Weld path optimisation for rapid prototyping and wear replacement by robotic gas metal arc welding

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Chapter 5

Preliminary Path Strategy Sensitivity Experiment

5.1 Aim of Experiment

Now that the weld path design strategies have been presented and the welding cell has been described, the thesis will test the effects of the weld paths on build process stability. These next three chapters present the preliminary path strategy sensitivity experiment that gauges how sensitive the build process is to the various weld path design strategies that were outlined in Chapter 3.

The weld path design strategies were trialled in the robotic GMAW cell in order to observe their effects on process stability and performance. The aim was to test whether the process was sensitive to the weld path strategies used and to examine the scope that weld path design has as a tool for controlling the stability and performance of the RP by GMAW process. If the performance of the weld path strategies varied significantly and the process was shown to be sensitive to the path strategies used, this would indicate that open-loop weld path design can be useful for improving process performance.

The various weld path design strategies that were trialled are summarised in the experimental method that is presented in the following chapter section. The sections of this experiment that relate to the raster weld paths are published in Siminski and De Boer [2002 a]. The welding trials focused on the following aspects of RP by GMAW process performance:

- Geometric stability
- Thermal stability
- Weld defects
- Total build time

5.2 Experimental Method

5.2.1 General Method Description

A series of solid object weld trials was carried out in the robotic GMAW cell. Each weld trial (or weld test) was assigned a combination of weld path strategy variants and an object shape, according to which the weld paths were calculated and was executed by welding one solid object. Each object was welded in the centre of one half of a base plate, with two objects per base plate. A total of 54 trials were carried out.

A number of different shapes were used for the solid objects, as shown in Table 5.1.

Table 5.1: Shapes used for welding trials

Solid Object Shape	Programmed Dimensions (mm)
Square	length and width = 80
Rectangle	length = 80; width = 26.5 - 26.7
Circle	diameter = 80
Smaller square (for the wall/fill sequencing tests)	length and width = 53.33

There were three sets of weld settings used for the trials, as shown in Tables 5.2 and 5.3.

Table 5.2: Weld settings used for welding trials (1)

Weld Type	Voltage (%)	Voltage (V)	Current (A)	Wire Feed Rate (m/min)
Thin wall	100	16.4	95	4
Ridge fill	120	20.3	125	5.5
Trough fill	150	27.4	159	7

Table 5.3: Weld settings used for welding trials (2)

Weld Type	Travel Speed (mm/s)	Vert. Incr. (mm/layer)	Heat Input (J/mm)	Deposition Area (mm^2)
Thin wall	5	1.45	310	8.48
Ridge fill	4	2.5	634	14.58
Trough fill	4	2.5	1090	18.56

The thin wall weld type was used for the thin wall boundaries. The ridge fill type was used for the "ridges" or "crests" in self-constrained filling, while the trough fill type was used for the "troughs" or "roots" in self-constrained filling. For the fill welds in non-constrained filling, the trough fill weld parameters were used in this experiment. The vertical increments were the vertical distances by which the torch position was adjusted between consecutive weld layers.

The thin wall weld settings, including the vertical increment, were chosen from among those successfully developed for thin wall welding by Jacono [De Boer, Jacono, et al., 2000] [Jacono, 1999]. Jacono confirmed the work of other researchers that only a very tight range of weld parameter combinations are suitable for thin wall welding, that small fast-freezing weld pools are essential and that the welding process must be as stable as possible [Ribeiro, 1998] [Ribeiro, 1999] [Ribeiro and Norrish, 1997] [Ribeiro, Ogunbiyi, et al., 1997] [Dickens, Pridham, et al., 1992]. As a result, the only "natural" transfer mode suitable for the making of thin wall welds is low current short-circuit transfer, which is the transfer mode used here. Out of the range of weld parameter combinations developed by Jacono, the one chosen for this thesis had a relatively high wall thickness. This was in order to make the experiment more robust by reducing the risk of the fill welds melting through the thin weld walls. This risk is something that all rapid prototyping by GMAW systems would need to consider if they are using the boundary method, though the actual thin wall weld parameters could vary.

