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

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Chapter 2

Literature Survey

2.1 Geometric and Thermal Stability Problems in Rapid Prototyping by GMAW

This literature survey chapter will outline past research that is pertinent to the study of weld path design and its effects on the stability of the rapid prototyping and wear replacement by GMAW process. The first part of the chapter will present research that illustrates the stability problems found in the RP and WR by GMAW process and the various research directions that have been taken to address them. Following this, the second part of the chapter will present various weld path and build process design strategies which are described in the literature.

2.1.1 Instability in the Rapid Prototyping by GMAW Process

Previous research has established that rapid prototyping by the GMAW process has problems with geometric and thermal instability. As more material is welded next to and on top of previous deposits there is a reduction in geometric precision and accuracy and the thermal conditions within the object become less predictable. These geometric and thermal instabilities are interrelated and lead to a deterioration in the quality of the objects produced. These are a major problem for RP by GMAW and make production of high quality objects more difficult.

Dickens found that as an object is being welded using RP by GMAW not all of the heat generated by the welding process escapes from the weldment and as a result there is an accumulation of heat inside the object [Dickens, Cobb, et al., 1993] [Dickens, Pridham, et al., 1992]. He found that this accumulating heat is a problem since the "heat build up due to the welding process can cause earlier welding passes to remelt and cause part distortion or collapse of the structure".

As well as thermal instability, Dickens also found that the process suffers from geometric instability [Dickens, Cobb, et al., 1993] [Dickens, Pridham, et al., 1992]. He found that the welding process produces geometric inaccuracies in the welds which accumulate as more metal is deposited. He stated that "inaccuracies in the welding and robot parameters can cause cumulative errors, resulting in the torch being too close or too far away from the surface".

Precise metal deposition is vital in RP by GMAW in order to reduce the errors arising from geometric instability. This was noted by Dickens who wrote that "the shape and dimensions of the weld bead are very important in the use of 3-D welding as a Rapid Prototyping system". He also noted that for normal welding applications it is "more important to develop new welding systems that can lay down as much weld as possible in a short time", but RP by welding "relies on precision methods that can be seen to be as much a 3D printing process, as a welding process". He noted that "solid layers (i.e. filling in of outline shapes) cannot be performed sufficiently accurately to form a smooth surface" and that as a result "gaps can occur inside solid objects" [Dickens, Cobb, et al., 1993] [Dickens, Pridham, et al., 1992].

Temperature fields and geometric phenomena in rapid prototyping by welding have also been investigated by Doumanidis. Doumanidis wrote about the importance of geometric and thermal behaviour in rapid prototyping. He wrote that "in modern thermal processing of materials, such as welding and rapid prototyping, the dimensional precision of functional products must be coupled to integrity of their material structure and mechanical properties" and that "these are dictated by the evolution of the temperature field during the process, resulting from the dynamic heat input distribution from the heat source on the part surface" [Doumanidis, 1996].

Furthermore, Doumanidis wrote that "the quality and productivity of ...[rapid prototyping] relies on precise geometric control of the dimensional tolerances of the product, as well as on thermal regulation of the resulting material structure and mechanical properties of the part" [Doumanidis, 1997]. He noted that "lack of ...[appropriate] thermal regulation in industrial practice often yields unacceptable part defects compromising its functionality, such as craters, pores, incomplete fusion, cracks, brittle material microstructure, and excessive residual stresses and distortions".

However Doumanidis also described the difficulty of controlling thermal fields in RP by welding, both by GMAW and GTAW, due to the fact that they are affected by various interactive phenomena. He noted that RP by welding involves "inherently coupled heat and material transfer mechanisms" which makes geometric and thermal control very difficult [Doumanidis and Fourligkas, 1997]. He claimed that off-line open-loop weld procedure generation "can not cope with unpredictable alterations of the process conditions, resulting in poor dimensional tolerances" and that it "often yields unacceptable material structure and mechanical properties, and thermal stresses and distortions limiting the product performance".

Kmecko and Kovacevic also experienced problems associated with the instability of the RP by GMAW process. They mentioned that in RP by the GMAW process, "because of complete melting, the accuracy as well as the surface quality of parts are generally lower than that of machined parts" [Kmecko, Hu, et al., 1999]. They described the geometric instability of the process, stating that poor geometrical qualities of parts produced are a result of "small defects in the previous layer that become more and more amplified in subsequent layers".

Kovacevic also described the process' thermal instability and its link to geometric instability. He wrote that the use of high heat inputs during the welding process causes "excessive remelting of the previously deposited layers" and that this "can disrupt the geometry of the earlier formed layers" [Kovacevic and Beardsley, 1998]. He wrote that as the welding of an object continues, "applying additional layers will introduce more heat into the substrate and make it more difficult to provide the conditions for building a straight wall layered structure".

Kovacevic also wrote about the importance of the cooling rate of newly deposited welds, since it affects the shape of the weld beads. He wrote that "if the newly deposited molten metal cools rapidly, a high and narrow bead will form" [Kovacevic and Beardsley, 1998]. However if a new weld cools slowly this "will allow time for the molten metal to spread over the previously deposited layer before solidification occurs", resulting in weld beads that are "wide and more flattened". These phenomena were also noted by Ribeiro, who found that heat build-up in a part and the amount of cooling time used between deposited weld layers affect the dimensions of the weld beads [Ribeiro, Ogunbiyi, et al., 1997].

Song was another researcher who reported geometric and thermal instability in the rapid prototyping by GMAW process [Song, Park, et al., 1998] [Song, Park, et al., 1999]. Song wrote that dimensional accuracy in rapid prototyping is very important, stating that it is a "critical issue…for the currently used rapid tooling techniques" [Song, Park, et al., 1998]. However Song noted that geometric and thermal instability is an inherent problem in RP by GMAW [Song, Park, et al., 1999].

Song stated that dimensional accuracy deteriorates as more and more of an object is welded, stating that "usually, each extra step required for the conversion process towards the final part implies a deterioration of its dimensional accuracy" [Song, Park, et al., 1998]. He also noted that the complete re-melting of the substrate at the weld pool has the effect of lowering geometric accuracy and surface finish and that thermal conditions within objects vary depending on the object geometry.

Geometric and thermal instability in RP by GMAW were also known to Spencer [Spencer and Dickens, 1995] [Spencer, Dickens, et al., 1998]. Spencer found that thermal conditions within objects vary greatly depending on the objects' geometry and depending on where on the objects the welding is taking place. However Spencer warned against excessive temperatures, writing that during the build process "excess residual heat not only ...[affects] surface finish but also the bead height, due to delayed solidification", which can result in "large amounts of porosity, poor surface finish and increased material flow".

Spencer noted that variations in weld bead height caused by retained heat in the weldment can cause the welds to form away from their intended positions [Spencer and Dickens, 1995] [Spencer, Dickens, et al., 1998]. Spencer also noted that such geometric instability can then cause the contact-tip to workpiece distance to vary unacceptably during the welding process, which further reduces the weld quality. Finally, Spencer stressed the need for "maximum possible accuracy by producing predictable welds".

Tinkler encountered problems related to geometric instability in wear replacement by robotic GMAW [Tinkler, Fihey, et al., 1991] [Tinkler, McNabb, et al., 1987]. Tinkler observed "inherent variability" in the weld deposit dimensions and stated that this "may cause the actual weld deposit geometry to deviate somewhat from that expected in the ... planning model" [Tinkler, McNabb, et al., 1987]. Tinkler also observed that "these positional errors may be cumulative in a multi-layer deposit".

