BEAD-ON-PLATE STUDY OF POLYCARBONATE HOT-GAS WELDING

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Abstract. *Considering the advantages of welding on joining of polycarbonate plates and the scarceness of works in this area, the objective of this work was carring out preliminary studies comprising the assessment of welding parameters such as temperature, welding speed and welding-rod's feeding speed. Firstly, it was studied the actual temperature that acts on the welding rod and plate. After this, it was investigated the influence of the nozzle type on the welding bead. Since Hot-Gas is inherently a hand-carried process, the results were obtained from several welds, performed by three different welders. Termocouples were used to measure temperatures at points related to the tool's terminal or nozzle. Sectioning, polishing and image analysis were used to study welding beads' shapes. Welding and feeding speeds were calculated using times assessed with a chronometer. The results show, for example, the suitable welding parameters range, and their effect on the welding bead. Temperatures at points of the nozzle related to the positions of welding rod and plate are significatively different from those selected at the tool. The nozzle type and the temperature greatly influence on the welding bead. Personal characteristics of the welders influence on welding parameters.*

Keywords*: polycarbonate, hot-gas welding, plastics, polymers, polymeric materials*

1. Introduction

Polycarbonate, PC, is one of the three most important engineering plastics (Mano, 1991), and, among them, PC is the only transparent one. This light material has half of the glass specific weight, and it also has a good mechanical resistance. Another remarkable property of PC is its impact resistance, between 230 and 250 times greater than glass' and 30 times greater than the impact resistance of some polymers like acrylic. This characteristic makes PC suitable to replace glass in some applications related to security, like bulletproof window glasses. PC have high thermal properties. Its glass transition temperature, T_g, about 150 ºC, is the highest among the polymers and, because of that, the material can be used in devices that can stand up to relatively high temperatures for some period, like surgical instruments. Because of its high viscosity, PC is not well suitable for injection-molding. On the other hand, blow-molding, and specially lamination are enhanced due to PC good dimensional stability. This fact, allied to PC good resistance concerning weather and aging, explains the large application of PC plates in roofing and façades of civil construction.

However, the use of PC plates in civil construction undergoes a drawback that is the need of complex joining elements, usually made of metal or wood. To better explore the structural strength of PC plates, and not only their barrier properties, it is very desirable to take in account a joining technique like welding. It could make easier the design of roofing elements, besides more reliability concerning protection against water infiltration. Hot-Gas Welding, also named Hot-Air Welding, seems to be the most suitable technique to weld PC plates in civil construction applications, because of its equipment lightness and easy-handling characteristics. Another reason of this suitability is the ability of the technique in providing several kinds of joints (Reitz and Oman, 2000; Grimm, 1995), such as right, curve, short or long ones, without high costs with tailored or specialized devices (Wise, 1997). In this technique, a heat-softened welding rod fills a joint between two plates, through the interpenetration of plates' and rod's polymeric chains. This phenomenon requires heating to soften the surfaces of joint and rod, and pressure between these components (Gumbleton, 1989). The process bears resemblance to TIG process, but in Hot-Gas Welding of thermoplastics the filler material does not melt, it is just softened.

Despite its advantages, Hot-Gas Welding has not been used on PC plates joining. There are some references of this application, for experimental purposes, in the literature, like Lai *et al.*(1991), Vieira Jr. *et al.*(2002) and Vieira Jr.(2003).This lack of utilization can be due to scarceness of researches, well-known practices or technical advices. It can be also pointed out that it is difficult to find one of the basic components of the technique, the welding rods. Besides, the relatively high cost of PC plates, if it is compared to other polymers, inhibits isolated efforts in developing this application.

