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

Michael Siminski
University of Wollongong

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Chapter 11

Discussion

11.1 Stability Improvement through Weld Path Design

The work reported in this thesis confirms the findings of previous researchers that geometric and thermal instability are inherent features of the rapid prototyping and wear replacement by GMAW processes [Dickens, Cobb, et al., 1993] [Dickens, Pridham, et al., 1992] [Doumanidis, 1997] [Kmecko, Hu, et al., 1999] [Kovacevic and Beardsley, 1998] [Song, Park, et al., 1998] [Spencer and Dickens, 1995] [Spencer, Dickens, et al., 1998] [Tinkler, Fihey, et al., 1991] [Tinkler, McNabb, et al., 1987] [Zhang, Li, et al., 2002].

Thermal instabilities can greatly reduce the quality of a weldment and need to be minimised. Geometric instability is cumulative and any instability that occurs in a lower part of a weldment cannot be reversed, unless material removal is used. Thus any geometric instability propagates through the rest of the weldment, compounded by any further instability that may occur. It has been shown that thermal instability always tends to produce geometric instability as well as tending to increase the risk of weld defects.

The need to control and reduce geometric and thermal instability goes right to the heart of rapid prototyping and wear replacement by GMAW, since the main reason for pursuing this technology is its potential ability to directly manufacture or repair fully functional metal parts. However this is not possible if the process cannot deliver the required level of geometric accuracy or an acceptable level of thermal control. Poor geometric accuracy and poor thermal control can lead to incorrect shape and reduced mechanical properties. Thus any useful rapid prototyping or wear replacement by GMAW requires a reliable method of countering the lack of stability. The required level of stability varies depending on the application, with higher geometric and thermal stability being required for applications such as machine parts compared to ground engaging tools.

This current thesis has established a new method for controlling and reducing geometric and thermal instability not previously considered. It has been shown that rapid prototyping and wear replacement by robotic GMAW can be made more stable through appropriate weld path design. It was found that the stability of the process is very sensitive to weld path design and that optimised open-loop weld path design can be used to greatly improve process stability and performance. A number of different mechanisms were identified through which the weld path design impacts on the stability and performance of the process and corresponding recommendations for weld path design were presented. The suitability of various weld path designs for different types of applications was assessed and the most optimal weld path designs for an expected wide range of applications were identified. The commonly used raster family of weld paths performed especially poorly when compared to other types of weld paths and is not recommended except for very undemanding applications.

Previous attempts at reducing instability include full real-time control of the heat and mass deposition onto the substrate. Research into this method was lead by Doumanidis, who claimed that off-line open-loop weld procedure generation "can not cope with unpredictable alterations of the process conditions, resulting in poor dimensional tolerances" [Doumanidis and Fourligkas, 1997]. The current work has shown that fixed weld path strategies with fixed weld parameters cannot adapt to dynamic changes in weldment and weld process conditions, but poor results are not always inevitable, since appropriate open-loop weld path design can greatly improve results.

Although the real time geometric and thermal control systems developed by Doumanidis [Doumanidis, 1994] are likely to improve the results obtained by rapid prototyping and wear replacement by GMAW, it is also possible to achieve improved results through appropriate open-loop weld path design that are acceptable to many rapid prototyping and wear replacement applications without the need for the extra expense and complexity. It is suggested that it is desirable to limit full real-time control to only those applications that cannot be catered for any other way. A rapid prototyping or wear replacement system that relies less on real-time control will be cheaper to obtain, cheaper to use, require less skilled operators, be more portable or easier to relocate, cheaper to maintain and possibly more robust and reliable. Increased portability would allow for increased flexibility in the way a system is utilised, making it easier to relocate depending on customer demands, with the ideal being a totally portable system that's instantly deployable to customer sites as required.

Another pre-existing method for controlling and reducing instability was through the use of a modified system that also incorporated material removal through CNC milling, such as the systems developed by Karunakaran, Song and Kmecko and Kovacevic [Karunakaran, Shanmuganathan, Jadhav, et al., 2000] [Karunakaran, Shanmuganathan, Roth-Koch, et al., 1998] [Song, Park, et al., 1998] [Song, Park, et al., 1999] [Kmecko, Hu, et al., 1999]. The advantage of such systems is that they remove some of the effects of the instabilities of the welding process during the CNC milling process. These systems can produce excellent results and may be very desirable for demanding applications, yet they require more equipment and therefore more expense and they have the added disadvantage of being very slow [Jandric and Kovacevic, 2001]. Increased stability through appropriate weld path design may eliminate the need to use such systems for some applications, yet it can also be used in conjunction with these systems to improve their performance.

The most time consuming aspect of these systems is material removal, which is very slow and minimising the amount of machining required can significantly reduce object build time [Kmecko, Hu, et al., 1999]. Jandric wrote that if "the surface of each deposited [weld] layer would be smooth enough ... many, if not all, of the layers could be deposited without introducing the milling operation, and the major disadvantage of this process [the slow speed] could be eliminated" [Jandric and Kovacevic, 2001]. Song also noted this, writing that "it would be best if the prototype tool can be manufactured directly without any secondary process" [Song, Park, et al., 1998]. Improved geometric & thermal stability through appropriate weld path design can improve the build quality such that the amount and frequency of machining can be reduced, thus speeding up the process. It should also be noted that surface grinding or milling is also often used in wear replacement. As in rapid prototyping, the use of appropriate weld paths can reduce the amount of material removal required or even eliminate it for some applications.

As has been outlined in the literature survey, it is also possible to reduce geometric instability by improving the regularity of individual weld beads by improving the stability of the GMAW metal transfer process. Thin wall welds are especially sensitive to the regularity of their weld beads and thus to the stability of the metal transfer process. Regular weld beads are always very important in rapid prototyping and wear replacement by GMAW, yet it is possible to add extra geometric stability by improving bead regularity still further, by making the metal transfer process even more stable. One way of doing this is through the use of pulsed GMAW and the kinds of metal transfer control systems developed by Kovacevic [Kmecko, Hu, et al., 1999] [Kovacevic, 1999] [Kovacevic and Beardsley, 1998] and another way is expected to be through the use of controlled short-circuit GMAW. This methodology of improving weld regularity is separate yet complimentary to the methodology developed in this thesis and both should be considered in an effort to improve object quality.