Zhang and Li also reported the effects of geometric and thermal instability in RP by GMAW [Zhang, Li, et al., 2002]. During their investigations into the welding of thin-walled objects, they found that weld starts and stops are particularly significant sources of uneven deposition. They also found that as the number of deposited layers increases this uneven deposition accumulates, stating that "due to the flow of molten metal, the error increases quickly and is very difficult to compensate for". They added that "after a few layers, a significant deviation from the originally expected shape will occur".

Finally, signs of geometric and thermal instability in rapid prototyping by robotic GMAW were also observed by the author in preliminary welding trials performed at the University of Wollongong.

2.1.2 Research Directions in Literature

After it had become clear that harmful geometric and thermal instabilities were characteristics of rapid prototyping by GMAW, researchers investigated various ways in which they could be controlled or overcome and the quality of the parts improved.

Dickens recommended the use of sensors and real time control of the build process [Dickens, Cobb, et al., 1993] [Dickens, Pridham, et al., 1992]. Dickens stated that "it is evident from these problems that some form of sensing is required to control the process". He wrote that "sensory feedback would be a requirement for improvement of the system quality through process monitoring and for post inspection purposes" and that sensors could be used "to prevent possible collapse of the part through temperature build-up". However Dickens noted that real time weld monitoring systems alone are unlikely to overcome all of the problems associated with process instability.

Dickens envisaged the need to pause welding "at intermittent stages to leave the part to cool down and avoid collapse due to heat build-up, or to implement forced cooling" [Dickens, Cobb, et al., 1993] [Dickens, Pridham, et al., 1992]. He suggested that sensors could be used to help decide how much cooling is needed and to perform post-inspection. He suggested that "this inspection information can be used to update the robot position to avoid cumulative errors, plot new robot trajectories to avoid gaps, and generally control the weld parameters".

Dickens also investigated the improvement of the quality of thin-walled objects through study of the weld parameters [Dickens, Pridham, et al., 1992]. Dickens researched the effects of various weld parameters on the dimensions of the weld beads and the surface quality of thin-walled objects, with considerable improvement.

The control of geometric and thermal instabilities in rapid prototyping by both GMAW and GTAW through the use of real time sensing and control techniques has been researched by Doumanidis for some time [Doumanidis, 1994] [Doumanidis, 1996] [Doumanidis, 1997] [Doumanidis and Fourligkas, 1997] [Doumanidis and Skordeli, 2000] [Skordeli and Doumanidis, 1999]. His research has been aimed at developing closed-loop control systems that guide the welding torch in real time.

The "scan welding" technique was developed by Doumanidis to sense and control the thermal field inside a substrate in real time during a welding operation. It moves point heat sources rapidly across a substrate and regulates their power in such a way as to achieve and maintain desired thermal fields. [Doumanidis, 1994] [Doumanidis, 1996] [Doumanidis, 1997] [Doumanidis and Fourligkas, 1997].

Doumanidis stated that "a thermal controller is particularly necessary to track the changing operating conditions in the variety of processed patterns, and to reject disturbances in the boundary conditions stemming from the variable geometry and heat flow as material is deposited or removed from the part" [Doumanidis, 1997]. He added that closed-loop thermal control "is also needed to handle parameter alterations of the material and heat source due to thermal drift, and to ensure a desirable dynamic performance during the constantly transient process conditions".

As well as real time control of thermal fields, Doumanidis also researched the real time modelling and control of weld geometry. He developed a model of a GMA weld pool based on physical principles of mass and energy and yet suitable for real time control of weld bead shape [Doumanidis and Kwak, 2001]. He used this model together with real time laser sensing of weld bead shape and real time infrared sensing of weld pool temperature to form a weld bead shape control system. He successfully tested this control system on straight line bead on plate welds.

Doumanidis also developed another model of welded geometry that is suitable for real time control of RP by GMAW, this time based on the deposition of spherical elements [Doumanidis and Skordeli, 2000] [Skordeli and Doumanidis, 1999]. It modelled material deposition in GMAW as the successive deposition of spherical elements representing molten metal globules and it modelled the surface topology of the weldment as a combination of unit deposition fields. Doumanidis was able to form a real time welded topology closed-loop control system, using this model together with real time laser sensing of weld bead shape. This control system would control the feed and motion of a GMAW torch in order to control the welded topology and Doumanidis successfully tested it on straight line bead on plate welds.

Finally, Doumanidis also developed a deposited geometry model, similar to the spherical model except using ellipsoidal elements [Kwak and Doumanidis, 1999]. Similarly to the spherical model, he incorporated it into a real time closed-loop torch control system. However Doumanidis extended this control system to also incorporate laser scanning of the underlying surface in front of the welding torch, with the control system taking the underlying topology into account when controlling the torch. He successfully tested the system in a GMAW cell on adjacent overlapping straight line bead on plate welds. Doumanidis concluded that this system was "shown to reject geometric disturbances introduced by the crooked contours of a previous pass, and deposit a straight edge bead".

Now, Kovacevic and Jandric researched the improvement of weld geometry in RP by GTAW through the control of weld parameters [Jandric and Kovacevic, 2001]. They investigated the control of weld bead shape while welding near areas of a substrate that have local differences in heat transfer conditions. They noted (for example) that when weld beads are made on top of sharp corners in a substrate, the heat transfer conditions are different than elsewhere on the substrate and lower heat inputs are required in order to produce constant penetration and weld bead dimensions. They performed experiments linking different welding parameters with the weld bead shape at different geometrical features such as edges, corners and internal channels.

Following their weld parameter experiments, Kovacevic and Jandric developed a hybrid control system to control heat input near geometrical features such as edges, corners and internal channels [Jandric and Kovacevic, 2001]. The control system was based on offline open-loop path planning and real time closed-loop weld bead size measurement. They tested the system in a GTAW cell, successfully making complex object shapes with good weld bead uniformity near the edges of the objects.

Karunakaran developed a hybrid rapid prototyping process based on welding and milling, after noting that the RP by GMAW process produced poor dimensional accuracy [Karunakaran, Shanmuganathan, Jadhav, et al., 2000] [Karunakaran, Shanmuganathan, Roth-Koch, et al., 1998]. Karunakaran's RP process used robotic GMAW for material deposition and CNC milling for material removal. It also used two different metals, one to make the actual object and one that was used as a sacrificial support material. This RP process machined away any unwanted material after each layer was welded, smoothed-out each layer and encased it in support material where necessary, before welding new material over the top. It thus avoided the problems associated with the instability of the RP by GMAW process, by relying on the CNC machining process for geometric accuracy and precision.

Kovacevic, Kmecko and Beardsley used the pulsed GMAW process for rapid prototyping. They recognised that overall geometric stability and object quality could be improved by minimising the irregularities in individual weld beads. They used the pulsed GMAW process because it is relatively stable at low welding currents and they investigated new ways of controlling it in order to make it even more stable and thus improve the regularity of individual weld beads [Kmecko, Hu and Kovacevic, 1999] [Kovacevic, 1999] [Kovacevic and Beardsley, 1998]. They developed methods of controlling the pulsed metal transfer in real time using laser sensing as well as high speed vision sensing. They demonstrated that maximising metal transfer stability and thus maximising the regularity of individual weld beads is very beneficial to rapid prototyping by GMAW, stating that "by precisely controlling the droplet growth process and instant of detachment, the maximum depth of penetration as well as the shape of the bead penetration profile can be controlled" [Kovacevic and Beardsley, 1998]. It should be noted however that Kmecko and Kovacevic found that the equipment required for their vision-based system was "expensive and not suitable for industrial applications" [Kmecko, Hu, et al., 1999].