Since Hot-Gas Welding is inherently a handy process, it was decided to research firstly the results directly obtained by a certain number of welders. To a later phase, it is planned experiments that will be carried out in automatized devices. In this situation, some welding variables like welding speed, filler material feeding speed and pressure over the welding rod will be settled beforehand. In the present work, it was studied several aspects like the repeatability of results, considering differences between welders' skills, and the influence of temperature, welding tips and techniques on handling the process. To better understand the influence of these agents, it was adopted the simplification technique of bead-on-plate welding, or simple deposal of welding beads on the plate. Figure 1 displays an application example of bead-on-plate welding on a PC plate. Figure 2 shows the rod and plate heating.

Figure 1. Bead-on-plate welding on a PC plate

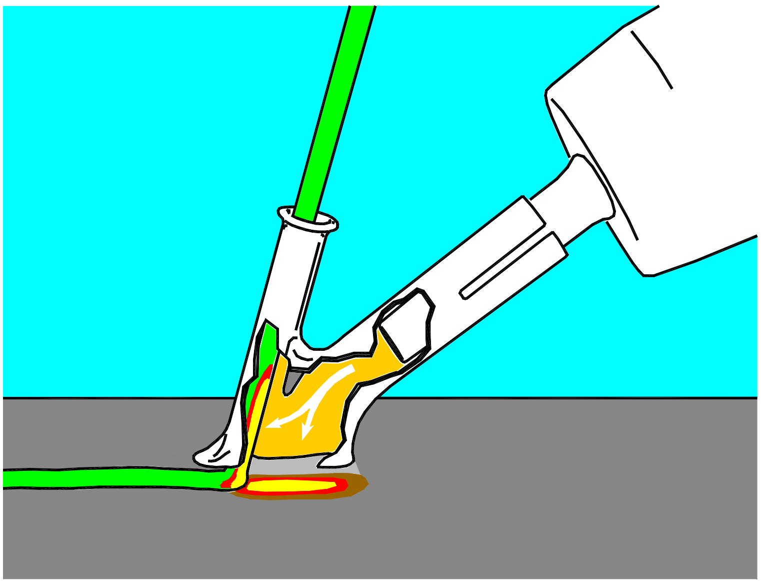

Figure 2. Simultaneous heating of rod and plate

2. Methodology

2.1. Equipments

It was used a portable welding tool with the feature of displaying the working temperature. According to the manufacturer of the tool, the displayed temperature occurs at a specific point situated 5 mm within the basic tip. Figure 3 shows the tool and the coupled basic nozzle. The tool is provided with a display that shows both the selected and the actual temperature.

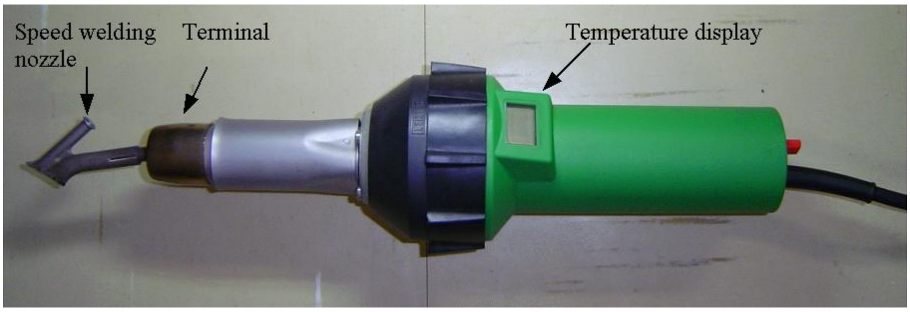

Figure 3. Hot-gas welding tool, with a speed welding tip

In hot gas speed welding, it is possible to interchange the nozzles. It was studied the nozzles that can be seen at Fig. 4. The shape and the dimensions of the nozzle influence on the hot gas flow and on the balance between rod heating and plate heating. Figure 5 shows the meaning and the adopted terminology for the main considered dimensions of the nozzles. The dimensions values, for each nozzle, are presented in Tab. 1.

