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

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Chapter 10

Conclusion of Weld Path Strategy Comparison Experiment

10.1 Discussion of Results

10.1.1 Constraint Strategy Discussion

The analysis of the roughness values from the surface profiles showed that all the self-constrained path strategies as well as all the inside-to-outside non-constrained path strategies had approximately equal results. At the same time, all the outside-to-inside non-constrained path strategies had approximately equal results. However the roughness values from the outside-to-inside non-constrained path strategies were almost twice as bad as the roughness values from the other path strategies. These results show that while the self-constrained and the inside-to-outside non-constrained path strategies produced similar results, the outside-to-inside non-constrained path strategies clearly performed much worse and should be avoided.

The surface profiles and the macrosections of the self-constrained path strategies showed that the self-constrained path strategies had approximately flat surface profiles except for a wave-like pattern. This wave-like pattern was shown to be caused by imperfectly matched ridge and trough weld settings, which resulted in the trough weld beads being a little too large for the space defined for them by the ridge welds. The results also showed that the weld beads in the self-constrained path strategies were not skewed in any one particular direction and were approximately symmetrical about the vertical axis.

These results show that the surface profiles produced by the self-constrained path strategies are sensitive to the weld settings used for the ridge and trough welds and that the surface profiles can be improved by improving the match between these weld settings. Thus it can be stated that the self-constrained path strategies can produce very even surface profiles on the condition that their ridge and trough weld settings are very well matched. These results also show that the weld beads in the self-constrained strategies formed evenly and in the desired locations, since they were symmetrical and not skewed. These are all advantages for the self-constrained welding strategy in terms of geometric stability and it can be concluded that this strategy has good geometric stability properties.

On the other hand, the surface profiles and the macrosections of the outside-to-inside non-constrained path strategies showed that these path strategies had very poor geometric performance. As has been mentioned previously, these path strategies had the most uneven surface profiles of all. The results showed that they had large accumulations of weld metal at the centres of the fill layers and depressions on either side. It could be seen that they deposited the weld metal very unevenly. The results also showed that these path strategies produced asymmetrical weld beads that were clearly skewed towards the centres of the fill layers.

The results showed that the very poor surface profiles of the outside-to-inside non-constrained strategies were caused by their weld beads forming away from their intended locations. The weld beads formed closer to the centres of the fill layers than intended, presumably due to the asymmetric constraint conditions which caused the weld beads to be skewed towards the layer centres. This was seen to reduce the space available for the central weld beads, which in turn were forced to form with raised profiles. A property of these weld path strategies was thus found to be that their weld beads form away from their desired locations which leads to too little metal deposition in some regions and too much in other regions. Thus it can be concluded that the outside-to-inside non-constrained path strategies are very geometrically unstable. Outside-to-inside non-constrained welding should thus be avoided, unless the welding application is very undemanding.

Finally, the surface profile and macrosection results of the inside-to-outside non-constrained path strategies showed that these path strategies produced approximately flat profiles except for possibly excessive weld metal deposition near the layer edges. They also showed that the weld beads were asymmetrical and skewed away from the centres of the fill layers, in an opposite manner to the outside-to-inside non-constrained weld beads.

The inside-to-outside non-constrained path strategies were similar to the outside-to-inside non-constrained strategies, except that their weld beads were made in the opposite direction. As noted above, their weld beads were also skewed like the weld beads from the outside-to-inside non-constrained strategies, except in the opposite direction.

Thus it was suspected that these path strategies also had weld beads that formed away from their intended locations, similarly to the outside-to-inside non-constrained strategies, except that any excessive metal accumulation would occur at the layer edges instead of the layer centre. However this could not be proven conclusively. If this was indeed the case, then the inside-to-outside non-constrained path strategies would also be inherently geometrically unstable, making all non-constrained welding in general geometrically unstable. As it is, it is concluded that the inside-to-outside non-constrained path strategies are unlikely to be as geometrically stable as the self-constrained strategies. It is recommended to avoid inside-to-outside non-constrained welding in favour of self-constrained welding, unless the welding application is very undemanding.