At this point, the possible benefits of controlled short-circuit GMAW to rapid prototyping can also be mentioned. Since the aim of controlled short-circuit GMAW is to make the short-circuit transfer mode more stable, it is expected that this form of GMAW would also offer benefits in terms of individual weld bead regularity, similar to the work by Kovacevic with pulsed GMAW.

However, while high weld regularity through high metal transfer stability is very important, it is not the only way to improve object quality. Kmecko and Kovacevic found that their pulsed GMAW control system did not achieve the level of geometric stability that they desired, stating that "in spite of our success in controlling the welding process, the rapid prototyping process based on 3-D welding alone does not provide satisfactory dimensional accuracy and surface quality" [Kmecko, Hu, et al., 1999].

As a result of these findings, Kmecko and Kovacevic also investigated rapid prototyping by a combination of welding and CNC milling and developed a hybrid RP system similar to that of Karunakaran [Kmecko, Hu, et al., 1999]. Once again, the hybrid system relied on precise material removal using CNC milling to remove the effects of the geometric instability of the robotic GMAW deposition system. This RP system is illustrated in Figure 2.1.

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Figure 2.1: RP using material deposition by GMAW and material removal by CNC milling [Kmecko, Hu, et al., 1999]

Kovacevic and Beardsley also investigated the use of finite element analysis to model the RP by GMAW process [Kovacevic and Beardsley, 1998]. They used it to model temperature and the depth of penetration of weld beads into the base plate. They made a list of the many phenomena that ideally should be included in a finite element analysis of the RP by GMAW process. However they stated that "numerically representing any one of these phenomena would be a very complex task", whereas "attempting to quantify the cumulative effect of these factors coupled together would be even more challenging, and nearly impossible to verify". They noted that "designing a feasible 3D welding operation requires a thorough understanding of how the part will respond to the repeated heating and cooling cycles".

Rapid prototyping by a combination of robotic GMAW and CNC milling was also researched by Song [Song, Park, et al., 1998] [Song, Park, et al., 1999]. Similar to other researchers, Song used the precise material removal capabilities of the CNC milling process to counteract the inherent geometric instability of the RP by GMAW process. In Song's system, after each new layer is deposited by robotic GMAW it is machined to give it a smooth top surface, before the next layer is added. Also, after a desired number of layers have been added, the side surfaces of the object are also machined. However, unlike Karunakaran, Song did not mention the use of a sacrificial support material.

Spencer addressed geometric and thermal instability in RP by GMAW through the control of weldment temperature as previously proposed by Dickens, stating that excess heat has to be removed from the object being built [Spencer, Dickens, et al., 1998]. Spencer used an infra-red temperature sensor to monitor an object's surface temperature and did not allow welding to proceed until the temperature fell to a pre-determined desired value. Spencer experimented with this form of thermal control using different temperature cut-off values as well as no thermal control at all, comparing surface finish, microstructure and residual stresses in selected test objects. It was found that keeping the surface temperature low in such a manner improved surface quality, but greatly increased object build time.

Tinkler employed arc signal monitoring and real time control of the welding torch position to try to overcome geometric instability in wear replacement by GMAW [Tinkler, Fihey, et al., 1991] [Tinkler, McNabb, et al., 1987]. In order to maintain constant standoff, Tinkler monitored arc voltage or current during the welding process and maintained them at constant levels by moving the welding torch up or down relative to the workpiece. As well as this, Tinkler's wear replacement system also used grinding to machine the deposited weld surfaces to the desired geometry.

Finally, in order to overcome the instability problems that they observed in the RP by GMAW process, Zhang and Li developed two special modifications to their welding procedures [Zhang, Li, et al., 2002]. The first was to rotate successive weld layers by a desired angle so that the geometric errors in the weld layers would be more evenly distributed throughout the object and not accumulate as dramatically. The second was a modification to the weld ignition and crater filling procedures, relying on weld path and weld parameter modification, in order to produce more even deposition in these areas. However Zhang and Li noted that the surface quality of the parts produced by their system still needed to be improved and that the weld paths used still needed further investigation.

2.1.3 Effects of Weld Path Strategies on Process Performance

This thesis examines the effects of open-loop weld path design strategies on the stability of the rapid prototyping by robotic GMAW process. It tests how a range of alternative weld path design strategies perform and how useful open-loop weld path design is in improving the stability of the process.

To the best of the author's knowledge, the effects of open-loop weld path design on the stability of RP by GMAW have not yet been well researched. The nearest research topics that have been found in literature were the investigations performed by Jandric and Zhang.

As described previously, Zhang found that process instability could be reduced by rotating successive deposition layers and by employing special modifications to the weld parameters and weld paths near arc ignition and crater filling regions [Zhang, Li, et al., 2002]. Jandric on the other hand developed a control system that could control heat input when welding in regions with different thermal transfer properties in order to maintain uniform weld bead shape and penetration [Jandric and Kovacevic, 2001].

However this thesis investigates a broader range of alternative open-loop weld path design strategies that have been identified in literature and focuses specifically on their effects on process stability. In doing so, it investigates the scope of open-loop path design in general as a tool for improving stability.

Material removal is not considered in this thesis in order to improve the RP by GMAW deposition process. This can improve RP by GMAW both with and without material removal. Material removal is time consuming and minimising the amount of machining required can reduce object build time [Kmecko, Hu, et al., 1999]. Jandric noted that if a greater amount of weld metal could be deposited between machining operations and the frequency of machining operations could thus be reduced, this would be a major improvement for RP by welding and milling process [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].

Real-time process sensing, feedback control, adaptive programming and real-time control of torch motion are not considered in order to focus on the performance of the various open-loop weld path strategies. Open-loop weld path design is the simplest and most ideal way of creating rapid prototyped parts. The following chapter section presents many different weld path design strategies that have been identified in literature, of which a selection will be tested. Knowledge of how these affect stability in RP by GMAW would aid in open-loop weld path design and could also improve systems that employ real-time control.

2.2 Tool Path and Build Process Design Strategies in Literature

This part of the literature survey presents the various kinds of weld path and build process design strategies that have been found in literature. Some of the design strategies presented here were developed specifically for GMAW, or have been previously applied to GMAW. However much of the research referenced here was aimed at processes other than gas metal arc welding, such as CNC milling, FDM or SDM, or for generic rapid prototyping. As such, many of the design strategies are intended for other processes, or are generic and not developed with GMAW specifically in mind. Such design strategies that were deemed to be appropriate for RP and WR by GMAW are presented here. Many of the design strategies appear in more than one place in literature and have been used for more than one process.

As a result of having come from a variety of processes, the design strategies presented here do not all relate to "weld paths". Not all the processes involve welding and not all involve the deposition of material. Literature about CNC milling refers to "cutting paths" or "tool paths", while literature about non-welding rapid prototyping may refer to "deposition paths". For the purpose of convenience, the terms "tool path" and "deposition path" will be used interchangeably in this chapter. The term "build process" is used to refer to the creation of an object using any form of rapid prototyping. "Build process design" refers to the task of analysing an object that is to be created and deciding how the build process should be structured.

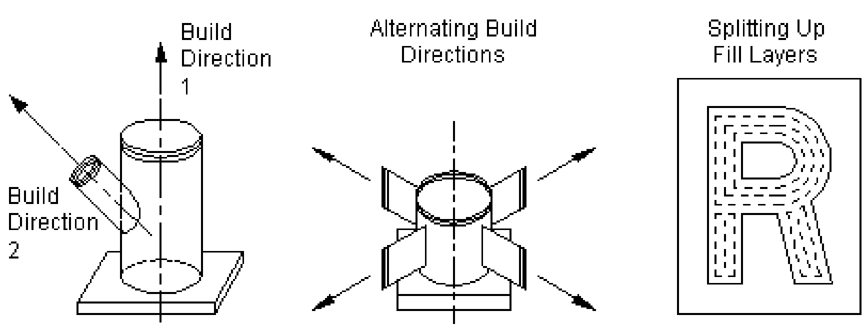
The tool path and build process design strategies presented in this chapter have been organised into groups and will be presented in the following chapter sub-sections.