Figure 4. Speed welding nozzles

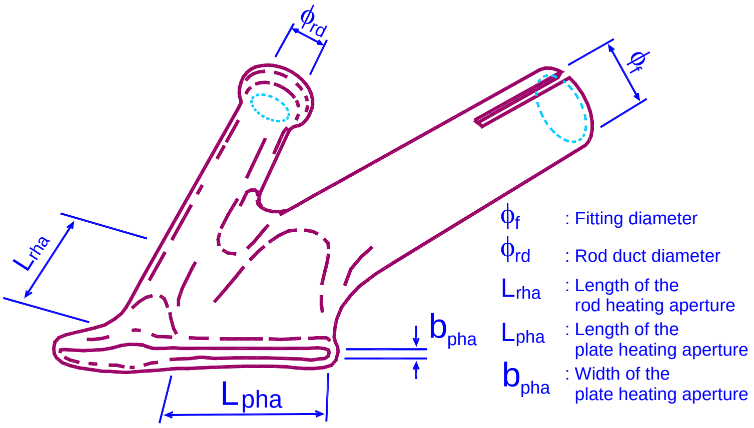

Figure 5. Speed welding nozzle and its dimensions

Table 1. Dimensions of the speed welding nozzles used in the experiments (according to Fig. 5)

Dimension symbol	Dimensions (mm)		
	Nozzle 1	Nozzle 2	Nozzle 3
ϕ_f	8.0	8.0	8.5
ϕ_{rd}	4.5	4.5	6.0
L_{rha}	9.0	10.5	7.5
L_{pha}	14.0	10.5	9.5
b_{pha}	1.5	2.3	4.5

2.2. Material

The testing plates were conceived as polycarbonate rectangular plates of 50 mm (width) × 500 mm (length) × 3.0 mm (thickness). Such a plate was capable of holding six welding beads of about 215 mm. As deposing material, it was used welding rods with diameter of 3 mm.

2.3. Temperature assessment

Considering the importance of temperature in hot gas welding of thermoplastics, the first developed activity in this work was the temperature assessment at several points of the terminal and nozzle. There was the need of testing the reliability of the temperature presented on the welding tool display. According to the manufacturer, the actual temperature can be checked at 5 mm inside the terminal, as can be seen in the left at Fig. 6, by using a thermocouple with diameter of no more than 1 mm. In addition, there was an interest in assessing the actual temperature at several points of the hot gas flow, when using the speed welding nozzle 1. It was considered that the temperature distribution inside and near the nozzle could vary in a great extent in relation to that presented on the welding tool display. The points where temperature was assessed, inside and near the speed welding nozzle, can be seen at Fig. 6 (right).

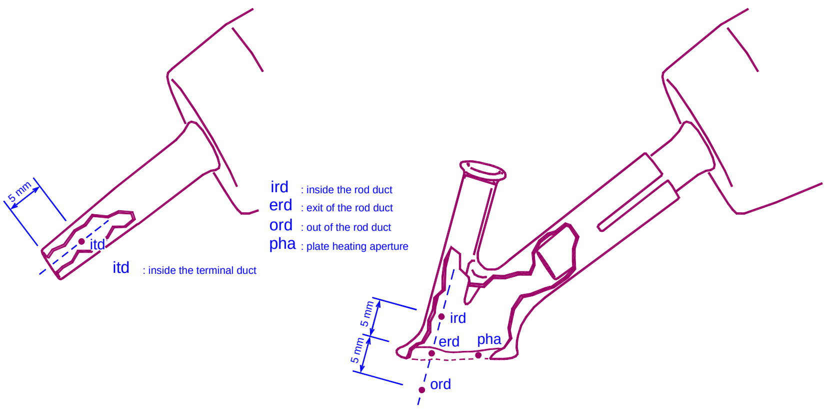

Figure 6. Points where temperature was assessed

2.4. Welding speed and feeding speed measurements

Bead-on-plate experiments were carried out to measure welding speed (S_{weld}) and feeding speed (S_{feed}). In each one of these experiments, a polycarbonate plate was placed in a fixture device. For each bead, it was measured, with a chronometer, the welding time between two marks over the plate. The length between the marks was set as 200 mm. Feeding speed was assessed indirectly. It was measured the length of the welding rod before and after the welding. Then, the consumed length was divided by a time that was calculated by dividing the bead length by the previously calculated welding speed.

