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

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Chapter 1

Introduction

1.1 Project Outline

Rapid prototyping is a large and rapidly growing industry with many different processes either under development or already available commercially. These processes offer fast and flexible production of objects from a wide range of materials. They vary from being able to produce only prototypes of products, through to being suitable for production of finished products ready for service. Rapid prototyping by robotic gas metal arc welding (GMAW) uses metal deposited by the GMAW process to build metal products with engineering properties suitable for service conditions. Wear replacement is the repair of worn metal surfaces through the deposition of weld metal, and can also be performed using robotic GMAW. Since both rapid prototyping and wear replacement by robotic GMAW involve the building up of metal objects from metal deposited by the GMAW process, it is possible to conduct research into them together.

This research was part of an effort to create an automatic robotic welding cell capable of both rapid prototyping and wear replacement. In order for such a cell to be possible, a capability must exist for automatic generation of the required weld paths and weld procedures. Successful automatic generation of weld paths and procedures for such a purpose can be a highly complex task and needs to be robust, efficient and practical for automatic rapid prototyping and wear replacement by robotic GMAW to be viable.

It was found however that the rapid prototyping process using GMAW may suffer from stability problems. Geometric instability seems to be an inherent feature of the process, resulting in relatively poor dimensional accuracy and surface quality. As a result researchers at other institutions have investigated ways of improving the geometric performance of the process, notably through improving weld regularity, real-time analysis and feedback control of the process, as well as through integrating it with machining processes [Siminski and De Boer, 2001].

In this thesis geometric stability is defined to mean the uniformity and predictability of the shape of deposited weld beads and weld layers. It is directly linked to the dimensional accuracy and surface quality of objects produced. Thermal stability is defined to mean the uniformity and predictability of the weldment surface temperatures on top of which welds are made.

This thesis investigates how the weld paths used in rapid prototyping by robotic gas metal arc welding affect the stability and performance of the process. It tests whether non-feedback weld path design can be used to improve process stability and performance. It studies a range of weld path design strategies, how they perform and compares them.

1.2 Robotic Gas Metal Arc Welding

1.2.1 The Gas Metal Arc Welding (GMAW) Process

Gas metal arc welding (GMAW), also called metal inert gas (MIG) or metal active gas (MAG) welding, is a fusion welding process that melts a localised area of a substrate and adds to it molten filler material so that the two molten metals mix and solidify to form a weld. The gas metal arc welding process uses an electric arc between a filler wire and a substrate to melt the filler wire and substrate metal. The electrode wire is continuously fed into the arc and it continuously melts and falls onto the molten area on the substrate called the weld pool. This process is also shielded from the atmosphere by a shielding gas, such as argon (Ar) or carbon dioxide (CO_2), or a mixture of gases. This process is illustrated below in Figure 1.1.

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Figure 1.1: The gas metal arc welding process [Kearns, 1978]

The most important parameter in the GMAW process is the welding current. This is the current supplied by the welding power supply that flows through the contact-tip, the electrode extension, the arc and the workpiece. The welding current is the dominant factor in how the welding process behaves. The nominal welding current is usually selected indirectly depending on the application and the mode of welding, usually between 50A and 450A. The instantaneous current, however, can vary greatly and rapidly depending on the welding process and the dynamics of the system.

The welding voltage is the voltage supplied by the welding power supply to the welding process. The nominal welding voltage also affects the welding process and also varies depending on the application and the mode of welding. The total voltage drop across the power supply terminals is the sum of the voltage drops in the welding cables, contact-tip, electrode extension, the arc and the workpiece. The instantaneous voltage across the welding process can also vary greatly and rapidly depending on the welding process and the dynamics of the system. If all other welding parameters remain fixed, for a constant arc length, the mean voltage and the mean current have a linear relationship [Norrish, 1992].