2.2.1 Object Partitioning

The object to be built may be partitioned into sections and any cross-sectional layers that are to be filled can also be partitioned into sections. Unlike many rapid prototyping processes, RP by GMAW may require complex shapes to be split-up into separate build processes. This may be because some object shapes are much better built with certain build directions, or because sometimes it is impossible to build-up a complex object in the one build direction.

Sometimes is may be beneficial to alternate between the build processes of various sub-components. When sub-components are symmetrically distributed around the object, for example, it may be beneficial to build them all simultaneously by regularly switching from one to another. This can have the effects of producing more symmetrical heat deposition and may reduce build time by avoiding waiting for a particular weld layer to cool.

Once an object has been sliced into fill layers, it is possible to partition the fill layers so that different sections are filled with separate fill patterns. This may be desirable for complex object cross-sections. Ramaswami proposed that complex shapes could be partitioned into simple convex polygons that are easier to fill [Ramaswami, 1997]. These various object partitioning concepts are illustrated in Figure 2.2.



(a) (b) (c)

Figure 2.2: Various object partitioning strategies

(a) Object partitioning with multiple build directions

(b) Alternating build directions for symmetrical heat deposition

(c) Splitting up fill layers and using different fill patterns

Chang researched surface recognition and shape partitioning for SDM [Chang, Pinilla, et al., 1999]. SDM is different to RP by GMAW in that it uses very thick material layers that can be of varying shapes. Thus object partitioning takes on a new significance in SDM where a whole object section may in fact be built as a single "layer". Chang also researched the use of "surface compact graphs" to automatically analyse and create a build sequence. An example of Chang's surface compacts and build sequence analysis diagrams is shown in Figure 2.3. Shape decomposition for SDM has also been investigated by Ramaswami [Ramaswami, 1997].

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Figure 2.3: Surface compacts, surface compact nodes and precedence edges
[Chang, Pinilla, et al., 1999]

Cooper also researched shape decomposition, adaptive layer shapes and thicknesses, "surface compact graphs" and automatic build procedure generation in RP by SDM [Cooper, 1999]. As well as this, Cooper also investigated the use of multiple build directions in SDM and the optimisation of build direction based on the minimisation of "staircase" error and build time, stating that the use of multiple build directions can be beneficial in the SDM process.

Dickens recommended dividing complex objects into simple and convenient smaller objects in rapid prototyping by GMAW [Dickens, Cobb, et al., 1993] [Dickens, Pridham, et al., 1992]. An example of an object made in this way is Dickens' welded thermostat housing, which was divided into two parts each with its own build direction and is shown in Figure 2.4. Dickens noted that some shapes are better built in certain directions, for example cylinders which are "best built in the form of rings laid on top of each other". Dickens also noted that in order to accommodate separate build operations with different build directions in RP by GMAW, a welding cell would require a robot with sufficient degrees of freedom and a programmable workpiece manipulator.

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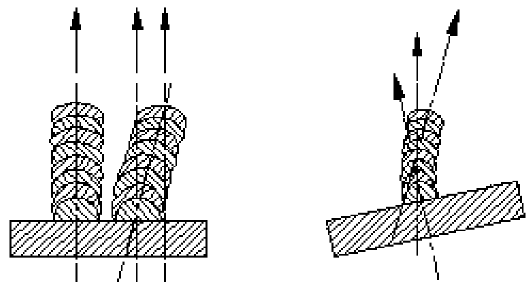
Figure 2.4: Welded thermostat housing [Dickens, Pridham, et al., 1992]

Ribeiro also wrote that in rapid prototyping by GMAW "depending on the complexity of the desired component, sometimes it is not possible to build the whole component in one go" [Ribeiro and Norrish, 1997]. He mentioned that in such cases the object to be welded would have to be partitioned into separate sections each with its own build procedure.

2.2.2 Thin Wall Welding

Thin wall welding in rapid prototyping by GMAW is the welding of walls of weld metal that are one weld bead thickness in width, by welding single welds on top of each other. Objects with thin cross-sections are made using thin wall welding, if the object's thickness falls within the suitable range. Thin walls are also used in solids welding when smooth outer surfaces are required. Thin walls may be vertical, or sloping and are usually made with a constant build direction and torch orientation. Thin walls made with constant and variable build directions are illustrated in Figure 2.5.



(a) (b)

Figure 2.5: Cross-sections of straight and sloping thin walls

(a) Made with a constant build direction

(b) Made with a variable build direction

De Boer and Jacono researched thin wall welding using robotic GMAW, concentrating on weld parameter selection [De Boer, Jacono, et al., 2000] [Jacono, 1999]. They tested a wide range of weld parameter combinations to see if they were suitable for thin wall welding and found that there is only a very narrow range of suitable parameters. A photograph of a thin wall that was made with wholly unsuitable weld parameters is shown in Figure 2.6. Jacono found that it is important to use small weld pools that freeze quickly with as little material flow as possible. To this end they recommended the short-circuit metal transfer mode with very low heat input and low deposition rate. They also stressed the need for a stable metal transfer process with constant standoff in order for the welds to be regular.

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Figure 2.6: A thin wall made with unsuitable weld parameters [Jacono, 1999]

Dickens also did some research involving parameter selection for thin wall welding using rapid prototyping by robotic GMAW. He noted that the shape and dimensions of the weld beads are important since they influence the range of wall thicknesses that can be produced and the surface quality of the walls [Dickens, Pridham, et al., 1992]. He performed some welding trials and studied how thin walls respond to various changing weld parameters, in an effort to improve thin wall quality and to start the construction of a weld parameter database. This led to a significant improvement in Dickens' weld walls, as is shown in Figure 2.7, however Dickens noted that further research was required especially regarding "the effects of multiple layers on weld bead dimensions".

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Figure 2.7: Cross-sections of Dickens' weld walls before and after weld parameter improvement [after: Dickens, Pridham, et al., 1992]

Thin wall welding in rapid prototyping by GMAW has also been well researched by Ribeiro [Ribeiro, 1998] [Ribeiro, 1999] [Ribeiro and Norrish, 1997] [Ribeiro, Ogunbiyi, et al., 1997]. Ribeiro investigated the effects on thin wall welding of weld parameter selection and found that highly tuned weld parameters and regular welds are essential. He investigated various aspects of weld path design for thin wall welding and developed an automatic object slicing and weld procedure generation system, complete with automatic weld parameter prediction. A photograph of a thin walled object created by Ribeiro is shown in Figure 2.8.

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Figure 2.8: A beer mug rapid prototyped by GMAW [Ribeiro, 1999]

Song also researched thin wall welding in rapid prototyping by GMAW, both with and without the incorporation of CNC milling [Song, Park, et al., 1998]. Song performed some experiments with thin walled objects and investigated the role of heat and the microstructure at different locations in the objects.

Thin wall welding in RP by robotic GMAW was also researched by Spencer [Spencer and Dickens, 1995] [Spencer, Dickens, et al., 1998] and Zhang [Zhang, Li, et al., 2002]. Spencer reported being able to produce thin walls of between 3mm and 6mm in thickness when using a 1mm diameter filler wire. However when attempting to produce walls thicker than 6mm, Spencer found that the "heat inputs are excessive and bead profiles [are] lost due to insufficient cooling rates" [Spencer and Dickens, 1995]. As a result, Spencer stated that walls thicker than 6mm require the use of multiple weld beads.

