technique allowed a sound bead to be produced over a wider range of travel speeds. In addition, beads welded using negative polarity had smaller fusion zones and narrower heat-affected zones but higher convexities.

Key-words: Double Wire MIG/MAG Welding; Negative Polarity; Filling Pass.

Avaliação do Uso de Polaridade Negativa em Soldagens de Passes de Enchimento pela Técnica MIG/MAG Duplo Arame

Resumo: O objetivo deste trabalho foi avaliar o uso da polaridade negativa no arame-seguidor no processo MIG/MAG Duplo Arame em soldagens de passes de enchimento na posição plana. Foi feito um estudo comparativo entre a técnica convencional (com os dois arames trabalhando em Pulsado CC(+)) e as propostas combinações Pulsado CC(+) no arame-líder e Pulsado CC(-) no arame-seguidor e Pulsado CC(+) no arame-líder e Curto-Circuito Controlado CCC(-) no arame-seguidor. As correntes médias em ambos os arames e a relação entre velocidade de soldagem e velocidade de alimentação (mesmo volume de cordão por unidade de comprimento de solda), além do material e diâmetro dos arames, da composição do gás de proteção e da preparação do chanfro (junta de topo na posição plana) foram mantidas constantes. Avaliou-se o acabamento superficial e geometria do cordão, a eficiência de deposição e a velocidade limite de cada combinação. Conclui-se que, em referência à técnica com dois arames trabalhando no pulsado CC(+), a capacidade de produção do processo (maior velocidade de soldagem para um mesmo cordão) aumenta com o uso de polaridade negativa no arame seguidor, mas ao custo da redução da robustez operacional (o modo convencional permite se manter um cordão em uma faixa maior de velocidades de soldagem). Em relação à geometria do cordão de solda, com polaridade negativa observou-se uma menor área fundida e menor zona afetada pelo calor, com maior convexidade.

Palavras-chave: MIG/MAG Duplo Arame; Polaridade Negativa; Passe de Enchimento.

1. Introduction

The capabilities of conventional MIG/MAG welding no longer meet all the market's needs. Dzelnitzki [1] notes that the maximum travel speed when using conventional MIG/MAG welding to produce beads with relatively small throats (from 3 to 5 mm) is around 1 m/min. Similar data were reported by Ueyama et al. [2], who achieved travel speeds of up to 1.5 m/min for butt joints in a flat position. According to these authors, when this speed is exceeded, discontinuities in the weld bead begin to appear (undercuts, porosity and humping). Other limitations of the conventional MIG/MAG process include operational difficulties, as accurate settings are required to prevent excessive spatter and an uneven weld bead finish. The processes' greatest limitation, however, is its productive capacity, expressed in units of wire (mass) per unit time that can be deposited. (It should be noted, however, that the productive capacity of a process is not dependent solely on the mass produced.) In the case of the conventional MIG/MAG welding, the productive capacity is limited by the maximum current, which in turn is limited because metal transfer starts to occur in the rotating-spray mode. In contrast, submerged-arc welding, for example, is not subject to the transfer problem and can therefore use a higher current and larger-diameter wires. However, submerged-arc welding cannot replace MIG/MAG welding in many applications because it is not sufficiently versatile or practical.

One way of increasing the productive capacity of the MIG/MAG process while preserving its versatility is to use double-wire MIG/MAG welding. Basically, this involves duplicating the process by using two power sources and two feed units with the wires coming together in a single torch consisting of two electrically isolated contact tips 10 to 25 mm apart. This version of the MIG/MAG process overcomes the limitations of conventional MIG/MAG welding in terms of deposition rate (according to Douglas et al. [3], deposition rates of 16 to 23 kg/h can be achieved) and travel speed (which can reach 4 m/min, according to Staufer [4]), while ensuring not only that metal transfer in each wire is stable but also that the operational flexibility of the process is retained. Although there are two different operational approaches to double-wire MIG/MAG welding (single potential and isolated potential), nowadays only the latter is used, as explained by Groetelaars and Scotti [5]. The isolated potential system, in which the current from each power source passes through separate contact tips, allows each wire to be used in different operational modes and with different current limits, increasing the technique's operational flexibility. The wires can be positioned in line with the joint (a lead wire and a trail wire) or in parallel across it.

Another way that the deposition rate of the MIG/MAG process can be increased is by using electrode negative polarity. Puhl [6], working with a single AWS ER70S-6 1.2 diameter wire and $Ar+2\%O_2$ shielding gas, observed that the melting rate can increase from 40 to 50 % when the polarity is changed from DCEP to DCEN. Puhl's results were obtained using welding currents in the range of 100 to 400 A. Similar results were reported by Souza et al. [7], who also observed an increase in the melting rate when DCEN was used. Another advantage of using electrode negative polarity in MIG/MAG welding was noted by Dutra et al. [8], who used DCEN and synchronized current polarity with torch movement to deposit coatings by MIG/MAG welding. Because electrode negative polarity was used, the resulting beads were diluted by only 13 %, and maximum penetration was 0.5 mm. In the classical literature, of which Norrish [9] is an example, electrode negative polarity in MIG/MAG welding is still considered to have little practical application and limited versatility. However, recent studies by Souza et al. [7] and Dutra et al. [8] show that the use of DCEN in MIG/MAG welding has potential if the shielding gas is chosen correctly and that the technique therefore has yet to be fully explored and can potentially be used in a vast range of applications.