2.5. Influence of the nozzle type

To evaluate the influence of the nozzle and temperature on the bead shape, it was carried out experiments in which these two agents were varied. It was used the three nozzles shown in Figure 4. The studied temperatures were: 350, 400, 450 and 500 ºC.

2.6. Influence of welders' personal skills

Since Hot-Gas is inherently a handy process, the welders' personal skills can influence on the welding results, concerning the welding speed, the feeding speed and the ratio between these two speeds, as defined by Eq. (1):

$$r_s = \frac{S_{feed}}{S_{weld}} \qquad (1)$$

where:
r_s: ratio between speeds;
S_{feed} : feeding speed;
S_{weld}: welding speed.

It is interesting to point out that the product of r_s and the welding rod area gives the welding bead area. So, welding bead area is proportional to r_s.

The study of repeatability for each of the welders was carried out considering the mean and standard deviation values related to six tests that were performed by each welder, for temperatures of 350 and 450 ºC. The objective of this study was to assess the standard deviation values and to verify if the change in temperature would vary these values for welding and feeding speeds. It was taken care of not allowing the same welder to perform two tests together, to avoid the influence of one test on another.

3. Results

3.1. Temperature distributions

The first studied issue was the reliability of temperatures presented on the welding tool display. Two tests were carried out to analyse the process repeatablility. Table 2 shows these results. As can be seen, there is a good agreement between the selected temperature and the temperature measured at the inner point of the terminal duct.

Table 2: Selected and measured temperatures

T_s	T_{itd} (ºC)	
(ºC)	Test 1	Test 2
97	100	102
150	154	153
200	203	200
250	255	252
300	300	303
350	361	352
400	410	406
450	463	454
507	506	502
550	559	549
600	605	604

T_s : Selected temperature shown on the welding tool display;
T_{itd} : Termocouple measured temperature inside the terminal duct (according to Figure 6)

Although results shown at Tab. 1 confirm the agreement between selected temperatures and those temperatures measured at a specific point inside the terminal duct, out of this point the temperature distribution varies at a great extent. Figure 7 shows a graphic of measured temperatures at several points of interest, concerning the heating of the welding rod and the plate. It is supposed that the oscilating characteristics of some of the graphics are due to a feature of the adopted welding tool. The manufacturer indicates that this tool always operates with the same air flow, even if the temperature varies. Nevertheless, this statement was not investigated in the present work

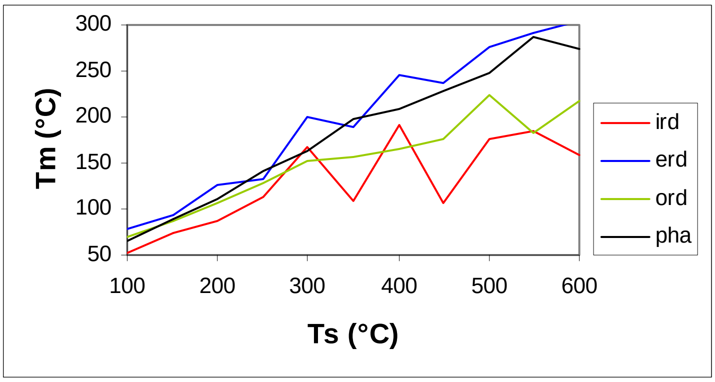

Figure 7. Termocouple measured temperatures at four points related to the nozzle (according to Figure 6)

3.2. Influence of temperature and nozzle on the bead shape

As can be seen in Fig. 8, nozzle and temperature have an evident influence on the bead shape. For all the temperatures, beads obtained by using nozzle 2 always present the greatest areas, followed by those obtained with nozzle 3 and, finally, by the obtained with nozzle 1. As can be observed in Tab. 1, nozzle 2 have smaller ratio between areas addressed for plate heating and for rod heating. Considering the heat balance between rod and plate, it leads to an easier rod softening and flowing. The lower plate heating reduces the attachment area between rod and plate, what also concurs to make easier the welding rod's flow and to reduce its stretching . These effects lead to higher speeds and beads with greater areas. Nozzle 3 has and intermediary ratio between areas for plate and rod heating, what explains the intermediary area values of beads obtained by using this nozzle.