Hensinger developed a path generation system for the Laser Engineered Net Shape (LENS) process that uses variable tool orientations [Hensinger, Ames, et al., 2000]. When depositing an object's outer surfaces, the tool is always kept perpendicular to both the deposition path and the normal to the part's outer surface at the point of deposition. Using this system, Hensinger was able to make complex parts with sloping walls and sloping outer surfaces that exceeded the maximum wall angle possible using a constant tool orientation. Hensinger showed that this was particularly effective when using the LENS process to make thin walls that had extreme or varying slopes.

2.2.3 Solids Welding

Solids welding in RP by GMAW is the welding of objects which have cross-sections too thick to be made using a single thin wall. If any region of an object has a cross-section that is thicker than the maximum wall thickness producible with thin wall welding, that region of the object needs to be welded using solids welding. Such thicker cross sections require larger areas to be filled with weld metal, requiring the use of some sort of layer filling technique.

It has been shown by De Boer and Jacono [De Boer, Jacono, et al., 2000] [Jacono, 1999], as well as by Spencer [Spencer and Dickens, 1995] [Spencer, Dickens, et al., 1998], that solid objects cannot be made in RP by GMAW by simply using multiple thin walls side by side. These researchers showed that doing so leads to lack of fusion because the thin wall welds do not have enough heat input to penetrate the surrounding substrate. They also showed that increasing the heat input in an effort to improve fusion leads to loss of object shape and poor surface quality. This is illustrated in Figure 2.9.

See print copy

(a) (b)

Figure 2.9: Cross-sections of low quality solid objects made using thin wall offsetting [Jacono, 1999]

(a) Showing lack of fusion due to inadequate heat input, but little loss of shape

(b) Showing loss of shape due to excessive heat input, but good fusion

Thus it can be seen that layer filling for solid objects in RP by GMAW needs to be performed using higher heat input welds than are suitable for thin wall welding. It can also be seen that if the objects require smooth outer walls then these need to be made using separate thin walls made around the perimeter of the fill layers. In other words, an outer boundary needs to be made using thin wall welding and then the interior needs to be filled in with larger welds. This "boundary method" was successfully used for RP by robotic GMAW by De Boer and Jacono [De Boer, Jacono, et al., 2000] [Jacono, 1999] as well as by Spencer [Spencer and Dickens, 1995] [Spencer, Dickens, et al., 1998] and Zhang [Zhang, Li, et al., 2002]. Zhang stated that in RP by GMAW a boundary is necessary otherwise "the surface error will be significant". A cross-section of a solid object made by Jacono using the boundary method is shown in Figure 2.10.

See print copy

Figure 2.10: Cross-section of a solid object made using the boundary method [Jacono, 1999]

Cooper used a boundary technique in RP by SDM [Cooper, 1999]. First the outer walls of a solid object are built, making sure that the material being deposited solidifies quickly and does not flow much before solidifying. Then the inner volume of the shape is filled by a separate operation while making sure not to melt the outer "thin walls", which act to contain the inner material. This process is illustrated in Figure 2.11.

See print copy

Figure 2.11: The boundary method as illustrated by Cooper [Cooper, 1999]

Hensinger used a form of boundary method for the LENS process [Hensinger, Ames, et al., 2000]. As described in the previous subsection regarding thin wall welding, Hensinger developed a path generation system for LENS that used variable tool orientation during the build procedure. Hensinger used the same system for making the exterior of solid objects as for thin walled objects, except that after the outer surface of each layer was welded, the interior was filled in with a layer filling technique. A similar form of boundary method was also used by Qiu for FDM [Qiu, Langrana, et al., 2001].

A novel technique for the welding of solid weld layers was developed by Kalligerakis [Kalligerakis and Mellor, 1992]. Kalligerakis invented the "double spiral overlay welding" technique and applied it to wear replacement (cladding) by GMAW. In the general case, it is referred to in this thesis as "self-constrained" filling. This technique involved first depositing one set of welds that were separate from each other and then another set of welds inside the gaps defined by the first set. Thus the first set of welds, called the "ridges" or "crests", act as constraints for the second set of welds, called the "troughs" or "roots". Kalligerakis' diagram of this technique is shown in Figure 2.12.

See print copy

Figure 2.12: "Double spiral overlay welding" [Kalligerakis and Mellor, 1992]

Kalligerakis wrote that since the "ridge" welds do not overlap each other they can be made with lower welding currents than in standard, "single spiral" or "non-constrained", layer filling [Kalligerakis and Mellor, 1992]. Kalligerakis also wrote that because the following "trough" welds are constrained in shape by the "ridge" welds, they can use high currents to burn off any slag from inside the channels and to ensure proper melting and fusion with the adjacent welds and the base material. Kalligerakis compared single and double spiral filling techniques and found that an advantage of the double spiral technique was that it produced smoother surface profiles, while a disadvantage was that it required two different sets of welding parameters to be devised instead of one.

The "double spiral overlay" or "self-constrained" welding technique was subsequently used by Kmecko and Kovacevic for their RP by GMAW and CNC milling process, as shown in Figure 2.1 [Kmecko, Hu, et al., 1999]. As can be seen in that figure, they also employed a kind of boundary technique where a separate weld is made to run along the outer perimeter of each fill layer.

The "double spiral overlay" welding technique was also subsequently used for RP by GMAW by Spencer, who illustrated it as shown in Figure 2.13 [Spencer and Dickens, 1995] [Spencer, Dickens, et al., 1998]. Spencer realised that this technique was not restricted to just spiral paths, but could be used with any layer filling procedure that allowed for the division of the fill area by "crest" welds and the subsequent filling of the remaining channels by "root" welds.

See print copy

Figure 2.13: The "double spiral overlay" welding technique
[Spencer, Dickens, et al., 1998]

Spencer also discussed the role of weld parameters in "self-constrained" welding [Spencer and Dickens, 1995] [Spencer, Dickens, et al., 1998]. Spencer reiterated that "trough" welds require a greater heat input than "ridge" welds, because "ridge" welds only require fusion at the bottom whereas "trough" welds need to melt and fuse with metal on three sides. However this would not necessarily have an adverse affect on weld geometry, since after the "ridge" welds are made they act as a constraint for the molten "trough" weld metal and help to control their shape. That being the case and under the condition that the heat input is sufficient for full fusion and the melting of slag, Spencer proposed that the "trough" weld heat input could be varied to help control weldment temperature. Finally, Spencer proposed the use of through-the-arc sensing for automatic "trough" weld control.

A slightly different form of fill weld constraint was used by Tinkler [Tinkler, McNabb, et al., 1987]. Tinkler used what will be called in this thesis "inter-layer self-constrained" welding. Tinkler's fill welds were made inside valleys produced by the previous weld layer. Thus the fill welds were still constrained to some extent, except that the constraint came from the fill welds from the previous layer.

Link presented a different solid object build strategy that should be mentioned, which is suitable for all metallic forms of rapid prototyping [Link, 1999]. The strategy is to use a suitably shaped pre-fabricated base object as an integral part of the solid object design. An example of this is illustrated in Figure 2.14. The advantages of this strategy could be reduced build time and reduced residual stresses, as less material would need to be deposited by the rapid prototyping system. This was also envisaged by Song, however Song used a combination of material deposition and material removal in his rapid prototyping system [Song, Park, et al., 1998].