Another approach to improving geometric stability also existed in the form of the hybrid weld parameter control system developed by Jandric and Kovacevic [Jandric and Kovacevic, 2001]. This control system recognised that local features of a substrate such as edges and corners create different thermal transfer conditions that impact on weld bead dimensions and shape. The control system was able to counteract these effects by suitably varying the weld parameters in those locations. This approach is also separate to yet complimentary to the methodology developed in this thesis and both may be considered simultaneously. Indeed Jandric's system may be especially useful for demanding applications, since the weld path design methodology developed in this thesis does not assist with the different local heat transfer conditions in those regions.

Yet another pre-existing methodology that might also be useful for controlling instability in rapid prototyping and wear replacement by GMAW is the thermal control methodology developed by Kondoh and Ohji for GTAW [Kondoh and Ohji, 1998]. This system predictively calculated the required heat inputs in discrete sections of straight bead-on-plate GTAW welds, in order to control surface temperature at desired discrete points. However while such a system might prove useful, further research would be required to expand the system to cover the many thermal conditions found in rapid prototyping and wear replacement by GMAW.

Since geometric and thermal instability are such inherent features of rapid prototyping and wear replacement by GMAW and since it is so important to reduce them as much as possible, it is envisaged that the methodology for reducing them developed by this thesis be considered in conjunction with some of these other methodologies for maximum results for a given application.

Finally, it should be noted that the results obtained in this thesis and the conclusions reached were not influenced by the weld parameters that were used for making the welds. The welding parameters in this thesis were set to reasonable values generally suited to rapid prototyping and wear replacement by GMAW, that would facilitate the extraction of the results discussed in this chapter. Since all of these results pertain to the effects of weld path design and not those properties of individual weld beads that are determined by weld parameters, the results of this thesis would have been the same if slightly different weld parameters had been used.

However while such generic weld parameters suited the purposes of the particular investigations undertaken in this thesis, practical rapid prototyping and wear replacement by GMAW systems would require more sophisticated weld parameter selection in order to best suit the needs of each particular application.

It may also be noted that the results from this thesis are also expected to be applicable to rapid prototyping by GTAW since the two processes are similar, though the decoupled heat and material transfer in GTAW may make it easier to control weldment temperatures during welding through control of the welding current.

11.2 Quality of Thin Wall Boundaries

It was found that when using the "boundary method" to create solid objects, the quality of the fill layers and of the object as a whole are very dependent on the quality of the thin wall boundaries. Any irregularity in the welds of the thin wall boundaries introduces problems that propagate upward through the rest thin wall boundary, permanently reducing it's quality. Since the thin wall boundaries in turn serve to define the shape of the fill layers, such thin wall irregularity also translates into fill layer instability.

As found by various researchers, thin wall boundaries require very tightly tuned weld parameters, constant standoffs and very regular weld beads and are highly sensitive to changes in substrate temperature [Ribeiro, 1998] [Ribeiro, 1999] [Ribeiro and Norrish, 1997] [Ribeiro, Ogunbiyi, et al., 1997] [Dickens, Pridham, et al., 1992] [De Boer, Jacono, et al., 2000] [Jacono, 1999] [Kovacevic and Beardsley, 1998] [Spencer, Dickens, et al., 1998]. Increasing substrate temperature leads to decreasing thin wall quality.

It was found that any overheating or melting of the thin wall boundaries by any fill welds is very detrimental to object quality and must be avoided.

11.3 Weld Starts and Stops and Thermal Control

It was found that weld starts and stops tend to be very detrimental to object quality because they involve arc ignitions, the risk of arc ignition failures, weld heating zones and crater filling zones, all of which tend to be problematic. It may be noted that short welds were thus also found to be problematic since they imply a greater number of weld starts and stops in a layer. It was found that special procedures are likely be needed to control object quality in these regions, depending on the application. However it is argued that it is very desirable to avoid such problems by avoiding weld starts and stops wherever possible during solid layer welding by using fewer individual welds per fill layer and fewer short welds.

The fact that weld starts and stops create problems such as these had also been recognised by Zhang and Li, who had found that weld starts and stops are particularly significant sources of uneven deposition in thin wall rapid prototyping by GMAW [Zhang, Li, et al., 2002]. They also recommended that weld starts and stops should be minimised if possible and they developed special procedures to improve geometric stability at weld starts and stops in thin walls by modifying the weld parameters and weld paths in those regions. This thesis confirms the findings of Zhang and Li, though it found that weld starts and stops are very problematic for all rapid prototyping and wear replacement by GMAW, not just thin wall welding and thus should also be avoided when performing layer filling.

Other researchers have also reported that rapid prototyping processes tend to suffer problems caused by deposition path starts and stops. Qiu and Tarabanis both found that in FDM path starts and ends tend to introduce unfilled voids and they both recommended that path starts and stops should be avoided [Qiu, Langrana, et al., 2001] [Tarabanis, 2001]. Tarabanis advocated avoiding path starts and stops through appropriate raster angle selection if using raster paths. These results for extrusion-based rapid prototyping were echoed by Rajan who noted that path starts, stops and corners tend to introduce uneven material deposition and recommended avoiding these path features as much as possible [Rajan, Srinivasan, et al., 2001]. Rajan developed an algorithm for generating raster paths with as few raster lines as possible, based on optimising the raster angle, in order to minimise these path features. Sarma noted that in rapid prototyping in general, deposition path corners, starts and ends in general should be avoided where possible during layer filling since "regions of sharp turns in the tool trajectory and ends of the tool trajectory are causes for concern as more/less material remains in those regions than otherwise estimated" [Sarma, 2000].

The current work confirms that rapid prototyping by GMAW is the same as other forms of rapid prototyping in the sense that path starts and stops always tend to introduce problems and minimisation of path starts and stops is to be recommended. Also, as will be expounded later in this discussion, the current work also confirms that it is possible to control the number of path starts and stops in a raster path through raster angle selection, though contour and spiral paths use far fewer starts and stops than is possible with raster paths.