Thus in summary, the self-constrained welding strategy was found to be the most geometrically stable and the most able to produce good surface profiles, on the condition that the ridge and trough weld settings are very well matched. The non-constrained strategy when welded from the outside inwards was shown to be the least geometrically stable, with weld beads forming away from their intended locations, very uneven deposition and material accumulation at the centre of the fill layer and the most uneven surface profiles. It was suspected that the non-constrained welding strategy was also geometrically unstable when welded from the inside outwards, although to a lesser extent, though this could not be proven conclusively. It is recommended that non-constrained welding in general should be avoided in favour of self-constrained welding, especially for demanding applications such as rapid prototyping, although it may be appropriate for less demanding wear replacement applications.

Thus it was concluded that the most geometrically stable constraint strategy was the self-constrained strategy, followed by the non-constrained strategy when welded from the inside outwards, followed by the non-constrained strategy when welded from the outside inwards which was clearly the least stable.

10.1.2 Number of Welds and Thermal Stability Discussion

The mean and upper decile surface temperature results from both the thin walls and the fill layers showed that the 'cno' path strategy was clearly the coolest, followed by path strategies 'cym' and 'cni' which were approximately equal and clearly hotter, followed by 'syi' and 'syo' which were approximately equal and clearly hotter again, followed by strategies 'sni' and 'sno' which were approximately equal and clearly the hottest of all. The numbers of welds per fill layer and the total build time results showed that the contour path strategies ('cym', 'cni' and 'cno') had the highest numbers of individual welds per fill layer and the slowest total build times, followed by the self-constrained spiral path strategies ('syi' and 'syo'), followed by the non-constrained spiral path strategies ('sni' and 'sno').

As well as this, the macrosection results showed that all the weld samples from all the path strategies experienced increasing weld bead widths with increasing fill layer number, which was a consequence of inter-layer thermal instability. The macrosection results also showed that the non-constrained spiral path strategies that were welded from the outside inwards suffered from gross thermal instability near the centres of the fill layers, which resulted in very large weld beads and heat affected zones near the fill layer centres.

Also, the analysis of the standard deviation of surface temperatures from both the thin walls and the fill layers showed that the spiral path strategies varied more than the contour path strategies. The standard deviations of temperature in all the contour path strategies ('cym', 'cni' and 'cno') were found to be approximately equal. At the same time, the standard deviations of temperature in all the spiral path strategies were found to be similar. Some variation may have been present among the spiral paths strategies, but the evidence was inconclusive. However the spiral path strategies had standard deviations of temperature that were approximately twice those of the contour path strategies.

It can be seen that increasing numbers of individual welds per fill layer allowed the path strategies to employ increasing numbers of cooling stops during layer filling, which in turn increased total build times. Longer build times in turn resulted in cooler final surface temperatures, as shown by the temperature results from both the thin walls and the fill layers. It can also be seen that the 'cno' path strategy had cooler final surface temperatures than the other contour strategies because it welded its contours from the outside inwards, which resulted in its shortest weld being made last. Thus it can be seen that the weld order in contour path strategies affects the surface temperatures of the weldment.

Now, greater numbers of cooling stops and lower final surface temperatures in a path strategy indicate that a path strategy has a greater scope for thermal control. It has more opportunities to pause the layer filling process to let the weldment cool down and to prevent the weldment from overheating. It thus has a greater potential to avoid intra-layer thermal instability that occurs when weld beads change shape due to being made on ever increasing surface temperatures. It can thus be seen that the most thermally stable path strategies were the contour path strategies ('cym', 'cni' and 'cno'), followed by the self-constrained spiral path strategies ('syi' and 'syo'), followed by the non-constrained spiral path strategies ('sni' and 'sno').

It can also be seen that contour paths have an added scope for thermal control through control of their weld order. Because its shortest weld was made last, the 'cno' strategy had the lowest final surface temperatures of all. However the most flexible contour path strategy in terms of contour weld order was the 'cym' strategy, due to it being self-constrained. This strategy does not have to weld its contours sequentially and can employ any weld order as long as the ridge and trough welds are made with the proper modes of constraint. If a different weld order had been chosen for the experiment, the 'cym' final temperatures would have been different.