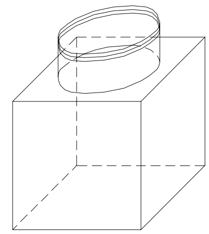

Figure 2.14: Use of a simple pre-fabricated base as an integral part of the object

2.2.4 Raster Fill Path Patterns

After a solid object has been sliced into layers, tool paths need to be designed that the tool can follow in order to fill the layers in. Three basic families of tool path patterns for the filling-in of layers have been identified in literature. These will be presented separately in the next three chapter sub-sections.

The path family presented here is the raster fill path family. Raster paths have also been known by other names such as "staircase" or "zigzag", however for the purposes of this thesis the name "raster" will be used. Raster paths involve regularly spaced parallel lines that cover the area to be filled, forming "staircase" or "zigzag" patterns.

Farouki described raster paths and mentioned that they are common in CNC milling [Farouki, Tarabanis, et al., 1994]. Farouki also briefly compared raster paths to contour paths and noted that raster paths are generally easier to compute for a given 2D shape, however contour paths are generally predicted to produce smoother surface finishes for a given deposition or removal process.

Raster path patterns were used by Fessler for the SDM process using laser welding [Fessler, Merz, et al., 1996]. Fessler investigated how various raster path patterns affected residual stress in SDM using laser welding.

Hensinger used raster paths for the filling in of solid layers using the LENS process [Hensinger, Ames, et al., 2000]. After the outer boundary of each layer had been welded, the interior of each layer was filled in using a raster path pattern. This is illustrated in Figure 2.15. Kmecko and Kovacevic also used the same raster fill technique, as shown in Figure 2.1 [Kmecko, Hu, et al., 1999]. Raster weld paths were also used by Song [Song, Park, et al., 1998] [Song, Park, et al., 1999].

See print copy

Figure 2.15: Welding of perimeter and layer filling using a raster path in the LENS process [Hensinger, Ames, et al., 2000]

Raster path patterns were also researched by Kamarthi for CNC milling [Kamarthi, Bukkapatnam, et al., 2000] [Kamarthi, Pittner, et al., 1997]. Kamarthi's research involved the mathematical description and optimisation of raster cutting paths inside convex polygons. Kamarthi developed an algorithm that could generate "near optimal" raster tool paths for convex polygons for CNC milling, concentrating on minimising the total path lengths and cutting times. A particularly useful observation made by Kamarthi was that the shortest total path length of raster paths inside convex polygons usually occurs when the raster lines are parallel to the longest side of the polygon.

Kulkarni and Dutta used raster paths for the FDM process and investigated how they affect the process [Kulkarni and Dutta, 1999]. The raster path that they used had linking sections that linked the end of one raster line to the start of the next, so that the entire fill layer is filled by one unbroken path that zig-zags its way across the layer as shown in Figure 2.16. Such raster paths will be referred to in this thesis as "continuous" raster paths, as opposed to "discrete" raster paths such as the one shown in Figure 2.15.

See print copy

Figure 2.16: A contour path and continuous raster paths, respectively [Kulkarni and Dutta, 1999]

Kulkarni and Dutta noted that a major problem with continuous raster paths is that they leave unfilled voids near the edges of the fill areas, when the deposition is performed with a circular filling tool [Kulkarni and Dutta, 1999]. This can be seen from Figures 2.16 and 2.17. They modelled the areas that remain unfilled as a function of the corner angle when using the FDM process. They found that the smallest voids are produced when the raster lines meet the edge of a fill area at 90º. Kulkarni and Dutta also noted that in order to reduce unfilled voids in layer filling in general, the number of corners or changes in direction in deposition paths should be minimised.

See print copy

Figure 2.17: Voids produced by continuous raster paths near fill area edges [Kulkarni and Dutta, 1999]

Nickel investigated the effects of various deposition path patterns on residual stress and cracking in SDM using low carbon steels [Nickel, 1999] [Nickel, Barnett, et al., 1999] [Nickel, Barnett, et al., 2001]. Some of the path patterns Nickel investigated were discrete raster paths. Using finite element modelling and experimentation he showed that residual stresses are greatest in the direction of the raster lines. He also compared the effects of two different raster path patterns used to fill in a narrow rectangle, as shown in Figure 2.18. Nickel showed that the path pattern that used the shorter raster lines, that is with the raster lines perpendicular to the longer rectangle sides, produced lower stresses and lower base plate deflection. Raster paths in SDM have also been researched by Ramaswami, who investigated the automatic generation of raster paths for the SDM process [Ramaswami, 1997].

See print copy

Figure 2.18: Discrete raster paths using different raster angles [Nickel, 1999]

Various kinds of raster paths were also researched by Qiu [Qiu, Langrana, et al., 2001] and Tarabanis [Tarabanis, 2001] for the FDM process. Qiu as well as Tarabanis investigated the generation and optimisation of raster paths for FDM, including both discrete and continuous raster and the effects on the FDM build process of varying raster angles. They both echoed the results of other researchers by finding that path corners, starts and ends tend to introduce unfilled voids and therefore should be avoided. Tarabanis investigated their minimisation through raster angle selection. Raster deposition paths in FDM were also used by Wenbiao, who also investigated problems with overfill at corners [Wenbiao and Jafari, 2000].

The generation and optimisation of discrete and continuous raster paths for machining and generic rapid prototyping has also been researched by Rajan [Rajan, Srinivasan, et al., 2001], Sarma [Sarma, 2000], and Vosniakos [Vosniakos and Papapanagiotou, 2000]. Rajan recommended that a raster path pattern should use as few raster lines as possible and developed algorithms for raster line minimisation in a given shape through raster angle optimisation.

Tinkler also used raster paths for wear replacement by robotic GMAW [Tinkler, Fihey, et al., 1991] [Tinkler, McNabb, et al., 1987]. Both discrete and continuous raster paths were used, as is illustrated in Figure 2.19. Tinkler noted that when using continuous raster 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]. Continuous and discrete raster paths were also used by Zhang for RP by GMAW [Zhang, Li, et al., 2002].

See print copy

(a) (b)

Figure 2.19: Tinkler's raster paths [Tinkler, Fihey, et al., 1991]

(a) Discrete raster; (b) Continuous raster

2.2.5 Contour Fill Path Patterns

Contour paths are another family of paths that can be used to fill in a layer. They use closed loops that are offset from the boundary of the layer and from each other, usually by a set constant distance. The closed loops are not connected to each other and each loop is a separate path segment. Contour fill paths have also been known as "offset curves" or "offset paths" as well as "window frame" paths due to the way they are generated and the appearance of the resulting path patterns.

Contour path patterns were described by Farouki, who noted that contour and raster path patterns were both common in CNC milling [Farouki, Tarabanis, et al., 1994]. Farouki described a number of methods that can be used to generate contour paths in various 2D shapes, including offsetting the shape boundary and using Voronoi diagrams and discussed some of the associated difficulties and limitations. Voronoi diagrams are also known as "medial axes" and the Voronoi diagram of a shape is the loci of the centres of locally maximal spheres inside the shape and can be thought of as a "skeleton" of the shape. A diagram showing the offsetting of a given shape is shown in Figure 2.20.

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Figure 2.20: Calculation of an offset from a 2D shape
[Farouki, Tarabanis, et al., 1994]

Farouki also described some of the general problems associated with contour path patterns, especially that areas of overfill and underfill can easily occur [Farouki, Tarabanis, et al., 1994]. This can happen where paths have discontinuous changes in direction, or are too close or too far apart. This is especially the case in areas near the inmost contours where there may not be a valid contour that is equidistant from itself and its neighbour and uniform area coverage may not be possible. These problems can lead to unacceptably uneven deposition or unfilled voids. Farouki noted that the seriousness of such problems depend on the particular deposition or material removal process used and that "if optimum structural integrity and dimensional accuracy are desired, ... explicit compensatory steps in the path planning may be necessary".