Due to the potentially very severe nature of the weld defects, unfilled voids and other disturbances caused by weld starts and stops, all rapid prototyping and wear replacement by GMAW systems would need to pay at least some attention to the way they execute weld starts and stops, depending on the demands of the particular application. This is because no matter what weld path is used and how much they are minimised, there is always at least one weld start and stop pair per fill layer. The more demanding the application, the more sophisticated the weld start and stop control would need to be. Systems that incorporate material removal could tolerate some of these problems to a degree, however the increased machining required would increase production time. It is recommended that all systems should seek to avoid these problems during layer welding by using fewer numbers of individual welds per fill layer.

A further stability issue was found in this thesis that is linked to the problems associated with weld starts and stops. It was found that a weldment heating up during a layer welding procedure is a source of thermal instability since later weld beads are made under different thermal conditions than earlier beads. This was found to result in potentially significant geometric instability in the form of uneven weld pool sizes, uneven weld bead shapes and an increased risk of melting the thin wall boundary. It was found that it is very desirable to counter this phenomenon by pausing the layer welding process to allow the substrate to cool, however this can only be done between separate individual welds. Thus the more individual welds per fill layer a weld path employs, the more scope there is for thermal control, due to the increased opportunities for the scheduling of cooling stops.

Dickens and Spencer had previously recognised that heat build-up in the substrate in rapid prototyping by GMAW is undesirable and leads to a deterioration in object quality [Dickens, Cobb, et al., 1993] [Dickens, Pridham, et al., 1992] [Spencer, Dickens, et al., 1998]. To try to combat heat build-up they advocated the use of thermal sensing and pausing the build process until the substrate reached a desirable temperature. This thesis confirms the need to remove excess heat from the weldment. However this thesis expands on this result by showing that any increase at all in substrate temperature is undesirable since it leads to a corresponding change in weld bead shape, thus introducing geometric instability. This thesis also makes the key observation that pausing for cooling is only possible between individual welds, as described above and thus that path strategies vary in their ability to accommodate cooling stops.

Thus it was found that the number of individual welds per fill layer used by a path strategy affects both the numbers of weld starts and stops and the ability to schedule cooling stops. Increased scope for thermal control through cooling stops also leads to a decreased ability to avoid the problems associated with weld starts & stops. It is suggested that a balance needs to be kept in terms of the number of individual welds per layer, between introducing layer-wide thermal instability and introducing problems near weld starts and stops. The more individual welds per fill layer a path strategy uses, the more it needs to rely on special procedures to control weld starts and stops, though this also varies with application. This conflicting link between the number of weld starts and stops and the opportunities for the scheduling of cooling pauses and the need to balance these through the number of individual welds per fill layer, has not appeared in existing literature.

Practical rapid prototyping and wear replacement by GMAW systems would need to make a judgement regarding the particular application's tolerance to the problems introduced by weld starts and stops, the performance of their weld start and stop control techniques (if any), the importance of thermal control and regularity to the particular application and the number of cooling pauses that may be necessary to adequately control weldment temperature during layer filling.

It is also suggested that discrete raster path strategies have too many individual welds per fill layer and more than any of the other path strategies. The actual number varied depending on the raster angle and layer shape, yet even in the best case scenario they still used twice as many as contour path strategies. As a result, they had the best scope for thermal control through cooling stops. However they also had unnecessarily high numbers of weld starts and stops and sometimes very short welds. As a consequence, the weldments they produced were found to be of very poor quality. The use of discrete raster path strategies is therefore not recommended in rapid prototyping or wear replacement by GMAW.

Nickel investigated the residual stresses produced by discrete raster paths in SDM using low carbon steels [Nickel, 1999] [Nickel, Barnett, et al., 1999] [Nickel, Barnett, et al., 2001]. Nickel found that the highest residual stresses occur in the direction of the raster lines and that lower residual stresses and lower base plate deflections can be produced by using higher numbers of short raster lines, rather than lower numbers of longer raster lines. This is consistent with the findings of Spencer, Matthes and Song, who all found that in rapid prototyping by welding, the greatest residual stresses occur in the direction of the weld bead [Spencer, Dickens, et al., 1998] [Matthes and Alaluss, 2001] [Song, Park, et al., 1999]. Song proposed a similar methodology for reducing stress as Nickel and recommended considering shorter weld beads instead of longer ones.

Even though the use of greater numbers of short welds may reduce residual stress and distortion in a weldment, this thesis shows that such a methodology has the serious disadvantage of increasing the number of weld starts and stops and this cannot be overlooked. Therefore such a methodology for reducing residual stress cannot be automatically recommended. The consequences of the problems introduced by increased numbers of weld starts and stops would need to be weighed against the stress relief benefits. However it also cannot be overlooked that residual stresses and distortion are a major problem in rapid prototyping and wear replacement by GMAW and must be controlled in some way in order for the process to be successful. If this stress and distortion reduction methodology is not used due to concerns about weld starts and stops, then some other stress control technique may be required.

It was found that the continuous raster path strategies and the single armed spiral path strategies had too few individual welds per fill layer. They only had one individual weld per layer and consequently avoided all but one weld start and stop pair. However they could not schedule any cooling stops during layer filling and thus were found to introduce very significant thermal instability. As a result of this thermal instability, it was determined that continuous raster paths and single armed spiral paths are not desirable, except for applications that are very undemanding. These two types of path strategies, especially the continuous raster paths, have very often been used in the past, yet the disadvantages reported here have not appeared in previous literature.

Contour path strategies were found to have an intermediate number of individual welds per layer: fewer than discrete raster paths yet more than continuous raster paths and spiral paths. They were found to have a desirable balance between thermal control and avoidance of weld starts and stops that should suit many types of applications. Contour paths would thus be an attractive choice for many rapid prototyping and wear replacement applications. While they have been used in the past, this positive attribute of theirs had not been previously identified. Though it should be noted that contour paths can generate very short welds in the centre of layers, depending on layer shape.

Double armed spiral paths always use two individual welds per layer, thus they were able to avoid more weld starts and stops than both discrete raster paths and contour paths. At the same time, it was found that the thermal instability that they introduced due to their very limited scope for thermal control did not have major consequences, especially if the spiral arms were welded from the middle of the layers outwards towards the edges. The thermal instability that they introduced was certainly of a much lower magnitude than that of single-armed spiral paths or continuous raster paths. Thus they were also found to have a desirable balance between thermal control and avoidance of weld starts and stops, which also had not been previously recognised. As a result, double-armed spiral paths would also be an attractive choice for many rapid prototyping and wear replacement applications.