The ridge and trough fill weld settings were chosen based on the solid objects work by Jacono, on the findings of other researchers and on preliminary welding trials conducted by the author [De Boer, Jacono, et al., 2000] [Jacono, 1999]. Jacono had recognised the need to use much higher heat inputs for fill welds than for thin wall welds, due to the need to burn off slag and penetrate much more substrate material. Those of Jacono's settings that produced good fusion, no weld defects and good mechanical properties were used as a guide for the parameters used here. Kalligerakis and Spencer both stated that trough welds in self-constrained welding need to use higher currents and heat inputs than ridge welds, since trough welds need to penetrate more material than ridge welds and since trough welds must also be hot enough to be good at burning away slag [Kalligerakis and Mellor, 1992] [Spencer and Dickens, 1995] [Spencer, Dickens, et al., 1998]. Yet at the same time, it was known that currents could not be too high, since the weld pools still needed to be of a modest size. As a result, the trough welds in this thesis were made in globular transfer mode and used a higher current and heat input than the ridge welds. The ridge welds were made in high-end short-circuit transfer mode and in turn used a higher current and heat input than the thin wall welds.

It was realised that in order to produce flat top surfaces, the ridge weld settings, the trough weld settings and the weld spacing in self-constrained welding would need to be perfectly matched. The match-up used in this thesis was developed after some initial trials performed by the author, but was not perfect and the implications of the selection of these parameters are discussed as part of the results discussion. The vertical increment for these welds was approximated after initial trials. The trough weld settings were also used for the non-constrained fill welds in this experiment for the purposes of simplification, since this would not have affected the type of results that this experiment was aiming to generate.

A contact-tip to workpiece distance of 15mm was used. This was the same contact-tip to workpiece distance as was successfully used by Jacono for all his welds [De Boer, Jacono, et al., 2000] [Jacono, 1999]. As outlined in the thesis introduction, longer contact-tip to workpiece distances and therefore longer electrode extensions allow for greater resistive heating of the electrode wire and therefore lower currents for a given wire feed speed. Since low currents are essential in thin wall welding, this can be seen to be an advantage. However as also outlined in the introduction, the greater the contact-tip to workpiece distance, the more the electrode tip wanders due to its curvature and the less controlled the weld pool. This has even more significance in rapid prototyping by GMAW, since tightly controlled weld pools and highly regular weld beads are absolutely essential, especially in thin wall welding. The electrode tip must be restrained from wandering as much as possible and so the contact-tip to workpiece distance must be kept short. However the other factor to consider is that the shorter the distance, the more risk of the welding torch hitting irregularly deposited regions of the weldment. This was observed in initial welding trials. It was most likely to occur in regions where many weld starts occurred, was highly detrimental to the process and cannot be allowed to happen in any rapid prototyping or wear replacement process.

Thus the contact-tip to workpiece distance must be balanced between restraining the electrode tip from wandering and reducing the risk of the welding torch coming into contact with any part of the substrate. This thesis made a conservative choice in terms of this risk, since any collision would have been very detrimental to the quality of the object being built and would have seriously compromised the experimental results of this thesis. The contact-tip to workpiece distance used by Jacono was deemed to be a good safe compromise for the purposes of this thesis, since it avoided collisions while still producing adequate weld quality in order to obtain the desired experimental results. Also, using the same contact-tip to workpiece distance as Jacono also ensured the integrity of his carefully established thin wall welding parameters. Real rapid prototyping and/or wear replacement by GMAW systems would need to make their own judgement about contact-tip to workpiece distance based on the particular application and they may well choose to use a smaller distance.