Kao researched the automatic generation of contour paths using medial axes techniques for rapid prototyping by SDM [Kao, 1999] [Kao and Prinz, 1998]. As well as this, Kao developed a new way of computing the medial axes of any shape and investigated the overfill and underfill problems that can easily occur in contour paths in the interior of objects.

Kao developed a method that used medial axes to test whether a generated contour path inside a given shape is feasible for manufacturing [Kao, 1999] [Kao and Prinz, 1998]. Kao also developed a system that automatically modified a shape by the minimal possible amount, in order to avoid overfill and underfill problems in the shape's interior. This system also automatically generated "optimal" contour paths directly from the optimised shape's medial axis transform. Diagrams illustrating some of the problems with contour paths, the concept of medial axes and Kao's shape optimisation system are shown in Figures 2.21 - 2.23. The generation of medial axes for 2D and 3D objects, as well as object modification and detail control using medial axes has also been researched by Storti [Storti, Turkiyyah, et al., 1997].

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Figure 2.21: Common problems with contour paths [Kao and Prinz, 1998]

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Figure 2.22: The medial axes transform of a shape [Kao and Prinz, 1998]

See print copy

Figure 2.23: Kao's shape optimisation and contour path generation system [Kao and Prinz, 1998]

As mentioned previously in the subsection dealing with raster paths, Nickel investigated the residual stresses produced by deposition paths in SDM using low carbon steel [Nickel, 1999] [Nickel, Barnett, et al., 1999] [Nickel, Barnett, et al., 2001]. As well as raster paths, Nickel also investigated the effects on stress of contour paths, though it should be noted that Nickel actually referred to contour paths as "spiral" paths. Nickel compared two different contour path variants as applied to square fill areas; one had its contour path segments deposited from the outside inwards and the other from the inside outwards. This is illustrated in Figure 2.24. Nickel found that the contour path pattern where the outer contour was deposited first and the inner contour was deposited last produced lower residual stresses and deflection.

See print copy

Figure 2.24: Contour path patterns with different deposition order [Nickel, 1999]

Contour paths and their generation for SDM have also been researched by Ramaswami [Ramaswami, 1997]. Ramaswami used both recursive offset methods and medial axes methods for contour path generation. However it should be noted that Ramaswami also referred to contour paths as "spiral" paths, similarly to Nickel.

Kulkarni and Dutta [Kulkarni and Dutta, 1999] as well as Tarabanis [Tarabanis, 2001] used contour paths for the FDM process. A contour path diagram by Kulkarni and Dutta is shown in Figure 2.16. Tarabanis decided to use inside-to-outside contour paths "for heat dissipation purposes", but did not elaborate any further. Tarabanis also described some algorithms for generating contour paths for complex fill area shapes for FDM and identified some common mathematical problems that can arise. Contour paths were also described by Sarma [Sarma, 2000] and Vosniakos [Vosniakos and Papapanagiotou, 2000], who investigated their generation using offsetting and medial axes.

2.2.6 Spiral Fill Path Patterns

Spiral fill paths employ continuous path segments that run unbroken between the centre of a fill area to its boundary. Each continuous path segment can be called an "arm" of the spiral path and there may be one or more spiral arms in a spiral path. The spiral arms wrap around themselves and each other so that they are always spaced out by a constant distance. In the classic spiral patterns, the radius from the centre of the fill area is a function of the angle.

Spiral path patterns were used by Kulkarni and Dutta for FDM [Kulkarni and Dutta, 1999]. They presented three different types of spiral path patterns, one for circular fill areas and two for square ones, as shown in Figure 2.25. The first of these, for circular fill areas, was the classic Spiral of Archimedes. The second spiral path, designed for square fill areas, they called the "pointwise spiral" which was based on the Spiral of Archimedes except that it used discrete points that were joined together with straight lines. However Kulkarni and Dutta noted that the "pointwise spiral" was never parallel to the sides of the fill area, which was undesirable since it would result in unfilled voids near the edges of the fill area. Thus they presented the third spiral, which they called the "desired spiral" for square fill areas. This spiral was parallel to the sides of the fill area, however Kulkarni and Dutta stated that it "does not have a compact mathematical representation".

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(a) (b) (c)

Figure 2.25: Spiral deposition paths presented by Kulkarni
[Kulkarni and Dutta, 1999]
(a) Spiral of Archimedes; (b) Kulkarni's square "pointwise spiral";
(c) Kulkarni's square "desired spiral"

Sarma also presented the Spiral of Archimedes as a deposition path suitable for the filling of circular shapes [Sarma, 2000]. Sarma also presented a spiral for the filling of square shapes, the same as the "pointwise spiral" presented by Kulkarni. As well as this, Sarma investigated the generation of spiral paths for more complex 2D shapes and mentioned that medial axes can be used to assist with spiral path generation, although the construction of medial axes for complex shapes can be computationally intensive. Spiral paths were also used by Spencer for rapid prototyping by GMAW, as is shown by a photograph of one of Spencer's weldments in Figure 2.26 [Spencer and Dickens, 1995]. It should be noted that this spiral is the same as Kulkarni's "desired spiral". It can also be noted that this is also an example of Spencer's use of the "self-constrained" welding technique.

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Figure 2.26: A square spiral weld path in RP by GMAW
[Spencer and Dickens, 1995]

2.2.7 Temperature and Residual Stress Regulation

Chin researched the evolution of residual stresses in multi-layer rapid prototyping by SDM using the microcasting process [Chin, Beuth, et al., 1996] [Chin, Beuth, et al., 2001 a and b]. Chin found that greater thermal gradients inside an object lead to greater residual stresses and thus residual stresses can be reduced through reduction of the temperature gradients. Chin also found that heat from newly deposited layers acts to relieve stresses already present in the weldment and that the rate of layer deposition does not greatly affect the final stresses. One way to reduce thermal gradients would be through uniform preheating of the entire object during the build procedure, however Chin noted that localised preheating would actually increase stress if it resulted in increased thermal gradients. Chin also noted that correct weld path design also has the scope for reducing thermal gradients and thus reducing residual stresses.

Chin also found that previously deposited adjacent droplets of metal have the effect of increasing stress in the direction of deposition, relative to the transverse direction [Chin, Beuth, et al., 2001 a and b]. Other recommendations made by Chin include that post processing such as heat treatment should be used to relieve residual stresses (although this may not help to reduce warpage), that baseplates should be firmly secured during a build procedure to help reduce stress and that ideally materials should be used that work-harden as little as possible.

As a result of his research, Dickens proposed a methodology for controlling weldment temperature in rapid prototyping by GMAW [Dickens, Cobb, et al., 1993] [Dickens, Pridham, et al., 1992]. Dickens envisaged that sensors could be used to measure the temperature of the object being welded in order to prevent it from overheating. He proposed that welding should stop and the build process be paused when the sensors detected that the weldment temperature was too high. The weldment would then be allowed to cool or be forced to cool until the desired temperature is reached, before welding resumed.

As mentioned in the previous chapter section dealing with instability in rapid prototyping by GMAW, Dickens' strategy was later researched by Spencer [Spencer and Dickens, 1995] [Spencer, Dickens, et al., 1998]. Spencer investigated how this strategy affected surface quality, microstructure and stress in RP by GMAW. However Spencer warned against forced cooling as it could lead to cracking [Spencer, Dickens, et al., 1998].