As well as this, it can be seen that the path strategies with the lower final surface temperatures were also found to have lower variations in surface temperature. This can be expected, since hotter objects cool faster than colder objects and thus in time the temperature variation between hotter and colder objects decreases. Since the cooler path strategies took longer to perform the layer filling, it can be expected that the temperature variations between various points on their weldment surfaces would be less. Greater variations in surface temperature promote greater thermal instability, which indicates once again that the contour path strategies were more thermally stable than the spiral path strategies.

Another result relating to intra-layer thermal instability was that the outside-to-inside non-constrained spiral path strategies were very thermally unstable near the centres of the fill layers. They deposited heat into the weldment in such a manner that a lot of heat accumulated in the centre of the layers, resulting in extreme overheating by the end of the layer filling procedures. The macrosections showed that this in turn caused the weld beads and the heat affected zones to be very large near the middle of the layers. This was a form of gross intra-layer thermal instability and shows that the non-constrained spiral paths that were welded from the outside inwards are particularly thermally unstable and should always be avoided.

However a similar, although smaller, phenomenon is also suspected in the self-constrained spiral paths that were welded from the outside inwards. This path strategy used a cooling stop during layer filling and the welds were more widely spaced and did not overlap, thus any thermal instability would be smaller. However this path strategy also used spiral arms that were welded from the outside inwards and it is suspected that these spiral arm welds would also have resulted in some unnecessary thermal instability at the centre of the fill layers. This cannot be proven conclusively in this experiment, however it is very likely. Thus the conclusion is made that the self-constrained spiral paths that were welded from the outside inwards are probably also unnecessarily thermally unstable near the centres of the fill layers and it is recommended to avoid them.

Another form of thermal instability that was found was inter-layer thermal instability. As mentioned previously, the macrosections showed that in every weld sample, the weld bead widths increased with increasing fill layer number. This was due to inter-layer thermal instability which occurs when successive fill layers are made under ever increasing surface temperatures. It can be seen from the macrosections that this form of thermal instability is detrimental to object quality and should be avoided.

Inter-layer thermal instability can be reduced by using longer inter-layer cooing stops to allow the weldment to cool to as close to ambient temperature as possible. Higher final weldment surface temperatures require longer inter-layer cooling stops. Thus in order to avoid inter-layer thermal instability, the non-constrained spiral path strategies would need longer inter-layer cooling stops than the self-constrained spiral path strategies, which in turn would require longer cooling stops than the contour path strategies.

Finally, it needs to be mentioned that greater numbers of individual welds per fill layer lead to greater numbers of weld starts and stops, which can be very detrimental to object quality. This was shown to be the case in the preliminary path sensitivity experiment, where arc ignitions, arc ignition failures, weld heating zones and crater fill zones were shown to introduce gross geometric and thermal instabilities as well as weld defects. It was concluded in that experiment that while these problem areas could be improved through special procedures or weld parameter tuning, it is undesirable to have to do so. It is thus very desirable to reduce the number of weld starts and stops in a layer filling procedure by using fewer individual welds per fill layer. Thus greater numbers of weld starts and stops brought about by greater numbers of individual welds per fill layer are a serious disadvantage for a path strategy.

Now, the non-constrained spiral strategies were found to have fewer individual welds per fill layer and therefore fewer weld starts and stops than the self-constrained spiral strategies, which in turn were found to have fewer than the contour strategies. Thus the contour path strategies suffer the most from weld starts and stops, which is a significant disadvantage. The self-constrained spirals suffer less, which is an advantage over the contour paths, while the non-constrained spiral paths suffer the least of all, which is an advantage over all the other path strategies.

Thus in summary, the most thermally stable path strategies were the contour path strategies ('cym', 'cni' and 'cno'), followed by the self-constrained spiral path strategies ('syi' and 'syo'), followed by the non-constrained spiral path strategies ('sni' and 'sno'). This was due to the numbers of cooling stops that the path strategies could use during layer filling and thus the level of thermal control that they had. It was also due to the contour path strategies producing lower variations in surface temperatures and having extra thermal control through control of the contour weld order.