The wire feed rate is the speed at which the electrode wire is fed into the welding process, measured by unit distance per unit time. The mean wire feed rate is set to a desired value depending on how quickly material is to be added to the welding process. However it must be carefully matched with the other welding parameters otherwise the welding process will be unstable. Usually a constant wire feed rate is used for the welding process, though some advanced welding systems vary the wire feed rate dynamically depending on the instantaneous behaviour of the weld process. Some power supplies are programmed to automatically predict optimal settings for other welding parameters such as welding voltage, based on wire feed rate selection.

The travel speed is the speed at which the welding torch is moved relative to the workpiece during welding. It affects the way in which heat and material are deposited into the workpiece and therefore also weld bead size and shape and penetration into the workpiece.

The deposition rate is the rate at which filler material is deposited into the weld, measured in unit mass per unit time. It is used as a measure of overall welding speed and productivity. Deposition rate is calculated as shown in Equation 1.1, where DR is deposition rate, ρ is the density of the filler wire, A is the cross-sectional area of the filler wire and WFR is the wire feed rate.

$$DR = \rho \times A \times WFR$$

Equation 1.1: Deposition rate

The deposition area is the cross-sectional area of the solidified filler material in the weld bead (perpendicular to the direction of travel). The weld bead itself is also made up of re-solidified substrate material, but this is not included in the deposition area. The deposition area is therefore a measure of the cross-sectional size of the deposition. It is approximated by Equation 1.2, however some filler material would also be lost due to phenomena such as spatter. This does not however provide insight into the actual shape of the weld bead which is determined by various other factors such as heat input and shielding gas. In Equation 1.2, DA is the deposition area, A is the cross-sectional area of the filler wire, WFR is the wire feed rate and TS is the travel speed.

$$\mathrm{DA} = \frac{\mathrm{A} \times \mathrm{WFR}}{\mathrm{TS}}$$

Equation 1.2: Deposition area

Heat input is a measure of how much heat is deposited by the welding process into the workpiece per unit travel distance and is measured in unit energy per unit distance. The mean total heat input into the system is calculated according to Equation 1.3, where HI is heat input, V is welding voltage, I is welding current and TS is travel speed. Heat input affects the temperature and size of the weld pool, the amount of penetration into the substrate and the shape of the weld bead. The greater the heat input, the more substrate material is melted, the greater the fusion between the filler material and the surrounding material, the hotter and larger the weld pool, the larger the total weld bead, the longer the weld pool takes to solidify and the wider and flatter the weld bead.

$$\mathrm{HI} = \frac{\mathrm{V} \times \mathrm{I}}{\mathrm{TS}}$$

Equation 1.3: Heat input

In gas metal arc welding, there are several distinct mechanisms by which electrode material can be melted and transferred to the weld pool. Which one of these "transfer modes" the weld process operates in depends on the welding parameters used and on whether or not a particular transfer mode is "artificially" induced or controlled by the welding power supply. There are a number of "natural" transfer modes that automatically occur depending on the parameters used. The welding current is the parameter that most influences the transfer mode, however other parameters such as shielding gas, wire feed speed and electrode type are also important [Norrish, 1992]. The three main "natural" transfer modes are: "short-circuit", "globular" and "spray". These transfer modes operate very differently and they affect the process stability, the amount of spatter generated, the weld quality, the positional capabilities of the process, as well as occurring in different current and therefore heat input ranges [Norrish, 1992].

Short-circuit transfer mode occurs when the electrode wire is being fed faster than it can be melted and it therefore comes into contact with the weld pool. Upon touching the weld pool, the current rises sharply, melting the electrode wire above the weld pool and re-establishing the arc. This can be a very unpredictable and unstable transfer mode that generates a lot of spatter and poor weld quality. However it alone out of the natural transfer modes can be used with very low welding currents and is thus useful for applications where low currents and low heat inputs are required. If the welding parameters are chosen well, the short-circuit transfer process can be made to occur regularly, producing acceptable levels of spatter and high quality weld beads [Norrish, 1992]. Because the short-circuit transfer mode uses low heat inputs and therefore small fast-freezing weld pools, it is well suited for applications such as the welding of thin steel sheet where burn-through must be avoided, welding in different orientations with respect to gravity and any applications that require small weld pools and fast-forming small weld beads.