As has been alluded to previously, the regions where welds start and stop were found in initial welding trials to be particularly problematic and tend to give rise to uneven deposition. In order to reduce the risk of these regions negatively affecting the rest of the results that this experiment was aiming to produce, weld settings were used for these regions that would reduce their impact on the rest of the deposition process. The implications of the problems introduced by these regions and the choice of weld parameters in these regions will be discussed later in the results and discussion chapters of the experiment.

The spacing used between the welds varied slightly depending on the weld test and was between 6.15mm and 6.67mm. All the welds within a weld test, thin wall welds as well as fill welds, were offset horizontally from each other by the same spacing distance. The actual weld spacing was allowed to vary within a very small range for the convenience of path generation and this would not have affected the type of results that this experiment was aiming to generate. Justification for the spacing used can be found in the paragraphs discussing the choice of fill weld parameters. The number of thin wall boundary layers used for every fill layer was 1.66667. The programmed number of fill layers was 6 for most of the weld tests, however tests 1 and 2 were programmed with 5. The rectangular raster fill path tests were programmed to have 12, however the number actually welded varied.

The thin wall boundary layers were welded in such a sequence relative to the fill layers, that the thin wall boundary was always higher than the fill except at the end of the weld test. To accomplish this, the thin wall boundary was welded two layer sets ahead of the fill layers. The exception to this was in the tests investigating the thin wall and fill layer sequencing methodologies, where some weld tests used two layer sets and some used zero.

In order to reduce the amount of heat in the weldments, cooling times were used at various stages of the object build processes. The wall/fill sequencing tests used a cooling time of 60s after each thin wall boundary layer and a cooling time of 240s after each fill weld. All the other weld tests did not use any cooling time between thin wall boundary layers, but used a cooling time of 120s after selected fill welds and after each fill layer. These cooling times were, however, occasionally extended manually to allow for visual inspection of the weldment and cleaning of the weld nozzle. Where this occurred, this extra waiting time was not included in the total build time, so the recorded build time was not affected.

The shielding gas used throughout this experiment was Argoshield 51 (otherwise known as Argoshield Universal), as described in Chapter 4 and for the reasons outlined in that chapter. The gas flow rate used was 15L/min for most of the weld tests, since this gas flow rate had been successfully used for all weld types by Jacono and since it would not have significantly impacted on the results [De Boer, Jacono, et al., 2000] [Jacono, 1999]. However the flow rate for test 15 was 25L/min and the effective flow rate for tests 1-14 is unknown since these were made with an undetected leak in the shielding gas delivery system. However since this was known when the results were being analysed, it did not affect the nature of the results. The weld tests also used the water cooled nozzle and automatic wire snipping before every weld start.

5.2.2 Measurements and Observations Recorded

For each weld test the following information was recorded:

- Photographs of the welded object
- Description of observed phenomena
- Description of observed weld path strategy performance
- The number of individual fill welds per fill layer
- The total build time of the first fill layer (including welding and cooling times)
- Instantaneous voltage, current, wire feed rate and gas flow rate weld signals
- The basic dimensions of the welded object (such as height, width and height)
- The approximate widths of selected thin wall welds and ridge fill welds and their corresponding trough channels

Every individual fill weld and every fill layer were visually inspected before being welded over throughout every weld test conducted. All distances were measured using vernier callipers. All welding parameter measurements were taken using the data monitoring and acquisition system described in Chapter 4 of this thesis. The welding parameter measurements were later analysed in Matlab to calculate the mean weld parameters for each weld type as presented in Tables 5.2 and 5.3. All layer build times were measured automatically by the robot controller during robot program execution.

Observations of geometric stability effects were based on visual observations supplemented where required by distance measurements using vernier callipers. Where clear evidence of geometric phenomena was observed, this was recorded. Possible geometric phenomena for which the evidence was less pronounced were also recorded but the uncertainty of the result was noted. More precise measurements of geometric stability were outside the scope of this experiment, to be addressed by the final experiment in this thesis.