The spiral path strategies that were welded from the outside inwards also had a special thermal instability disadvantage in that they generated higher weldment temperatures and larger weld beads and heat affected zones near the centres of the fill layers. This was clearly proven in the outside-to-inside non-constrained spiral strategy, however a similar but smaller thermal instability was also deemed very likely in the outside-to-inside self-constrained spiral strategy. It was thus concluded that this is a disadvantage of all outside-to-inside spiral strategies and it was recommended that they be avoided in favour of the inside-to-outside spiral strategies. As well as this, inter-layer thermal instability was found to be present and undesirable and those path strategies that produced higher final weld temperatures would require longer inter-layer cooling times to avoid it.

However, those path strategies that used more individual welds per fill layer also used more weld starts and stops and were thus more exposed to the serious instabilities and weld defects that they can cause. Thus the path strategies that were found to suffer the least from the problems associated with weld starts and stops were the non-constrained spiral path strategies ('sni' and 'sno'), followed by the self-constrained spiral path strategies ('syi' and 'syo'), followed by the contour path strategies ('cym', 'cni' and 'cno'). It should also be noted that the number of individual welds per fill layer used by the contour path strategies would increase with increasing fill layer size, whereas the number of welds per fill layer used by the spiral path strategies would always be constant.

10.1.3 Weld Defects Discussion

The macrosection results showed that the only prevalent type of weld defect that was present in the weld samples was slag inclusions. The only other weld defect that was found was a crack that was caused by a high concentration of slag inclusions in one particular location. There were not very many inclusions found per weld sample, but they are a concern that requires special attention since high concentrations have been shown to cause cracks and since the burning off of slag is difficult in some locations. However overall, the performance in terms of weld defects was seen as reasonably good, considering that slag was not cleaned off the weldment during welding. No variation in weld defects could be seen between the various weld path strategies and the choice of path strategy was not seen to affect the weld defects.

10.1.4 Weld Path Strategy Comparison Summary

The performances of all the weld path design strategies were summarised, in order to see which performed best overall and which performed worst. The advantages and disadvantages of each weld path design strategy were listed alongside the strategy name as shown in Table 10.1. Relatively major advantages were given two ticks, minor advantages were given one tick, major disadvantages were given two crosses and minor disadvantages were given one cross. The comparison was designed so that one tick would cancel out one cross.

Table 10.1: Weld path strategy comparisons
Major advantage = ✔ ✔ ; minor advantage = ✔ ; major disadvantage = ✕ ✕;
minor disadvantage = ✕; each ✔ cancels one ✕

Path Strategy	Advantages	Disadvantages	Score
'cym'	✔ Self-constrained strategy is geometrically stable ✔ ✔ Most thermal control and best thermal stability due to most cooling stops	✕ Most problems with weld starts and stops due to highest number of individual welds per fill layer	✔ ✔
'cni'	✔ ✔ Most thermal control and best thermal stability due to most cooling stops	✕ Most problems with weld starts and stops due to highest number of individual welds per fill layer ✕ Inside-to-outside non-constrained strategy is suspected to be inherently geometrically unstable (better to avoid)	-
'cno'	✔ ✔ Most thermal control and best thermal stability due to most cooling stops	✕ Most problems with weld starts and stops due to highest number of individual welds per fill layer ✕ ✕ Outside-to-inside non-constrained strategy is inherently very geometrically unstable	✕
'syi'	✔ Self-constrained strategy is geometrically stable ✔ Fewer problems with weld starts and stops due to fewer individual welds per fill layer ✔ Less thermal control and worse thermal stability due to fewer cooling stops		✔ ✔ ✔
'syo'	✔ Self-constrained strategy is geometrically stable ✔ Fewer problems with weld starts and stops due to fewer individual welds per fill layer ✔ Less thermal control and worse thermal stability due to fewer cooling stops	✕ Some geometric and thermal instability likely at centre of fill layers due to overheating due to the outside-to-inside spiral strategy (better to avoid)	✔ ✔
'sni'	✔ ✔ Fewest problems with weld starts and stops due to fewest individual welds per fill layer	✕ Least thermal control and worst thermal stability due to no intra-layer cooling stops ✕ Inside-to-outside non-constrained strategy is suspected to be inherently geometrically unstable (better to avoid)	-
'sno'	✔ ✔ Fewest problems with weld starts and stops due to fewest individual welds per fill layer	✕ Least thermal control and worst thermal stability due to no intra-layer cooling stops ✕ ✕ Geometrically and thermally unstable at centre of fill layers due to overheating due to the outside-to-inside spiral strategy ✕ ✕ Outside-to-inside non-constrained strategy is inherently very geometrically unstable	✕ ✕ ✕