The present authors believe that to take advantage of the benefits of a double-wire MIG/MAG system it should be used with one of the wires working with negative polarity, as the use of negative polarity in both wires, although potentially offering a significant increase in deposition rate, would lead to unstable operation, poor penetration and an irregular bead finish. In contrast, with a combination of positive and negative polarity, a better balance can be achieved between a weld bead with sufficient penetration and lateral melting (positive polarity) and, at the same time, a higher deposition rate (negative polarity). One application where the aim is to achieve only adequate penetration and high deposition rates is in filling passes.

This study therefore seeks to investigate the use of electrode positive polarity (on the lead wire) and negative polarity (on the trail wire) in a flat position using the double-wire MIG/MAG process. This combination is expected to provide adequate penetration with an increased trail-wire melting rate, which should increase productive capacity when making filling passes.

2. Experimental Procedure

Three combinations of operating modes and polarities were used, as shown in Table 1. The use of negative polarity was assessed by comparing the existing conventional technique, i.e., both wires working in pulsed mode with positive polarity, with the other combinations proposed in this study, both of which use negative polarity in the trail wire. Two approaches were used to increase weld stability with negative polarity: the use of pulsed current and the use of controlled short circuit (CSC).

Table 1. Combinations of operational modes for the lead and trail wires and the respective designations used here.

Combination of operating modes	Polarity	
	Lead	**Trail**
Pulsed(+)-Pulsed(+)	DCEP	DCEP
Pulsed(+)-Pulsed(-)	DCEP	DCEN
Pulsed(+)-CSC(-)	DCEP	DCEN

Two special commercial power sources that allow synchronized or separate operation were used. The power sources were only synchronized when Pulsed(+)-Pulsed(+) welding was used so that the pulsed current in the lead wire occurred in the background of the current in the trail wire, corresponding to a delay of 5.8 ms, as shown in Figure 1. According to Scotti et al. [10], at low current levels staggering is advisable to minimize magnetic interaction between the arcs. The staggering was achieved with a dedicated connection between the power sources so that one source (the power source supplying the lead wire) could control the other (the source supplying the trail wire). In both cases, each power source could also control the pulsed current and CSC parameters independently. It should be pointed out that, unlike in the more modern version of the power source, which was not available for the authors when this study was carried out, the short-circuit transfer control in the power source used had not yet been optimized, so that the performance may have been adversely affected.

Although filling passes were being produced, it was decided to work with currents that were not very high as the proposed technique was expected to be used not only in the flat position (as in the present study), but also in other positions. To compare the different combinations, the mean current in each wire was kept constant (≅280 A in the lead wire and ≅180 A in the trail wire) even though this meant that the deposition rates that could be achieved with the trail wire in each operating mode were different. The feed velocity for each wire was adjusted until a short arc length was obtained for the desired mean currents. Another parameter used in the comparison was the amount of metal deposited per unit length of weld bead, which was kept constant. Hence, to ensure the same mean current and the same amount of material deposited per unit length, the travel speed was adjusted accordingly (total wire feed rate/travel speed = constant). This ensured a more sensitive and practical assessment of the techniques.

For the purposes of comparison, the other conditions/parameters were kept constant (the diameter of the consumable and the material it was made of, the chemical composition of the shielding gas, the contact tip-to-workpiece distance - CTWD, the interwire distance, the test plate material and the groove geometry). The test plates were made of ABNT 1020 carbon steel flat bars. A thickness of 9.52 mm was chosen to avoid the

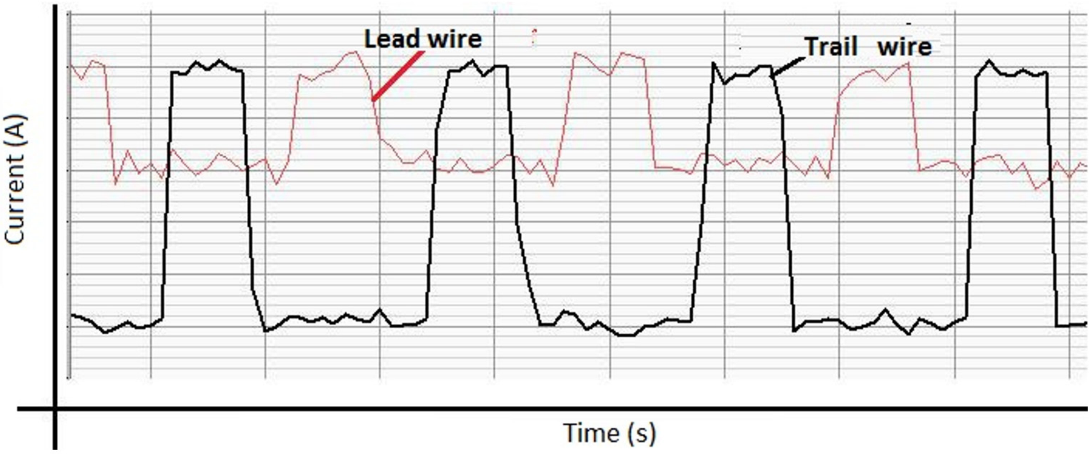


Figure 1. Synchronization between power sources for double-wire MIG/MAG welding in staggered Pulsed(+)-Pulsed(-) operation.