It would also be possible to use self-constrained spiral paths with four or more spiral arms, thus further increasing the scope for thermal control achievable through spiral paths. Though of course such paths would then use more weld starts and stops and thus need to rely more heavily on special techniques to control these areas.

Finally, a new observation was made regarding the number of individual welds per fill layer versus layer size, when using contour or spiral path strategies. It was observed that the number of individual welds per fill layer used by contour path strategies increases with increasing layer size, whereas the number of welds per layer used by spiral path strategies is always constant. At the same time, reduced thermal control due to fewer opportunities to schedule cooling stops may be less of a problem with larger layer sizes due to the heat being distributed over a larger area. Thus it is predicted that the desirability of double armed spiral paths would increase with increasing layer size, whereas the desirability of contour paths would decrease. Thus it can be seen that layer size may also affect the choice of weld path strategy in rapid prototyping and wear replacement by GMAW.

11.4 Weld Path Performance at Layer Edges

It was found in this thesis that certain path strategies produce very significant geometric & thermal instabilities and weld defects at fill layer edges. It was also noticed that this can lead to overheating and melting of the thin wall boundaries. Based on the instabilities and defects identified, a number of important recommendations were developed for weld path design near layer edges.

It is recommended by this thesis that layer edges be filled by a single weld running unbroken all the way along the inside of the layer perimeter. While it may be possible to improve weldment quality near layer edges through other special localised techniques, it was found that it is very desirable to avoid having to do so by following this recommendation where possible. This recommendation was foreshadowed by Farouki, who predicted that in rapid prototyping in general contour paths would tend to produce smoother deposition near the edges of a layer than raster paths, because they are offset from the layer boundary [Farouki, Tarabanis, et al., 1994]. This thesis confirms this prediction for the case of rapid prototyping and wear replacement by GMAW.

All of the spiral and contour path strategies investigated in this thesis were found to do this and were found to perform very well at layer edges as a result. However by the nature of their design, it is impossible for any raster path strategy to do this and all the various raster path strategies investigated in this thesis performed very poorly at layer edges. Depending on layer shape and raster angle, they were found to produce many defects such as large unfilled voids, uneven deposition, thermal instability and melting of the thin wall boundary. The spiral paths that were employed for circular layers in this thesis also failed to follow this principle. These circular spirals did not properly fill the edges of the circular layers at all, producing large unfilled voids and other associated defects as a result. These circular spiral path strategies were therefore found to be totally unsuitable for circular layers in their current form and would need to be re-designed or augmented with special edge filling techniques.

These results echo the results of past researchers investigating the performance of continuous raster paths at layer edges in FDM [Kulkarni and Dutta, 1999] [Qiu, Langrana, et al., 2001] [Tarabanis, 2001] [Wenbiao and Jafari, 2000]. They found that the many corners that these raster paths use are responsible for producing very significant unfilled voids and uneven deposition at the layer edges in FDM. In order to try to minimise these defects, they advocated minimising the number of corners or changes in direction used by continuous raster paths. However this thesis showed that continuous raster paths can never perform as well at layer edges as contour or spiral paths. Kulkarni and Dutta also found that the voids produced by continuous raster paths at layer edges are smallest when the raster lines meet the edge of the layer at 90º. Continuous raster paths were also found to be problematic in wear replacement by GMAW by Tinkler. Tinkler found that corners in continuous raster paths introduce thermal instability in wear replacement by GMAW, stating that when using these paths "it is important that process parameters be carefully controlled during the reversing stage of each pass in order to maintain good quality" [Tinkler, Fihey, et al., 1991].

This thesis confirms that weld path corners at layer edges in rapid prototyping and wear replacement by GMAW produce voids and inconsistent deposition and should be avoided, otherwise special techniques would need to be employed to control deposition in these regions. The recommendation in this thesis to use a single weld running along the inside of the layer perimeter is thus a corollary of these results. However it should also be noted that systems that include material removal may be able to ignore this recommendation, though doing so would increase the amount of material that they would need to remove, which would increase their production time.

Furthermore, on the topic of spiral path strategies, it may be noted that Kulkarni and Dutta as well as Sarma proposed the Spiral of Archimedes for the filling of circular layers [Kulkarni and Dutta, 1999] [Sarma, 2000]. However as mentioned previously, this thesis found that spiral paths based on the Spiral of Archimedes alone are totally unsuitable for circular shapes in rapid prototyping and wear replacement by GMAW. They would either need to be totally redesigned, which would increase the complexity of their calculation, or have special edge filling procedures added to them. The only systems that could possibly use spiral paths based on the Spiral of Archimedes alone for circular shapes may be systems that use material removal, though they would need to remove large amounts of material which would significantly increase their production time.

Kulkarni, Dutta and Sarma also proposed a spiral path for the filling of square layers that was made up of linked straight line segments, the position of whose corners was a function of their angle about the centre [Kulkarni and Dutta, 1999] [Sarma, 2000]. However Kulkarni and Dutta noted that the spiral arms of such a path are never parallel to the sides of the layer and rightly predicted that this would lead to large unfilled voids at the layer edges. As a result, they proposed the type of spiral path for rectangular layers that was used by Spencer and was also used in this thesis with good results, since it followed the method recommended by this thesis [Spencer and Dickens, 1995]. It may also be noted that a convenient mathematical description was developed in this thesis for this type of path, for the case of rectangles and squares.

Another recommendation for weld path design near layer edges advocated by this thesis was that any fill welds that cannot be parallel to the thin wall boundary and that need to approach or leave the edge of a layer should do so perpendicularly to the boundary, in order to minimise geometric instability. This recommendation was formulated after it was found that unfilled voids at layer edges increase in size when the angle is more acute. This confirmed the findings of Kulkarni and Dutta who found that this was the case in FDM [Kulkarni and Dutta, 1999]. Another reason for this recommendation was also found to be that the weld pool metal of fill welds tended to be attracted to the thin wall boundary due to surface tension, which distorted the fill weld bead shape at the boundary interface.