Another interesting aspect that can be noticed with the analysis of Fig. 8 is the trend of forming air bubbles in the beads edges as the temperature grows. Beads also tend to be more flattened with temperature increasing.

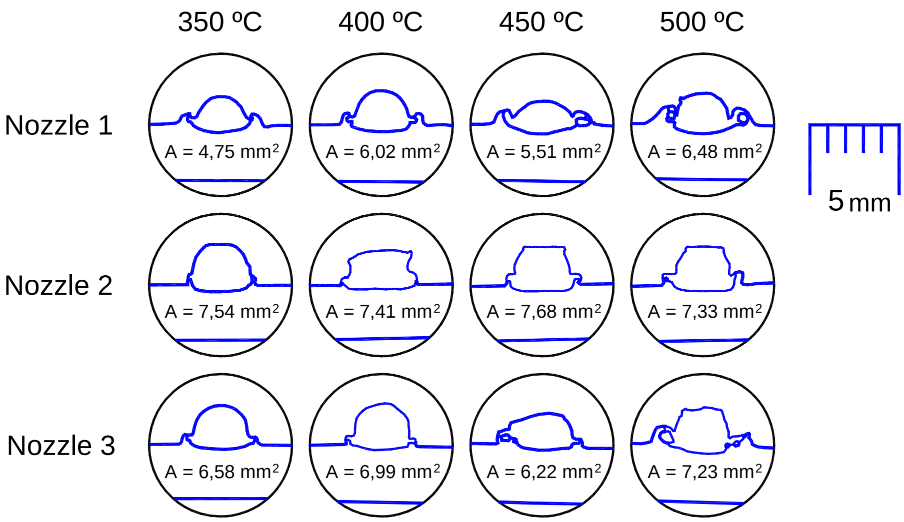

Figure 8. Shapes and areas of the welding beads

3.3. Influence of welders' personal characteristics on welding and feeding speeds

Figures 9 and 10 show, respectively, the welding speed (S_{weld}) and the rod feeding speed (S_{feed}) with temperature, for three different welders. Figure 11 displays the ratio (r_s) between feeding and welding speed, for these three welders. In general, there is good agreement between values calculated for welders 1 and 2. It was noticed, during the experiments, that welder 3 has a special characteristic of imposing lower pressure to the welding rod. The welding process occurs with a combination of two movements which have opposite components concerning the welding direction: welding tool motion and rod feeding onto the bead. When it comes to welder 3, welding tool motion prevails in relation to the rod feeding motion. In this way, his ratios r_s are lower than those of welders 1 and 2.

In all figures, it can be noticed that S_{weld}, S_{feed} and r_v increase with the temperature, although r_v tends to become stabilized for higher temperatures. Figure 12 shows the mean values for S_{weld}, S_{feed} and r_v with temperature, considering the results obtained from the three welders. In general, the increase of S_{weld} and S_{feed} with temperature is almost linear.