bars being perforated during welding and to prevent any ambiguity when observing penetration and the heat-affected zone (HAZ). A groove in the shape of a 4 mm-deep 10 mm-wide semi-ellipse was machined in the middle of the bar. The remaining thickness of the plate, in this case approximately 5.5 mm, simulated a completed root pass. The appearance and final dimensions of the test plate are shown in Figure 2. The two electrode wires were 1.2 mm-diameter class AWS ER70S-6 and were arranged in tandem position 15 mm apart. The work angle and angle of attack were 90°, as shown in Figure 3. The CTWD measured from the bottom of the groove was 21 mm. A shielding gas blend with a nominal chemical composition of Ar+8%CO_2 was used.

The discussion of the results was based on an analysis of the weld bead surface (qualitative assessment), weld bead geometry (penetration, size of the fusion zone - FZ, size of the HAZ and convexity index) and economic factors (related to spatter and travel speed to fill a joint of a given size) for beads with the same volume produced using the three combinations shown in Table 1. First, the travel speed required to ensure that the groove was completely filled for a given combination was determined. Then the travel speed for each combination was increased progressively to find the range of viable speeds for each combination. In this way, an operating envelope was determined for each technique separately so that the results could be presented in terms of maximum practical travel speed. Maximum travel speed was considered to be that speed at which there are no serious discontinuities in the bead (humping or undercuts), but an irregular finish can first be observed. The achievable speed is the travel speed at which a high degree of irregularity can be observed in the bead and discontinuities can be seen with the naked eye.

The settings used for each of the three combinations (Pulsed(+)-Pulsed(+), Pulsed(+)-Pulsed(-) and Pulsed(+)-CSC(-)) are shown in Tables 2, 3 and 4, respectively. It should be noted that, as in any double-wire MIG/MAG welding process, the aim of pulsing the current is not to control droplet transfer.

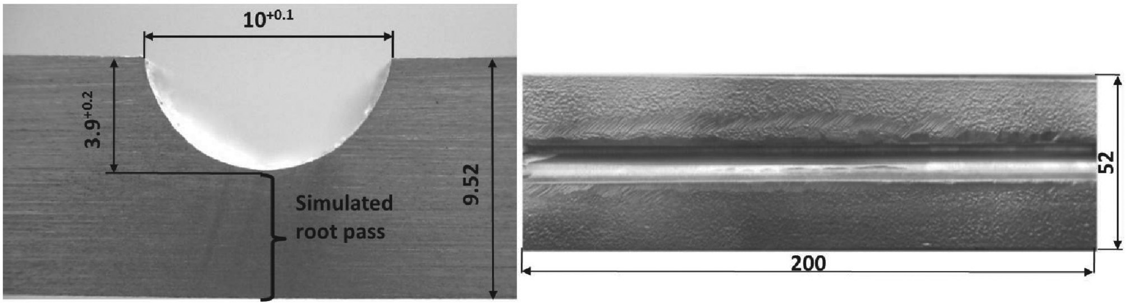


Figure 2. Test plate used for the filling passes (single pass) in the flat position.

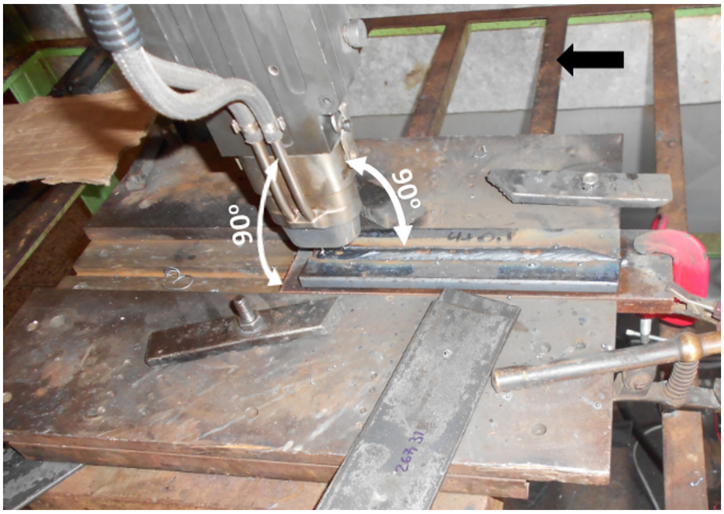


Figure 3. Position of the welding torch in relation to the test plate. The angle of attack, work angle and welding direction are shown (the wires exit the torch in parallel).