The final recommendation for weld path design near layer edges developed by this thesis concerned the filling of layer corners. It was recommended that corners in a layer perimeter that had been defined by a thin wall boundary should be filled using an unbroken weld that follows a path offset from that of the thin wall boundary and passes right into and through the corner apex. Spiral and contour paths were found to do this and were most successful at filling such corners. On the other hand, it was found that raster paths could only do this in special circumstances. Where raster paths did not do this, they were found to produce unfilled voids and possibly other defects and in some circumstances significant thermal instability. However it was also found that while it is very useful, this recommendation on its own is insufficient to guarantee good fill quality at the apex's of sharp corners in a layer perimeter, without also melting through the thin wall boundary. Some special localised procedure may still be required to guarantee good fill quality at the apex's of sharp corners in a layer perimeter. It may be noted that Kulkarni and Dutta as well as Qiu proposed varying the deposition rate in extrusion-based rapid prototyping such as FDM in order to eliminate unfilled voids at the apex's of corners in layer edges [Kulkarni and Dutta, 1999] [Qiu, Langrana, et al., 2001]. Some similar methods may be required in rapid prototyping by GMAW.

Overall, the contour and spiral path strategies investigated in this thesis performed much better at the edges of layers and in the corners than the various raster path strategies. The only exception being the spiral path strategies used to fill circular layers, which were not suitable on their own in their current form. This thesis thus showed the very significant differences in performance in these regions of raster paths compared to contour and spiral paths, the supremacy of these latter two not having been clearly stated in existing literature. This result increases the attractiveness of contour and spiral path strategies for rapid prototyping and wear replacement by GMAW.

11.5 Weld Path Corners

It was found by this thesis that all corners in a weld path, not just those at the edges of fill layers, tend to introduce instabilities that would better be avoided. Corners in weld paths were found to be potentially very significant sources of thermal instability due to the welds moving through their own trailing temperature fields. It was seen that this caused temporary rises in surface temperature at the weld pool and thus localised changes in weld bead shape. It also increased the risk of melting the thin wall boundary if the weld path corner was at the edge of a layer. This fact that transient variations in surface temperature occur at weld path corners would have been known to investigators of rapid prototyping or wear replacement by GMAW, yet the significance of it had not been explicitly explored.

A number of simple yet very useful recommendations were made for weld path design for minimising the instabilities introduced by corners. Despite their usefulness and simplicity, they had not been clearly advocated in previous literature for rapid prototyping or wear replacement by GMAW. It was recommended that weld paths should be designed to have corners in the weld path such that the included angles be as close to 180° as possible and the radii of curvature be as large as possible. That is, that corners be as straight as possible, with the ideal being no corners at all. It was also recommended that weld path corners be as far away from each other as possible. For a given layer shape, it is easy to implement these recommendations since they prescribe the use of contour or spiral type weld paths. Yet layer shapes with sharp corners in their perimeter will still necessitate the use of sharp corners in the weld path. Where required, extra control of weld bead behaviour at weld path corners could be achieved through special localised techniques such as the variation of welding current.

Both contour and spiral path strategies were found to make good use of the weld path corner design recommendations. They could not avoid corner angles and curvatures that were dictated to them by the layer perimeter, but they did avoid introducing their own extra corner instabilities. The only exception to this was at the centre of layers where they could not avoid using weld path corners that were close together. This is another advantage of contour and spiral style weld paths that should add to their attractiveness for rapid prototyping and wear replacement by GMAW, yet it had not been expressed in existing literature.

In contrast, it was found that continuous raster paths introduced many unnecessary corner-induced instabilities, because they had to move from one raster line to the next. Furthermore, these corner-induced instabilities all occurred at the layer edges, where they were found to be prone to damaging the thin wall boundary, as was discussed in the previous section of this chapter. These unnecessary corner-induced instabilities were found to be even worse in cases where the raster lines were not perpendicular to the layer boundary and also where the raster lines were short. This disadvantage of continuous raster paths was found to significantly degrade the quality of the objects they produced, yet it had also not been expressed in existing literature.

As far as continuous raster paths go, Kamarthi claimed that the optimal ones in convex polygon layers for CNC milling were those that had their raster lines parallel to the longest side of the polygon, since it conserved total path length and therefore machining time [Kamarthi, Bukkapatnam, et al., 2000] [Kamarthi, Pittner, et al., 1997]. This principle is expected to be advantageous for rapid prototyping and wear replacement by GMAW, since it is expected to minimise the weld path corners occurring in a continuous raster path. However even in this best case scenario, continuous raster paths will still introduce much more corner-induced instability than contour and spiral paths. Combined discrete and continuous raster paths were also found to introduce unnecessary corner-induced instabilities, though to a lesser extent than continuous raster paths, since they were forced to follow every second raster line.

It was found that the fundamental need of continuous and combined raster paths to traverse successive raster lines, or every second raster line, was an unnecessary source of significant instability near the path corners. The ability of contour and spiral paths to avoid any unnecessary corner-induced instability and to use all the space available to them was found to be a new key to improved path performance beyond what can be achieved through balancing the number of individual welds per layer alone.

It is possible that this attribute of contour and spiral paths may also help to reduce residual stresses. This attribute is expected to also translate into more symmetrical heat distributions in the substrate, which in turn should lead to reduced residual stresses according to Ramaswami and Chin [Ramaswami, 1997] [Chin, Beuth, et al., 1996] [Chin, Beuth, et al., 2001 a and b]. However more research would be necessary before making such recommendations for stress reduction through open-loop weld path design. Nevertheless, the possibility of residual stress control through open-loop weld path design is worth pursuing through further research since it could greatly benefit the process. Some stress control methodologies rely on pausing deposition in order to execute some explicit stress reduction procedure, whereas the ideal would be to rely as much as possible on time efficient methodologies such as weld path design.

Finally, it can be noted that a known added problem with weld path corners is that they can lead to too much material being deposited at the corner apex. This had been recognised by Kmecko and Kovacevic and many other researchers investigated rapid prototyping by GMAW, as well as being predicted to be the case for all rapid prototyping in general by Sarma [Kmecko, Hu, et al., 1999] [Sarma, 2000]. A common approach to solving this problem is to reduce the amount of material deposited at the apex, either by temporarily increasing the welding speed or by temporarily decreasing the wire feed rate under synergic control. In any case, it is best to avoid such weld path corners where possible and this is an added reason to adopt the corner minimisation recommendations put forward in this thesis.