It was found that the 'cym' path strategy, that used a self-constrained contour path with a minimised cooling time weld order, performed quite well. It used the self-constrained welding strategy which was found to have good geometric stability properties. Along with the other contour paths, it also had the greatest level of thermal control and was the most thermally stable due to the highest number of intra-layer cooling stops that it could employ. However it also had the most problems associated with weld starts and stops due to the highest number of individual welds per fill layer.

The 'cni' path strategy, that used an inside-to-outside non-constrained contour path, did not perform as well as the 'cym' path strategy. Just like the 'cym' path strategy, it was the most thermally stable and had the best level of thermal control due to the highest number of intra-layer cooling stops that it could employ. It also had the same number of problems with weld starts and stops due to the same high number of individual welds per fill layer. However unlike the 'cym' path strategy, it did not use self-constrained welding. Instead, it used inside-to-outside non-constrained welding, which was suspected of being inherently geometrically unstable and is better to avoid.

The 'cno' path strategy, that used an outside-to-inside non-constrained contour path, performed worse than the 'cni' path strategy. Just like the 'cni' path strategy, it was the most thermally stable and had the best level of thermal control due to the highest number of intra-layer cooling stops that it could employ. Also just like the 'cni' path strategy, it had the most problems with weld starts and stops due to the highest number of individual welds per fill layer. However unlike the 'cni' path strategy, it used the outside-to-inside non-constrained path strategy. Whereas the inside-to-outside non-constrained strategy was suspected to be somewhat geometrically unstable, the outside-to-inside non-constrained strategy was clearly proven to be even worse. The outside-to-inside non-constrained strategy was clearly shown to be inherently very geometrically unstable.

Now the 'syi' path strategy, that used an inside-to-outside self-constrained spiral path, was found to perform the best overall out of all the path strategies. It used the self-constrained welding strategy which was found to have good geometric stability properties. It also had fewer problems associated with weld starts and stops than the contour path strategies because it used fewer individual welds per fill layer. Finally, it had reasonably good thermal control capabilities and therefore thermal stability because it could employ an intra-layer cooling stop, though it was not quite as thermally stable as the contour strategies.

The 'syo' path strategy, that used an outside-to-inside self-constrained spiral path, was found to perform very similarly but not quite as well as the 'syi' strategy. Just like the 'syi' path strategy, it used the self-constrained welding strategy which had good geometric stability properties. It also had fewer problems associated with weld starts and stops than the contour path strategies because it used fewer individual welds per fill layer. As well as this, it also had reasonably good thermal control capabilities just like the 'syi' strategy because it also could employ an intra-layer cooling stop.

However the outside-to-inside spiral welding direction was found to be a disadvantage, since it is likely to reduce the strategy's thermal stability. It was deemed likely that this strategy would suffer some thermal and therefore geometric instability at centre of fill layers due to localised overheating due to the welding direction. Therefore, it is better to avoid this strategy in favour of the 'syi' strategy.

On the other hand, the 'sni' path strategy was found not to perform so well overall. It used an inside-to-outside non-constrained spiral path. It was found to have the least problems associated with weld starts and stops, along with the other non-constrained spiral strategy, because it could only ever have one individual weld per fill layer. However at the same time, it could not employ any intra-layer cooling stops and therefore had the least thermal control and therefore poor thermal stability. As well as this, it did not use the self-constrained strategy, but instead used the inside-to-outside non-constrained strategy. As mentioned for the 'cni' strategy, the inside-to-outside non-constrained strategy was suspected of being inherently geometrically unstable and it is better to avoid it.