3. Results and Discussion

Table 5 shows the mean and RMS values of the parameters monitored for welds made using the settings shown in Tables 2, 3 and 4; the corresponding current and voltage oscillograms are shown in Figures 4, 5 and 6. Analysis of the data in the table reveals that the melting rate for the trail wire, which in this case can be determined from the wire feed rate, increased by up to 60 % for a given mean current when the polarity was changed from positive

Table 2. Settings used for the Pulsed(+)-Pulsed(+) combination.

Wire	Ip (A)	Ib (A)	tp (ms)	tb (ms)	WFR (m/min)	Target Im (A)
Pulsed Lead Wire(+)	350	250	3.5	8	10.3	280
Pulsed Trail Wire(+)	350	100	3.5	8	4.4	180

NB: Ip – pulsed current; Ib – background current; tp – pulse time; tb – background time; WFR – wire feed rate; Im – mean current.

Table 3. Settings used for the Pulsed(+)-Pulsed(-) combination.

Wire	Ip (A)	Ib (A)	tp (ms)	tb (ms)	WFR (m/min)	Target Im (A)
Pulsed Lead Wire(+)	350	250	3.5	8	10.3	280
Pulsed Trail Wire(–)	–350	–98	3.5	8	7.7	–180

NB: Ip – pulsed current; Ib – background current; tp – pulse time; tb – background time; WFR – wire feed rate; Im – mean current.

Table 4. Settings used for the Pulsed(+)-CSC(-) combination.

<table>
<tr><th colspan="10">Pulsed Lead Wire(+)</th><th rowspan="2">TS (mm/s)</th></tr>
<tr><th colspan="2">Ip (A)</th><th>Ib (A)</th><th colspan="2">tp (ms)</th><th colspan="2">tb (ms)</th><th>WFR (m/min)</th><th colspan="2">Target Im (A)</th></tr>
<tr><td colspan="2">350</td><td>250</td><td colspan="2">3.5</td><td colspan="2">8</td><td>10.3</td><td colspan="2">280</td><td rowspan="6">8.5</td></tr>
<tr><th colspan="10">CSC Trail Wire(–)</th></tr>
<tr><th>Ia1 (A)</th><th>Ia2 (A)</th><th>ta1 (ms)</th><th>ta2 (ms)</th><th>Ic1 (A)</th><th>Ic2 (A)</th><th>tc1 (ms)</th><th>tc2 (ms)</th><th>Ic3 (A)</th><th>Ia3 (A)</th></tr>
<tr><td>–320</td><td>–210</td><td>2</td><td>3</td><td>–95</td><td>–105</td><td>0.5</td><td>0.6</td><td>–224</td><td>–120</td></tr>
<tr><th>tr1 (ms)</th><th>tr2 (ms)</th><th>kr</th><th>di3 (A/ms)</th><th>Ucc (V)</th><th>WFR (m/min)</th><th>Target Im (A)</th><td></td><td></td><td></td></tr>
<tr><td>0.6</td><td>0.6</td><td>1.8</td><td>–160</td><td>–10</td><td>7.9</td><td>–180</td><td></td><td></td><td></td></tr>
</table>

NB: Ia1 – peak current; Ia2 – current to increase the melting rate; ta1 – duration of current Ia1; ta2 – duration of current Ia2; Ia3 – arc maintenance current; di3 – rate of increase of current during short circuit in A/ms; tr1 – ramp time from level 1 to level 2; tr2 – ramp time from level 2 to level 3; tc1 – droplet settling time; tc2 –reopening wait time; Ic1 –droplet settling current; Ic2 –current when the metal bridge is broken; WFR- wire feed rate; Im –mean current; TS – travel speed.

Table 5. Values of the parameters monitored for the three combinations used to produce a single filling pass weld.

Combination	Wire	Im (A)	Um (V)	Irms (A)	Urms (V)	WFR (m/min)	WFR_t (m/min)	TS (mm/s)	Q (g/m)
Pulsed(+)–Pulsed(+)	Lead	272.0	26.8	276.6	27.1	9.7	14.3	6.8	311.0
	Trail	173.0	24.2	205.6	24.8	4.6			
Pulsed(+)–Puled(–)	Lead	282.8	27.3	278.3	27.5	9.6	16.9	8.2	308.5
	Trail	–174.0	–21.8	204.8	22.7	7.3			
Pulsed(+)–CSC(–)	Lead	282.0	28.0	286.0	28.1	9.7	17.2	8.3	311.9
	Trail	–172.0	–22.2	181.6	23.2	7.5			

NB: Im – mean current; Um – mean voltage; Irms – RMS current; Urms – RMS voltage; WFR – wire feed rate for each electrode; WFR_t – accumulative wire feed rate for both electrodes; TS – travel speed; Q –amount of metal deposited per unit length.