11.6 Constraint Strategies

It was found in this thesis that the self-constrained and non-constrained welding strategies had very different geometric stability properties. Self-constrained strategies were found to produce symmetrical, evenly formed weld beads that were not skewed and that formed in their intended locations. This was because each weld type in self-constrained welding is made under symmetrical constraint conditions. This was found to be a very important advantage of self-constrained welding in terms of geometric stability, that had not appeared in existing literature.

It was also found that self-constrained welding had another useful attribute when used with contour and discrete raster path strategies. It was found that when used with these path strategies, self-constrained welding gave extra scope for thermal control while conserving build time, through flexibility of the weld order of individual welds. Unlike non-constrained welding, self-constrained contour and discrete raster paths can employ any weld order as long as the welds are made with the proper modes of constraint. This enables welds that are relatively far away from each other to be made in quicker succession with reduced cooling time in between, due to the reduced thermal impact of one upon the other. In this way, it is possible to design the weld order such that thermal control is maintained while reducing total build time. This useful advantage of self-constrained welding had also not appeared in existing literature.

It may also be recalled at this point that Ramaswami had advocated symmetrical heat deposition into substrates in SDM for reduced residual stresses and that this was supported by the work of Chin, who found that greater thermal gradients inside an object lead to greater residual stresses [Ramaswami, 1997] [Chin, Beuth, et al., 1996] [Chin, Beuth, et al., 2001 a and b]. It is expected that the flexibility in weld order afforded by the self-constrained welding strategy could also be used to increase the symmetry of the heat deposition and thus reduce residual stresses. However further research would be required to more fully investigate this possibility. Also, Fessler claimed that in SDM by laser welding the self-constrained welding strategy itself inherently reduces stress compared to non-constrained welding, irrespective of weld order [Fessler, Merz, et al., 1996]. However Fessler failed to recognise that the experiment that was used to test this was flawed, since it compared raster paths with different raster angles. As has been discussed previously in this chapter, the raster angle itself is known to affect residual stresses.

However self-constrained welding was found to have one significant disadvantage. The self-constrained welding strategy requires two sets of welding parameters for two different types of welds, ridge and trough, unlike the non-constrained welding strategy that only require one. It was found that the two sets of welding parameters must be perfectly matched with each other and with the gap between the welds in order to produce a good result. Otherwise, self-constrained welding cannot produce flat, even layers. This had also previously been recognised by Kalligerakis and Spencer, who both presented this as a disadvantage of self-constrained welding [Kalligerakis and Mellor, 1992] [Spencer and Dickens, 1995] [Spencer, Dickens, et al., 1998].

However a positive feature that comes out of using two different weld types, with the trough welds having their shape constrained by the ridge welds, is that the trough welds' current can be varied within a certain range for other useful purposes. Spencer proposed varying the trough welding current to help control weldment temperature and Kalligerakis proposed varying the current to help control penetration and dilution for demanding wear replacement applications

[Spencer and Dickens, 1995] [Spencer, Dickens, et al., 1998] [Kalligerakis and Mellor, 1992]. However it needs to be remembered that the trough welding current needs to be high enough to burn away slag that tends to accumulate in the troughs and to penetrate and fully fuse with the surrounding substrate on all three sides of the weld bead. It also needs to be low enough not to melt through the adjacent ridge weld beads. Spencer also proposed the use of through-the-arc sensing for automatic control of the trough weld parameters to help achieve these goals. It would also be possible to employ some form of thermal sensing and feedback, either of the surface immediately ahead of the weld pool or of the entire substrate, to help with the control of substrate temperature.

Thus the self-constrained welding strategy was found to be very attractive, however the need to use two very well matched sets of weld parameters is a problem that would need to be addressed by rapid prototyping and wear replacement by GMAW systems that use this strategy. These weld parameters cannot be predicted using the simple formula for mean weld bead area based on filler wire diameter, wire feed speed and travel speed. This is because the height of the deposited layer depends on the height of the ridge weld beads and therefore on their heat input and the substrate surface temperature. The geometry of the trough channels that the trough welds need to fill thus depend on the shape of the ridge welds as well as the weld bead gap. The higher and narrower the ridge weld beads, the greater the weld bead area required from the trough welds.

In order to overcome the disadvantage of having to precisely match the two sets of weld parameters and the gap between the weld beads, it may be desirable to consider real-time control systems that can sense the geometry of the trough channels and set the trough weld parameters accordingly. It is envisaged that such control systems would need to use a laser sensing system to sense the shape and size of the channel immediately ahead of the trough weld and vary the weld parameters to suit. This could then ensure flat and even deposition and remove the need to predict the required trough weld parameters in advance. If such a control system is not used, then rapid prototyping and wear replacement by GMAW systems would need to set their ridge and trough weld parameters based on a database of pre-programmed proven weld parameter pairs and/or predictive calculations of ridge weld bead shape.

On the other hand, the non-constrained welding strategy was found to produce skewed asymmetrical weld beads that form shifted away from their intended locations. This was found to be due to the asymmetric constraint conditions under which the welds are made, with the direction of the skewness and the positional shift being dependent on the weld order of the weld beads. This property of the non-constrained welding strategy was found to result in potentially grossly uneven material deposition, with less material being deposited in some locations and more in others, depending on the layer shape and the particular path strategy used. Thus the non-constrained welding strategy was found to be an inherent source of very significant geometric instability and this was found to be a very important disadvantage of the strategy that had not appeared in existing literature.

As a result, non-constrained welding is generally not recommended for rapid prototyping applications, which are generally not expected to tolerate this geometric instability and which should consider using self-constrained welding instead. However the results produced by non-constrained welding may be adequate for less demanding wear replacement applications such as the surfacing of ground-engaging tools. Also, systems that incorporate material removal may be more tolerant of non-constrained welding, though it is expected to slow them down due to the removal of extra material. The one advantage of non-constrained welding over self-constrained welding is that it only uses one set of weld parameters, not two.