As previously mentioned in the subsection on raster path patterns, Fessler investigated the effects of some raster path variants on residual stress in SDM using laser welding [Fessler, Merz, et al., 1996]. Fessler proposed and successfully tested two methods for reducing stress in

SDM using laser welding. The first was to maximise surface area by using a discrete raster path pattern, with every second raster line being deposited first forming separated ridges (or "towers") of material, before filling in every other raster line. Fessler argued that the intermediary protruding material deposits have greater surface area and thus cool faster, as well as allowing for greater stress relief. Fessler's technique was later also used by Ramaswami [Ramaswami, 1997]. The other method to reduce stress was to use materials with very low coefficients of thermal expansion.

Kondoh and Ohji developed a method for automatically controlling the thermal field in straight line bead on plate GTAW [Kondoh and Ohji, 1998]. They achieved this by varying the heat input in different discrete sections of the straight line welds, in order to develop the desired temperatures at various discrete locations next to the welds. They successfully tested their system experimentally, resulting in more homogenous temperature fields and more uniform weld bead shapes.

Link proposed a system of controlling the residual stresses in rapid prototyping, based around the number of layers that had been deposited or the height of the layers that had been deposited [Link, 1999]. Link proposed that after a desired number of layers had been built, or after a desired deposition height had been reached, the whole part be heat treated to reduce residual stress. After the part had been heat treated, deposition would continue and the cycle would be repeated.

Nickel found that in SDM using low carbon steels, an object created using a greater number of thinner layers has lower residual stresses and deflection than an object created using a smaller number of thicker layers [Nickel, 1999] [Nickel, Barnett, et al., 1999] [Nickel, Barnett, et al., 2001]. Nickel simulated how residual stress varies with the number of layers used to make an object of a given height. He found that as the number of layers used approaches infinity and the thickness of each layer thus approaches zero, residual stress and deflection decrease asymptotically.

Another significant deposition path design strategy related to temperature and stress that should be noted was presented by Ramaswami [Ramaswami, 1997]. Ramaswami recommended that an object should be created in such a way so that the heat is deposited into it as symmetrically as possible. Doing so will help to make the temperature distribution inside the object more uniform and thus help to reduce thermal stresses.

Song investigated thermal effects versus the height of objects produced in RP by GMAW [Song, Park, et al., 1998]. Song described how heat dissipates faster when welding layers close to the base plate and dissipates slower when welding layers that are high above the base plate. He wrote that as an object being welded grows taller, heat accumulates in the object "until an equilibrium between heat input and dissipation is achieved". He found that these differences in thermal conditions affect weld bead dimensions and microstructure, causing both of these to vary depending on their height above the base plate. Song proposed the variation of weld parameters when welding layers depending on the height of the layer above the base plate, in order to control heat build-up, surface temperatures, stress and microstructure. Similar investigations were also performed by Spencer as part of Spencer's temperature control work [Spencer and Dickens, 1995] [Spencer, Dickens, et al., 1998].

Song also recommended preheating base plates, using thicker base plates, heat treating parts and cooling parts down as slowly as possible in order to reduce warpage and produce more uniform microstructure in RP by GMAW [Song, Park, et al., 1999]. In his RP by GMAW and CNC milling system, Song allowed each layer to cool to room temperature before it was machined. As well as this, Song also modelled the effects of weld direction on warpage using finite element analysis. Similar to other researchers, he found that "deposition with long [weld] beads causes more warpage than with short beads" and recommended that when selecting the welding direction "the bead length should be taken into consideration".

Finally, Vasinonta investigated weld pool length in thin wall welding using the LENS process [Vasinonta, Beuth, et al., 2001]. Vasinonta studied the effects on weld pool length of various process parameters as well as wall height. It was found that the weld pool length in the LENS process increases dramatically as wall height increases from zero and then stabilises as the height becomes large and the heat transfer effect of the base plate is lost. Vasinonta argued that this would also be the case for other metallic rapid prototyping processes.

2.2.8 Other Tool Path and Build Process Design Strategies

Tool path design through real time closed-loop control of tool motion, power and feed has been researched by Doumanidis, as reported in the previous chapter section dealing with instability in rapid prototyping by GMAW. Doumanidis investigated various models and control systems for controlling geometric and/or thermal properties of prototyped parts. Further details regarding this research can be found in the previous chapter section.

Also as reported in the previous chapter section, Kovacevic and Jandric investigated weld bead shape and penetration control through control of the heat input in RP by welding [Jandric and Kovacevic, 2001]. They developed a control system that maintained uniform weld bead dimensions and penetration when welding near areas such as edges that have varying heat transfer conditions. Further information can be found in the previous chapter section.

Kmecko and Kovacevic mentioned two weld procedure design strategies for RP by GMAW regarding weld corners and the making of internal channels [Kmecko, Hu, et al., 1999]. They recognised that when welds are made to turn tight corners they can result in uneven deposition as too much material is deposited in the same location. Thus they proposed that during the welding of corners, "the quantity of metal added to the weld pool has to be reduced". Regarding the forming of internal channels in a part, they suggested that an open channel should first be left unfilled in the part, which may then be filled in with a support material such as sand and covered with a thin sheet of metal. Finally, new welds should then be deposited over the top of the sheet metal as normal, leaving the internal channels inside.

Kulkarni and Dutta proposed a method of reducing unfilled voids that can occur near corners in rapid prototyping by FDM, by changing the deposition speed or amount of material deposited [Kulkarni and Dutta, 1999]. A similar methodology was also described by Qiu [Qiu, Langrana, et al., 2001]. Kulkarni and Dutta also presented a methodology for helping to reduce the accumulation of errors between successive fill layers. This was done by rotating the deposition path pattern between one fill layer and the next, as is shown in Figure 2.27.

See print copy

Figure 2.27: Rotating fill paths between fill layers [Kulkarni and Dutta, 1999]

A few noteworthy recommendations for deposition paths and layer filling in general were also mentioned by Ramaswami [Ramaswami, 1997]. Ramaswami stressed the importance of avoiding unfilled voids, avoiding uneven deposition and avoiding revisiting points during layer filling. Any deposition path pattern that revisits points or runs across itself would result in twice the desired material being deposited at the revisited location, which would cause uneven deposition. Also, Sarma made the point that 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].

Finally, Zhang and Li also presented some weld procedure design strategies for RP by GMAW that echoed some presented previously by other researchers for other processes [Zhang, Li, et al., 2002]. As outlined in the previous chapter section dealing with instability in RP by GMAW, Zhang and Li found that in thin wall welding arc ignitions at the starts of welds and crater fills at the end of welds are a significant source of instability. They recommended that weld starts and ends should be minimised if possible and developed modifications to their weld parameters and weld paths near those areas to help reduce the instability. They also recommended a system of fill layer rotation similar to that presented by Kulkarni, where successive fill layers are identical except for being rotated with respect to one another. This system helped reduce accumulated geometric error by distributing sources of error more evenly throughout the object.

2.3 Literature Survey Summary

The literature shows that previous researchers have encountered geometric and thermal instability in the RP and WR by GMAW process and have found these instabilities to be very problematic. The literature also shows that various research directions have been taken in the past in order to address these problems. However the effects of open-loop weld path design on process stability have not yet been well researched. At the same time, the literature shows that many different tool path design strategies exist that can be adopted for the RP and WR by GMAW process. The effects of many of these path strategies on the performance of other forms of RP have previously been well investigated by researchers, however their effects on RP & WR by GMAW have not. This thesis will therefore investigate the effects of such path strategies on the RP & WR by GMAW process in order to determine whether open-loop weld path design can be used to improve stability.