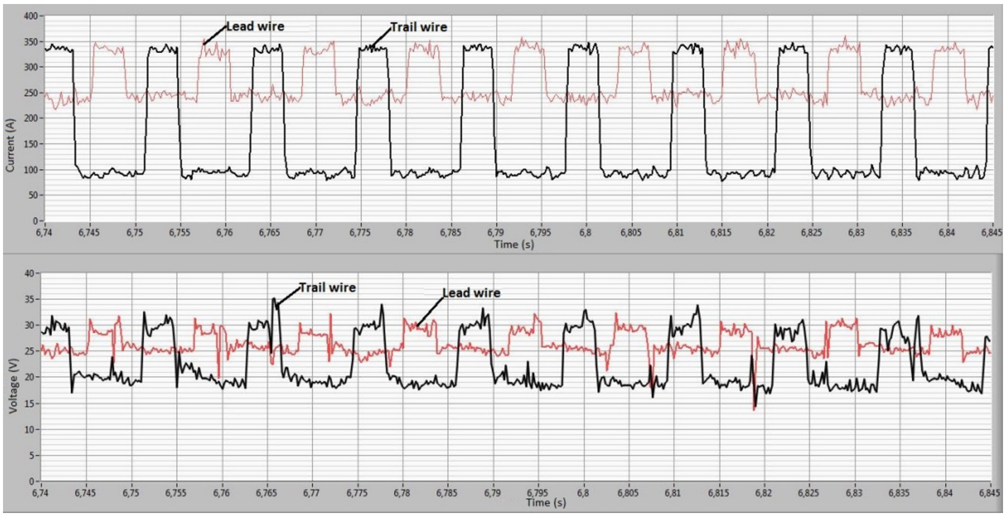


Figure 4. Typical current and voltage oscillograms for the Pulsed(+)-Pulsed(+) combination.

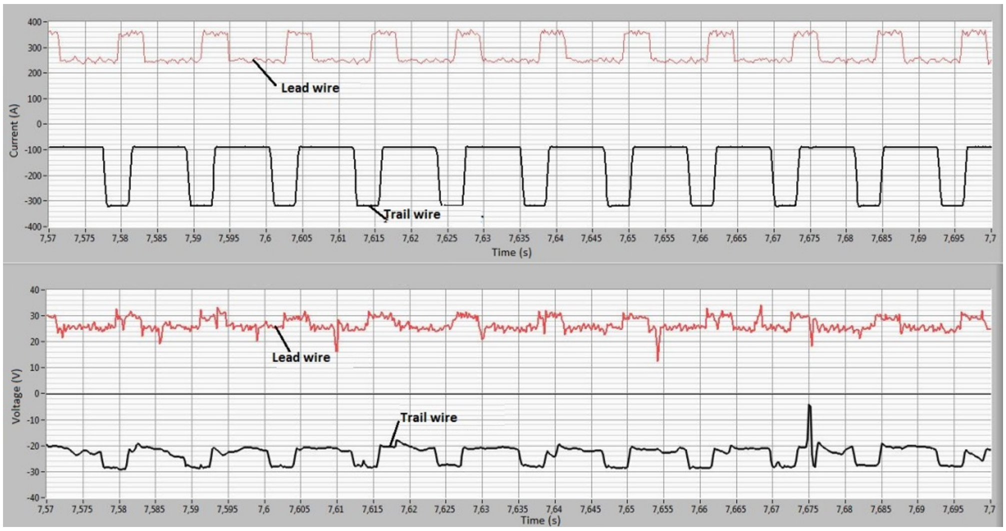


Figure 5. Typical current and voltage oscillograms for the Pulsed(+)-Pulsed(-) combination.

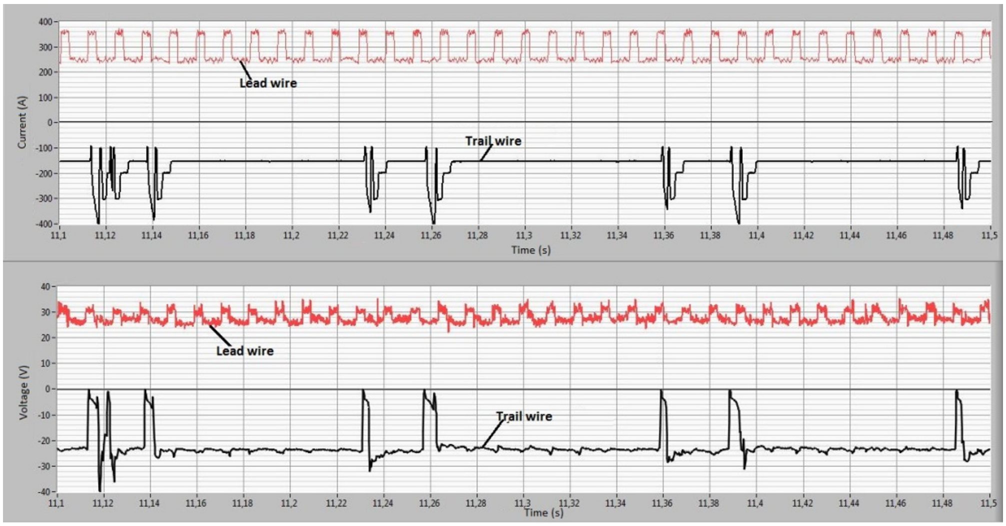


Figure 6. Typical current and voltage oscillograms for the Pulsed(+)-CSC(-) combination.

to negative. This is in agreement with the literature [6]. Consequently, the travel speed had to be increased by 1.4 to 1.5 mm/s to fill the same groove, showing one advantage of welding with negative polarity. The oscillograms show that pulsed DCEN in the trail wire (Pulsed(-)] resulted in irregular behaviour because of short circuits (as expected), while the CSC(-) condition was unable to reproduce controlled transfer.