Therefore self-constrained welding was found to have much better geometric stability properties than non-constrained welding, which had not previously been shown to be the case in existing literature, on the condition that the ridge and trough weld settings are very well matched. Self-constrained welding would be recommended for most applications, especially demanding ones, though non-constrained welding may still be appropriate for less demanding wear replacement applications. It may be noted that Kalligerakis had previously claimed that self-constrained welding produced smoother surface profiles than non-constrained welding in wear replacement, but did not elaborate further and did not prove this to be the case, concentrating rather on comparing other advantages and disadvantages of these two welding strategies [Kalligerakis and Mellor, 1992].

11.7 Welding Direction

It was found in this thesis that path strategies that first fill-in the outer regions of a layer and work their way inwards towards the centre, tend to promote increased heat concentration in the centre of the layer and thus extra thermal instability. At the same time, it was found that path strategies that fill-in a layer in the opposite manner do not produce such heat concentration in any region, since they deposit heat in an ever wider area. This result is in agreement with the decision made by Tarabanis to use contour paths that started in the centre and worked their way outward rather than the other way around in FDM "for heat dissipation purposes", though Tarabanis did not elaborate at all on this decision [Tarabanis, 2001].

This form of thermal instability was very evident with the non-constrained single armed spiral path strategy, when programmed to weld from the outside of a fill layer inwards. This path strategy produced significant thermal and geometric instability at the centres of fill layers that would be particularly harmful for rapid prototyping and wear replacement by GMAW applications where thermal cycles or dilution levels are especially important. This was thus found to be a significant new disadvantage of this particular path strategy and it is not recommended for such applications.

Such extra thermal instability at the centres of layers is however always undesirable and it is therefore recommended in general to consider using path strategies that work from the centre of a layer outwards instead, or at least to keep this in mind when designing cooling pauses in the build process.

It may be noted here that Nickel compared inside-outwards non-constrained contour paths with outside-inwards ones in SDM using low carbon steel and found that the outside-inwards contour paths produced lower residual stresses and deformation [Nickel, 1999] [Nickel, Barnett, et al., 1999] [Nickel, Barnett, et al., 2001]. However it needs to be pointed out that this path strategy was found in this thesis to have especially poor geometric properties in rapid prototyping and wear replacement by GMAW, courtesy of the non-constrained welding strategy and is therefore not recommended. Also, as discussed previously, all contour paths have the ability to schedule cooling pauses between any two contour welds, the design of which would affect the residual stresses and deformation. Therefore more research would be required before making recommendations for stress reduction based on weld path design.

11.8 Inter-Layer Thermal Control

It was found in this thesis that not letting a weldment cool enough between layers results in inter-layer thermal instability, which results in weld bead shapes varying in shape between layers. This is an undesirable source of instability and it is recommended that it be avoided. It is recommended that for maximum inter-layer stability, the welding of new layers should begin with the weldment being at a constant temperature for all layers. Those path strategies that generate higher surface temperatures at the end of a layer filling procedure would thus require longer inter-layer cooling stops.

This result is in step with Dickens and Spencer who advocated the use of thermal sensing and of pausing the build process to allow the weldment to cool to a desired temperature before continuing [Dickens, Cobb, et al., 1993] [Dickens, Pridham, et al., 1992] [Spencer, Dickens, et al., 1998]. Spencer trialled this and found that it is especially beneficial for thin wall welding, though any cooling time is added directly to the total build time. Spencer contemplated forced cooling yet stated that this could lead to cracking and recommended that "extensive" further research is still needed into cooling techniques and their effects on object properties. It may be noted at this point that, as has been previously discussed, different path strategies have different scope for thermal control during layer filling. However, it is recommended that all layer filling should begin with a surface temperature that is as constant as possible. Using a temperature sensor may be a good way of doing this.

The phenomenon of heat build-up as an object grows in rapid prototyping by GMAW was also recognised by Song, who found that it was undesirable since it affected weld bead dimensions and microstructure, causing these to vary depending on the height above the base plate [Song, Park, et al., 1998]. Song also showed that as an object grows, the cooling rate of the layer being welded decreases due to the changing object geometry. To try to combat such heat build-up, Song proposed varying the welding parameters as a function of the layer's height above the base plate. However while this may be useful, one would still need to remain within the range of suitable welding parameters, since welding parameters also affect other issues such as penetration, inclusions and thin wall regularity. The variation in cooling rate during the build process, though, may be another reason to use thermal sensing since the time a layer needs to reach a certain temperature would vary. However it needs to be remembered that the more sensing and feedback a rapid prototyping or wear replacement by GMAW system uses, the more expensive and complex to operate it would tend to be. Any such thermal sensing would need to be as robust and cost-effective as possible.

Another important factor to consider in this discussion is residual stress. Chin found that greater thermal gradients inside an object lead to greater residual stresses in SDM by microcasting [Chin, Beuth, et al., 1996] [Chin, Beuth, et al., 2001 a and b]. Since welding of any kind inherently deposits heat, Chin recommended always keeping substrate temperatures high as well as uniform and constant and recommended uniform preheating of the entire object during the build process in order to reduce residual stresses. A similar result was obtained by Matthes, who found that reducing or removing inter-layer cooling time in rapid prototyping by welding and thus allowing weldment temperatures to grow, reduces residual stresses [Matthes and Alaluss, 2001]. In thin wall welding by GMAW, Spencer found that hotter thin walls have lower residual stresses but decreased surface finish and recommended a compromised level of cooling to balance thin wall regularity with residual stresses [Spencer, Dickens, et al., 1998]. However Spencer did not offer any recommendations for heat and stress control in solid object welding. Song presented a similar set of recommendations for the control of stress and microstructure in rapid prototyping by GMAW. Song recommended the preheating of base plates, the use of thicker base plates, the periodic heat treatment of weldments and cooling rates for weldments that are as low as possible [Song, Park, et al., 1999].

As has been discussed throughout this chapter, this thesis stresses the need for maximum thermal consistency and recommends weld path design methodologies that maximise thermal stability. This is consistent with the recommendation of Chin that weldment temperatures should be as uniform and constant as possible in order to reduce residual stress [Chin, Beuth, et al., 1996] [Chin, Beuth, et al., 2001 a and b]. It is consistent both in terms of intra-layer thermal stability where weld path design plays a major role, as well as in terms of inter-layer thermal stability as discussed in this section of the chapter.