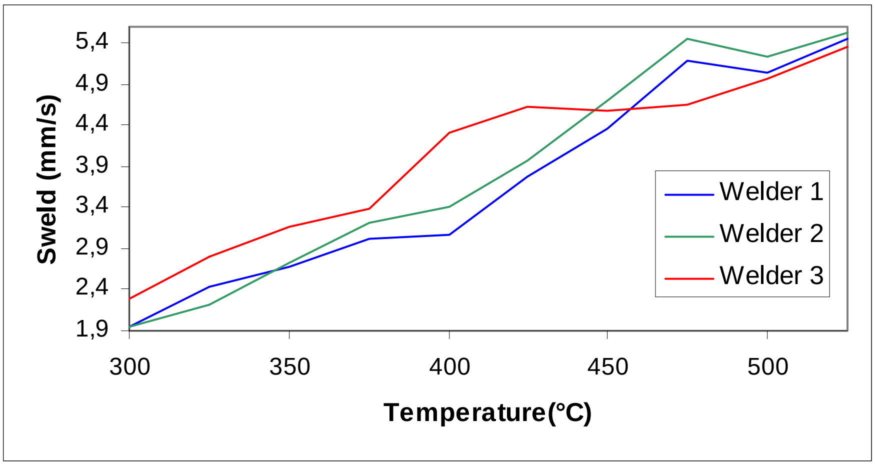

Figure 9. Welding speed as a function of temperature for three different welders

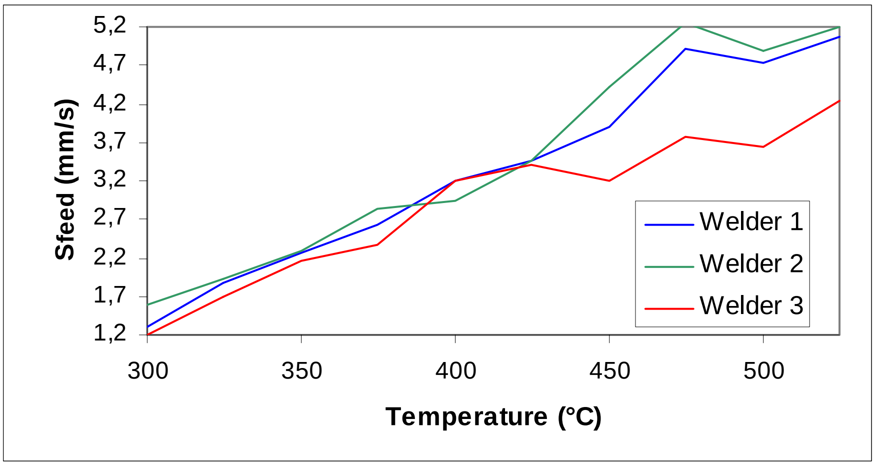

Figure 10. Feeding speed as a function of temperature for three different welders

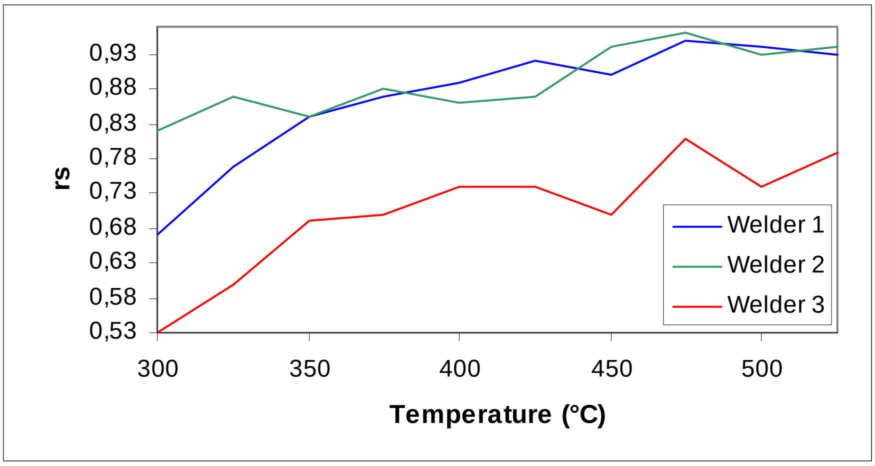

Figure 11. Relation between welding and feeding speeds for three different welders