It can be seen from the photographs of the weld beads in Figure 7 that at lower travel speeds the groove is filled completely and the bead has an acceptable visual finish. These were the conditions used to compare the performance of each of the three combinations. It should be remembered that the beads produced with higher travel speeds were used to establish the maximum travel speeds for each technique and were not assessed according to the same criteria as the other beads. The measurements in Figure 8 were taken from three cross sections of each weld bead with a commercial software package that allows measurements to be taken with a resolution of 0.1 mm. The values in Figure 8 are therefore the mean of three measurements for each geometric weld bead parameter. However, the analysis of the results is qualitative.

It can be seen from Figure 8 that, contrary to what was expected, the welds made with negative polarity tend to have greater penetration than those made with the Pulsed(+)-Pulsed(+) combination. Theoretically, positive polarity results in greater penetration than negative polarity. Furthermore, to maintain the same deposition rate per unit weld length, the welding energy was greater (higher travel speed for the same mean currents) for the Pulsed(+)-Pulsed(+) combination. Nevertheless, some studies in the literature, such as a paper by Souza et al. [7], suggest that polarity is not always the governing factor affecting penetration but that, depending on the composition

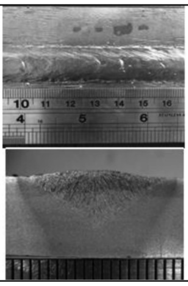
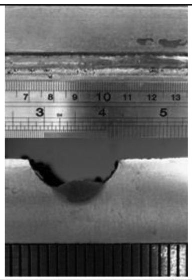
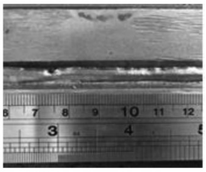
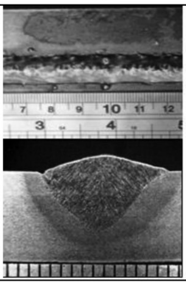
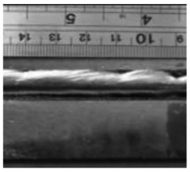
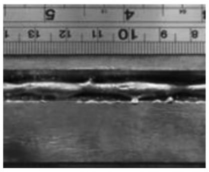
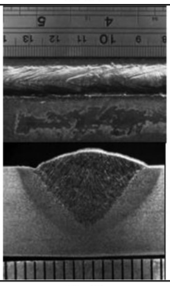
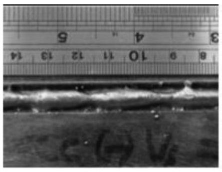
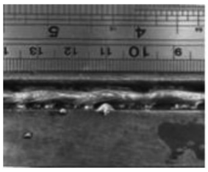
Combination	Visual appearance and cross section			
Pulsed(+)-Pulsed(+)				
TS	6.8	25 .7	47 .3	52 .1
Pulsed(+)-Pulsed(-)				-
TS	8 .2	14 .6	24 .7	
Pulsed(+)-CSC(-)				-
TS	8 .3	14 .6	24 .4	

Figure 7. Visual appearance and cross sections of weld beads made with the three combinations (*TS = travel speed in mm/s).*

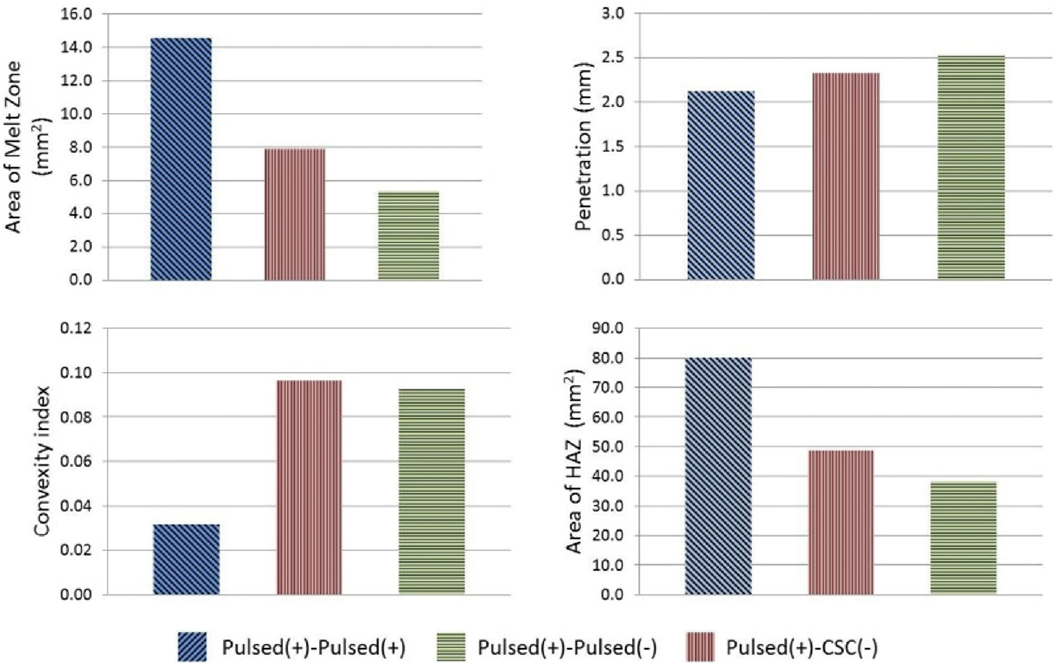


Figure 8. Geometric parameters of the weld beads produced using the three combinations in a single pass in a flat position.