Finally, the 'sno' path strategy, that used an outside-to-inside non-constrained spiral path, was found to clearly perform the worst overall out of all the path strategies. Same as the 'sni' strategy, it had the least problems associated with weld starts and stops because it could only ever have one individual weld per fill layer. However just like the 'sni' strategy, it could not employ any intra-layer cooling stops and therefore had the least thermal control and therefore poor thermal stability.

In addition to that, it was also shown to have extra geometric and thermal instability at the centre of fill layers due to localised overheating due to the spiral arm welding direction. This problem was deemed to be very likely in the 'syo' path strategy, however here it was certainly present and magnified due to the non-constrained welding strategy. Finally, it used the outside-to-inside non-constrained strategy. This strategy, as mentioned for the 'cno' path strategy, was clearly shown to be inherently very geometrically unstable.

Thus it was found that the path strategy that performed the best overall in terms of geometric stability, thermal stability, weld defects, total build time and numbers of welds per fill layer, was the inside-to-outside self-constrained spiral path strategy ('syi').

However, the self-constrained contour path strategy using the minimum waiting time weld order ('cym') may be the best path strategy to use in situations where thermal stability and control over weldment surface temperature are crucial. This is because this path strategy uses more individual welds per fill layer and therefore has more problems with weld starts and stops, but in exchange has better thermal properties. If the arc ignition, weld heating and crater filling zones of a weld were to be improved to the point where they no longer introduced any instabilities or weld defects and if there were never any arc ignition failures, then this path strategy would be the best path strategy.

On the other hand, the outside-to-inside non-constrained spiral path strategy ('sno') was found to be clearly the worst path strategy out of all the path strategies tested in this experiment.

10.2 Experimental Conclusions

A selection of weld path design strategies were tested and compared, in order to further investigate their effects on process stability and to establish which strategies perform best. Each path strategy was tested in terms of geometric stability, thermal stability, weld defects, build time and the number of individual welds per fill layer. It was found that:

1) The self-constrained welding strategy can produce good geometric stability on the condition that the ridge and trough weld settings are very well matched.

2) The non-constrained strategy when programmed to weld from the outside of a fill layer inwards is inherently very geometrically unstable. It caused weld beads to form away from their intended locations and caused very uneven deposition.

3) The non-constrained strategy is also suspected of being inherently geometrically unstable when programmed to weld from the inside of a fill layer outwards, though this could not be proven conclusively. Non-constrained welding in general is not recommended for rapid prototyping although it may be appropriate for less demanding wear replacement applications.

4) Path strategies with more individual welds per fill layer can employ more cooling stops during layer filling and therefore have lower final surface temperatures and tend to be more thermally stable. However more individual welds per fill layer leads to more problems associated with weld starts and stops.

5) Non-constrained (single armed) spiral path strategies that are programmed to weld from the outside of a fill layer inwards have added significant thermal and geometric instability at the centres of fill layers. It was suspected that self-constrained (double armed) spiral path strategies programmed to weld in the same direction also have a similar, but smaller added instability, though this could not be proven conclusively.

6) Inter-layer thermal instability causes weld beads to increase in width with increasing fill layers. Path strategies with higher final surface temperatures require longer inter-layer cooling times in order to avoid this problem.

7) The only prevalent type of weld defect found occurring through the central cross-sections of weldments was slag inclusions. There were not very many slag inclusions found through the central cross-section of each weldment, yet inclusions do require special attention.

8) The choice of path strategy was not seen to affect the weld defects occurring through the central cross-sections.

9) Out of the path strategies that were studied in this experiment, the path strategy that performed best overall was the self-constrained spiral path strategy programmed to weld from the inside of a fill layer outwards.

10) The self-constrained contour path strategy that uses the minimised total waiting time weld order was found to be best in situations where thermal stability and control over weldment surface temperature are critical. This path strategy has improved thermal performance at the cost of more problems associated with weld starts and stops.

11) Out of the path strategies that were studied in this experiment, the path strategy that performed worst overall was the non-constrained spiral path strategy programmed to weld from the outside of a fill layer inwards.