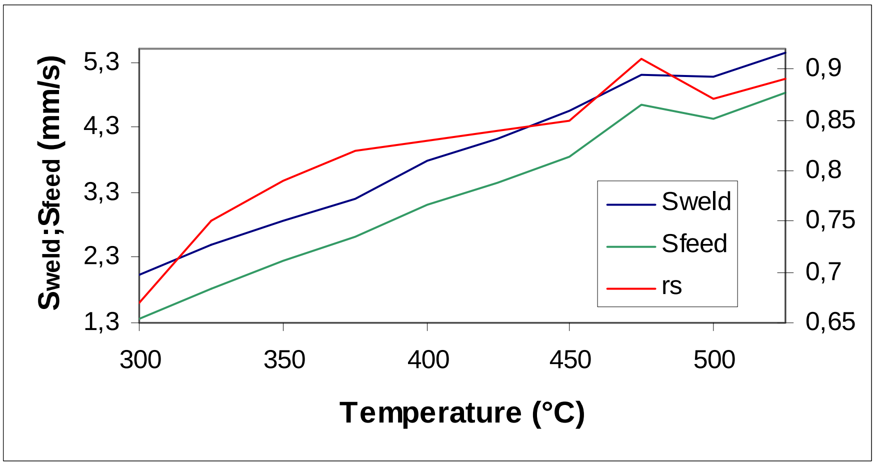

Figure 12. Mean values, resulting from three different welders, for welding speed, feeding speed and relation between feeding and welding speeds

Table 3 depicts the mean values for welding speed and feeding speed, for each of the welders and for two temperatures. Each result was calculated considering six tests. As it was said before, welder 3 impose lower pressure to the welding rod. This explains his lower feeding speed values. On the other hand, welder 1 is capable of performing welds with low standard deviation values for r_s, mainly for the temperature of 350 ºC. In general, it can be said that standard deviations for r_s are, in percentage, lower than those of welding or feeding speed. For a given temperature, it appears that r_s is a personal characteristic of each welder.

Table 3. Repeatability and varyability of speed values for two temperatures

Welder	Temperature: 350 ºC			Temperature: 450 ºC		
	S_{weld} (mm/s)	S_{feed} (mm/s)	r_s	S_{weld} (mm/s)	S_{feed} (mm/s)	r_s
Welder 1	3.38 ± 0.15	2.59 ± 0.11	0.77 ± 0.01	4.18 ± 0.24	3.75 ± 0.25	0.90 ± 0.02
Welder 2	3.07 ± 0.12	2.53 ± 0.22	0.83 ± 0.05	4.50 ± 0.21	4.18 ± 0.21	0.93 ± 0.03
Welder 3	3.28 ± 0.27	2.20 ± 0.33	0.67 ± 0.05	4.53 ± 0.06	3.55 ± 0.24	0.78 ± 0.06
G. Mean(*)	3.24 ± 0.22	2.44 ± 0.28	0.75 ± 0.08	4.40 ± 0.23	3.83 ± 0.34	0.87 ± 0.07

(*) General mean values considering all the welders

4. Conclusions

From the obtained results it is possible to conclude on the feasibility of polycarbonate hot-gas welding. The used welding tool showed to be reliable concerning the agreement between displayed, or selected, and measured temperatures at the specified point, although those temperatures are very different at other points out of the terminal. For rods with the used diameter, it is possible to use any of the three studied nozzles. Nevertheless, nozzles with greater ratios between areas for plate heating and areas for rod heating, seems to lead to greater contact areas between bead and plate. Temperatures higher than 350 ºC tend to cause bubbles at the beads' borders. Anyway, it was found that, to work with rods with diameters greater than 3 mm, it is necessary to use temperatures above 350 ºC.

Even if the welding beads present the same aspect, the personal characteristics of the welder do influence on welding parameters such welding and feeding speeds. Welding beads produced by welders that apply lower pressure to the welding rod tend to have slightly smaller areas. In these cases, welding speeds tend to be higher and, on the other hand, feeding speeds tend to be lower.

The main effect of presence of residues in the nozzle occurs when these residues are at the plate-heating aperture. In this case, both welding and feeding speeds increase.

5. Acknowledgements

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