of the shielding gas, penetration with negative polarity may be only 60 % of that achieved with positive polarity. It should be mentioned that the results reported by Souza et al. [7] for negative polarity were obtained using single-wire MIG/MAG welding, a constant current and a shielding gas with a different chemical composition (Ar+2%O_2). A search of the literature published to date failed to reveal any results related to pulsed DCEN or double-wire welding. However, it should be borne in mind that in double-wire welding there is magnetic interaction between the two arcs, which have different polarities.

The results for the FZ and HAZ were as expected and welding with the Pulsed(+)-Pulsed(+) combination produced a significantly larger FZ and HAZ. In the literature, negative polarity is considered to produce low heat input; Tong et al. [11], for example, using AC MIG/MAG welding, observed a reduction in heat input when the percentage of DCEN was increased in the cycle. Another factor that may have had an influence is the lower welding energy with this polarity. According to Souza et al. [7] apud Talkington [12], in DCEP (when the wire is the anode), approximately 70 % of the energy in the arc is used to heat the metal base and the remaining 30 % to melt the wire. However, Frolov [13] states that most energy is released in the anode rather than the cathode but does not specify in which process. There are therefore no reliable data on how energy is actually distributed between the anode and cathode spots. Theoretically, it can be assumed that in the case of DCEN more heat is involved in melting the wire and that the rest of the energy is used to heat the metal base. This hypothesis appears reasonable, as it would explain the increased melting rate for the wire electrode. Comparison of the FZ and HAZ for the Pulsed(+)-Pulsed(-) and Pulsed(+)-CSC(-) combinations reveals that they are slightly larger for the former. This may be a consequence of the slightly lower travel speed (greater heat input). Another reason may be the action of the trail arc, which in the case of the CSC(-) remains off during the short circuit, significantly reducing the heat input to the material.

Analysing the weld beads in Figure 7 made with the Pulsed(+)-Pulsed(-) and Pulsed(+)-CSC(-) combinations and travel speeds of 14.6 and 24.7 mm/s, it is clear that there are major problems related to morphological instability. The result of this instability is known in the literature as humping. According to Soderstrom and Mendez [14], various factors can lead to humping, the main one being high travel speed. The authors reviewed the models proposed in the literature to explain the phenomenon of humping and found that it can be classified into two typical morphologies: gouging region morphology (GRM) and beaded cylinder morphology (BCM).

A model based on Rayleigh capillary instability involving BCM would appear to represent well the humping observed in the present study. According to this model, the predominant force leading to humping in horizontal welding is surface tension. The weld bead, which in the model is considered a cylinder, tends to separate into shorter cylinders because of surface tension. This happens when the weld bead reaches a critical length known as the instability length. The pictures of weld beads taken with negative Polaroid film in Figure 7 show that the bead is divided into regions separated by necks. In their article [14], Soderstrom and Mendez analyse the role played in this instability by the main welding parameters, such as the chemical composition of the shielding gas, the shape of the electrode and the chemical composition of the base metal. However, they do not discuss the role played by the polarity of the current.

Analysis of the convexity index (Figure 8), which is characterized by the width/penetration ratio (the larger the index the greater the convexity), showed that the results agree with the findings reported in the literature for a single wire. For example, Tong et al. [11], using an AC MIG/MAG welding power source with a single wire and varying the percentage of DCEN during one pulse cycle, found that the greater the percentage of DCEN, the greater the weld reinforcement. In the present work, the weld beads made using negative polarity had greater convexity than those made using positive polarity. Tong et al. [11] suggest that this may be caused by the lower temperature of the deposited metal and the lower wettability, leading to convex beads with irregular surfaces. Another explanation is the greater travel speed, which, together with the typical characteristics of an arc working with negative polarity, makes the weld bead more convex.

A different approach used by some authors to compare the various combinations involves an analysis of economic factors. The costs that have the greatest influence on the overall cost of an MIG/MAG welding operation are the labour costs and the cost of the wire and shielding gas. For example, according to Sarma [15], who measured the costs in an Indian factory, the overall cost of an MIG/MAG weld can typically be broken down as follows: 10 % labour, 69 % wire, 13 % shielding gas and 8 % electricity. In technologically more advanced countries, however, the breakdown is different: 78 % labour, 20 % filler metal and 1 % shielding gas. Other costs, such as cleaning, preparation, supervision and non-destructive testing, were excluded. In any case, irrespective of the proportion of the overall cost accounted for by labour costs, it is reasonable to suppose that the costs associated with shielding gas and labour will be lower if a given weld (same bead volume) is made more quickly. Therefore, the greater the travel speed that can be achieved, the more economical the process will be.