Weldment surface temperatures were not measured since a suitable temperature measurement sensor was not available at the time of this experiment. Observations regarding weld temperatures and thermal stability were made based on visual observations and intuitive reasoning, however these serve only as a guide and do not in themselves prove temperature related phenomena. Direct measurements of thermal stability were thus also outside the scope of this experiment, to be addressed by the final experiment in this thesis.

Cross-sectioning the welded objects was also outside of the experimental scope, to be addressed by the final experiment in this thesis. This was due to the size of the experiment and to the fact that the experiment was only designed as a preliminary experiment. As a result, there is only limited scope for identifying weld defects in this experiment. Some of the worst weld defects such as large voids and unfilled regions were clearly visible and such observations were recorded. Other weld defects such as inclusions and porosity could not be measured.

The total time it took to build a fill layer in every weld test was recorded by measuring how long it took to build the first fill layer. This build time included any cooling time incorporated into the build process, but was independent of any extra cooling time added manually when the operator was inside the welding cell. The number of instances that cooling time was employed and the length of the cooling time that was used affected the total build time, yet this was measured in this manner because cooling times are an integral part of fill layer welding. Since cooling time can only be employed when the robot is not welding, the number of individual (i.e. separate) fill welds per fill layer was also recorded and analysed, along with the inter-relationship between this number and the total fill layer build time.

5.2.3 Path Strategies Examined

The weld path strategies investigated in this experiment were those presented in Chapter 3 of this thesis. They consisted mainly of various layer filling strategies, however the final four weld tests were devoted to trialling the methodologies for sequencing the deposition of thin wall boundary and fill layers.

The weld path design strategies that were investigated were:

- Raster weld paths
    - Discrete or continuous
        - Constant for all fill welds
        - Combined (different for ridge and trough fill welds)
    - Raster angle (relative to the object)
        - 0°
        - 45°
        - 90°
    - Weld order of path segments
        - Thermally symmetrical weld order
        - Sequential weld order
        - Minimised total waiting time weld order
- Contour weld paths
    - At centre of fill area
        - Contour weld
        - Line weld
    - Weld order of fill weld contours
        - Sequential from inside outwards weld order
        - Sequential from outside inwards weld order
        - Minimised total waiting time weld order
    - Welding direction of fill weld contours (clockwise or anti-clockwise)
        - Constant
        - Alternating
- Spiral weld paths
    - Number of spiral arms
        - 1
        - 2
    - Welding direction of spiral arms
        - From inside outwards
        - From outside inwards
- Constraint strategies
    - Self-constrained
    - Non-constrained
- Thin wall and fill sequencing strategies
    - Thin wall boundary layers level with fill layers
    - Thin wall boundary layers ahead of fill layers

The raster angle refers to the angle between the raster lines and the fill area of a particular object. The raster angle 0° was defined to be parallel to the long axis of the base plate and in the case of a rectangular object, also parallel to the long axis of the rectangle. The "minimised total waiting time weld order" was a fill weld order that minimised total waiting time in self-constrained welding, while ensuring that adjacent welds were not welded one directly after another without any cooling time in between.

Combinations of these various strategies were devised and trialled. As mentioned previously, various object shapes were also used and most strategy combinations were tested with more than one object shape. One weld test was allocated per strategy and object shape combination, resulting in the 54 tests that were carried out. It should also be noted that not all strategy combinations were possible, since some strategy options are mutually inclusive or exclusive. For example, weld orders other than sequential are only possible when using self-constrained filling. Another example is that non-constrained filling with spiral paths can only be achieved using one spiral arm. A summary of what weld tests were carried out is shown in Table 5.4.

Table 5.4: Summary of weld tests executed

Weld Test Numbers	Square	Rectangular	Circular	Smaller Square
Raster Paths	1 - 14	15 - 22	23 - 26	-
Contour Paths	27 - 32	33 - 35	36 - 39	-
Spiral Paths	40 - 43	44 - 46	47 - 50	-
Wall/Fill Sequencing	-	-	-	51 - 54