However the above authors also recommend keeping weldment temperatures high, as well as constant, in order to reduce stresses. Yet many researchers have found that the quality of thin weld walls deteriorates very quickly with increasing surface temperature [Ribeiro, 1998] [Ribeiro, 1999] [Ribeiro and Norrish, 1997] [Ribeiro, Ogunbiyi, et al., 1997] [Dickens, Pridham, et al., 1992] [De Boer, Jacono, et al., 2000] [Jacono, 1999] [Kovacevic and Beardsley, 1998] [Spencer, Dickens, et al., 1998]. Furthermore, this thesis found that any imperfections in the thin wall boundary propagate throughout the rest of the weldment, that very high quality thin wall boundaries are a key to good object quality and that melting or even overheating of the thin wall boundary by the fill welds is very bad for object quality.

Thus the methodology of reducing stresses by keeping weldment temperatures high is inconsistent with the need to maximise thin wall quality. It would be technically possible to keep weldment temperatures high and then cooling them down very slowly to room temperature before performing further thin wall welding and then heating the weldment up again, however this would drastically increase production time and it is not expected to be practical. It should also be noted at this point that if this thesis had used uniform weldment preheating it would not have affected the findings of the thesis and the results of the thesis are valid whether uniform preheating is used or not. Furthermore, controlled heating and cooling of weldments implies extra equipment and therefore expense. Therefore more research is needed into the optimisation and balancing of the various needs of rapid prototyping and wear replacement by GMAW.

11.9 Weld Defects

It was found that slag inclusions are a common type of weld defect in rapid prototyping and wear replacement by GMAW. In order to avoid slag inclusions, the fill welds must be set such that they generate enough heat to burn the slag away. Apart from slag inclusions and instances where various defects occurred through bad weld path design as discussed previously, no other weld defects were found to be a problem. The cross-sectional samples that were taken all showed full fusion.

The boundary method used in this thesis, previously successfully used by Spencer, Zhang, De Boer and Jacono, was once again confirmed to work well and it is practical for use in rapid prototyping by GMAW systems [De Boer, Jacono, et al., 2000] [Jacono, 1999] [Spencer and Dickens, 1995] [Spencer, Dickens, et al., 1998] [Zhang, Li, et al., 2002]. It allows for full fusion, yet at the same time it also allows for control of the outer wall geometry through the use of the thin wall boundary. Yet once again it should be noted that it depends on the thin wall boundary being of very high quality and not being melted or overheated as a result of the layer filling. One disadvantage of the boundary method is that it relies on a separate set of welding parameters for the thin wall welds. As a result, rapid prototyping by GMAW systems would need to balance the height of the thin wall welds with the fill welds in order to produce flat top surfaces. However this would be less of an issue with systems that incorporated material removal.

It was found that the most likely place for slag inclusions to occur is at the inner side of the thin wall boundary. However it was also found that it is particularly difficult to burn slag away from this region, because of the need to melt right down into the corner where the thin wall boundary and fill layer meet, without melting the thin wall boundary. This result had not appeared in existing literature. This is therefore another negative attribute of the boundary method, since weld defects cannot be tolerated and special attention must be given to these regions. Fill welds with higher heat inputs than normal might be required in these regions, in conjunction with longer cooling times to allow the thin wall boundary to cool down to a desirable temperature.

11.10 Final Recommendations

It was found in this thesis that the best naturally performing and most attractive path strategy for an expected wide range of applications in rapid prototyping and wear replacement by GMAW, is the self-constrained double-armed spiral path strategy when programmed to weld from the inside of a layer outwards. This path strategy was found to have the optimum mix of geometric, thermal and weld defect properties, though this would vary depending on the particular application.

For applications requiring extra scope for thermal control, where control over weldment temperature is critical, this thesis recommends the self-constrained contour path strategy. This path strategy was found to have better natural scope for thermal control than the above mentioned double-armed spiral path strategy, however this was at the cost of having a much reduced capacity to avoid the problems associated with weld starts and stops. As a result, it would need to rely more heavily on special measures to control the regions near weld starts and stops.

Raster weld path strategies and the non-constrained welding strategy are not recommended except for undemanding applications.

One disadvantage of contour and spiral paths that has so far not been mentioned in this discussion is that they can be significantly more complex to generate for a given layer shape than raster paths. Further information regarding the generation of contour and spiral paths has been provided in previous work by Farouki [Farouki, Tarabanis, et al., 1994], Kao [Kao, 1999] [Kao and Prinz, 1998], Ramaswami [Ramaswami, 1997], Sarma [Sarma, 2000], Tarabanis [Tarabanis, 2001] and Vosniakos [Vosniakos and Papapanagiotou, 2000]. This is something that rapid prototyping and wear replacement by GMAW systems would need to accommodate in order to benefit from the use of these path strategies.

Thus by using one of these two path strategies that were found to be most attractive, rapid prototyping and wear replacement by GMAW systems can enjoy improved geometric and thermal stability and fewer problems with weld defects, simply through the choice of weld path. This is a significant new way of combating geometric and thermal instability that had not been achieved by previous researchers investigating rapid prototyping and wear replacement by GMAW.

In conclusion, it can be seen that there are various issues critical to the success of RP/WR by GMAW, such as dimensional accuracy and surface quality, residual stresses and distortion, avoidance of weld defects and unfilled voids, as well as build time. Other issues such as cost, robustness, portability are also important. However as found in this thesis, many of these issues tend to oppose one another and it is difficult to address all of them since improving one may harm another. As mentioned previously, much still remains to be investigated and there is need for still further research into rapid prototyping and wear replacement by GMAW.

However it can be concluded that in order to best address the various important issues, a flexible and multi-faceted approach is required. It is predicted that the most successful rapid prototyping and wear replacement by GMAW systems in practice will probably use some combination of:

- Stability and weld defect control through open-loop weld path design
- Special techniques to improve deposition quality at weld starts, stops and corners
- Controlled heating and cooling for controlling stress and microstructure, either explicit and/or as part of the deposition process
- Some form of material removal
- And some form of robust and cost effective temperature and/or substrate geometry sensing with real-time control of some aspects of the build process.