Comparison of the weld beads in Table 6 shows that a lower travel speed is required to fill the same groove when the Pulsed(+)-Pulsed(-) combination is used. The Pulsed(+)-CDC(-) combination had the highest travel speed of the three techniques and the same deposition efficiency as the Pulsed(+)-Pulsed(+) combination. The limited spatter (wasted material) and superior travel speed give Pulsed(+)-CSC(-) an advantage over the other two combinations. This is because of the control of metal transfer, which works even when negative polarity is used (it will be recalled that the equipment used was not optimized for operation with CSC(-)).

Analysing the appearance of the weld beads (Figure 7), the largest operating envelope in terms of travel speed was observed for the Pulsed(+)-Pulsed(+) combination, for which the operating range was approximately 7 to 55 mm/s (range of confirmed, feasible parameters, as shown in Figure 9). Pulsed(+)-Pulsed(-) and Pulsed(+)-CSC(-) had significantly smaller operating envelopes and only gave satisfactory results for travel speeds in the region of 8.2 to 8.3 mm/s. Hence, the disadvantages of the two combinations with negative polarity on the trail wire is that they have restricted operating envelopes. The Pulsed(+)-Pulsed(+) combination was the most stable and easiest to control; satisfactory deposition efficiency and a large operating envelope were therefore observed with this combination.

Table 6. Typical data used to compare the cost of making weld beads of a given volume for the three combinations.

Combination	TS (mm/s)	WFR_t (m/min)	Deposition efficiency (%)	Shielding gas flow rate (L/min)
Pulsed(+) – Pulsed(+)	6.8	16.3	93.0	25
Pulsed(+) – Pulsed(-)	8.2	17.0	88.4	
Pulsed(+) – CSC(-)	8.3	17.2	94	

NB: TS = travel speed, WFR_t = total wire feed rate (two wires).

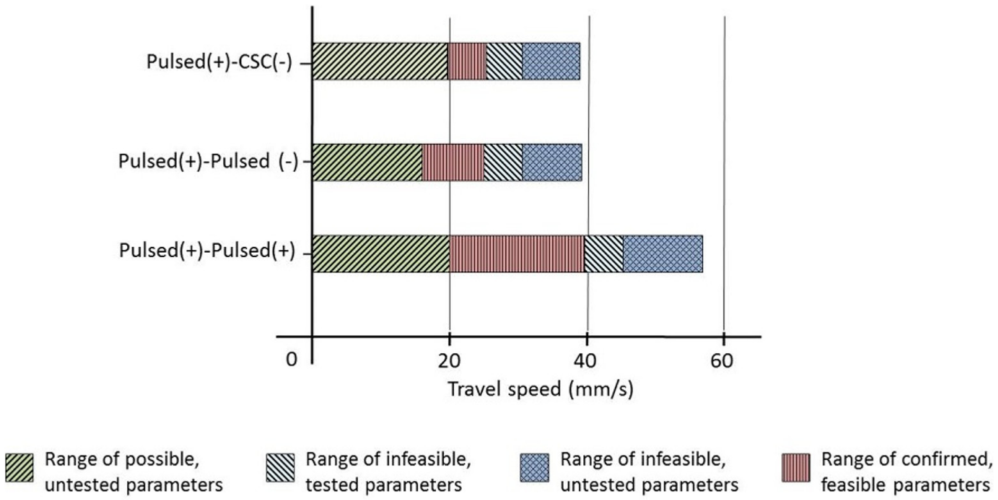


Figure 9. Travel-speed operating envelope for each combination using the same mean current in a simulated butt-joint.

4. Conclusions

The main aim of this study was to assess the use of negative polarity in filling passes using double-wire MIG/MAG welding in the flat position by comparing this mode with the conventional operating mode (pulsed DCEP on both wires). The findings indicate that for the welding equipment used and the specific conditions investigated (carbon steel, mean currents of 280 and 180 A in the lead and trail wires, respectively, and a constant volume of metal deposited per unit length), negative polarity in the trail wire improves the performance of the process by:

- increasing the melting rate for a given mean current, allowing a higher travel speed to be used to make the same weld bead (more economical welding);
- reducing the heat input, leading to a smaller FZ and HAZ (lower thermal stresses).

It was also observed that the use of negative polarity in the trail wire rather than the conventional positive polarity tends to result in greater weld bead penetration for a given travel speed. However, the use of negative polarity in the trail wire adversely affects performance by:

- drastically reducing the operating envelope in terms of feasible travel speeds;
- increasing spatter if there is no current control, as in the controlled short-circuit mode (reducing deposition efficiency).

It can also be concluded that, for the conditions investigated, the use of the CSC(-) mode has a number of advantages over Pulsed(-) in terms of stability (greater control over the process and less spatter). However, beads made with Pulsed(+)-Pulsed(-) have a lower convexity index than those produced using Pulsed(+)-CSC(-).

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