For steel electrode wires, shielded by Argon-based gases, short-circuit transfer normally occurs with welding currents below approximately 100 - 150A, however this depends on electrode wire diameter and composition as well as shielding gas composition. The regular operational sequence is as follows. The tip of the electrode wire touches the weld pool, a short-circuit is formed and the arc is extinguished, causing a sudden rise in welding current. The temporarily high current then melts a section of the electrode wire and this molten metal is transferred to the weld pool, causing a small new gap to form again between the electrode wire and the weld pool. The welding arc is then re-established and the cycle is repeated. A diagram of the short-circuit transfer mode is shown in Figure 1.2 below.

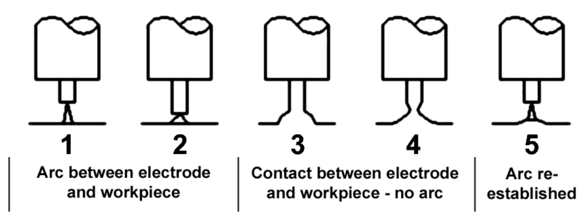

Figure 1.2: The short-circuit transfer mode

Globular transfer occurs when the electrode wire is being melted at a high enough rate to stop it from touching the weld pool, but the electromagnetic force created by the current is not great enough to force rapid regular transfer of molten metal to the weld pool. The molten metal collects as a droplet at the tip of the electrode wire, held together by surface tension and grows and does not detach until the force of gravity is large enough to force it to drop into the weld pool [Norrish, 1992]. It occurs at higher current levels than short-circuit transfer but lower than spray transfer and therefore produces higher heat inputs and larger weld pools than short-circuit transfer. For steel electrode wires, shielded by Argon-based gases, globular transfer normally occurs with welding currents between approximately 100 - 250A, though this again depends on electrode wire diameter and composition as well as shielding gas composition. It is thus used for applications requiring larger heat inputs, greater melting of the substrate material and larger weld beads than with short-circuit welding, but smaller than with spray welding. However due to its reliance on gravity, globular transfer has very limited positional capabilities [Norrish, 1992]. A diagram of the globular transfer mode is shown in Figure 1.3.

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Figure 1.3: The globular transfer mode [Cary, 1979]

Spray transfer mode occurs when the welding current is large enough to not only melt the electrode wire as it is fed, but to also create a large enough electromagnetic force to regularly pull the molten metal from the tip of the electrode. Small droplets of molten metal, of a diameter similar to or smaller than that of the wire, are regularly detached from the wire tip and are projected in a steady stream to the weld pool [Norrish, 1992]. It occurs at welding currents higher than that of globular transfer and therefore produces higher heat inputs and larger weld pools. For steel electrode wires, shielded by Argon-based gases, spray transfer normally occurs at welding currents higher than 250A, though once again this depends on electrode wire diameter and composition as well as shielding gas composition. As the welding current continues to increase, the size of the droplets continues to decrease and their speed continues to increase, eventually resulting in what is called "streaming" transfer [Norrish, 1992]. Spray transfer tends to be stable with little spatter [Lincoln Electric, 1998]. Spray transfer is used for applications where large heat inputs, large weld beads and high deposition rates are needed. However due to the large, slow-freezing weld pools, it still has limited positional capabilities [Norrish, 1992]. A diagram of the spray transfer mode is shown in Figure 1.4.

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Figure 1.4: The spray transfer mode [Cary, 1979]

In addition to the three "natural" transfer modes, there are also two "artificial" ones that are commonly used: pulsed GMAW and controlled short-circuit. Pulsed GMAW allows spray-style droplet detachment from the electrode wire while using a low mean welding current. In pulsed GMAW, the welding current is periodically pulsed to a high value, but is kept low for the rest of the time. The low "background" current keeps the arc alive and keeps the overall mean current low. The regularly pulsed high current creates temporary large electromagnetic forces which cause regular controlled detachment of droplets from the electrode tip. The result is regular spray-style transfer at low mean currents, with less spatter than short-circuit transfer and lower heat inputs, smaller weld pools and better positional capabilities than spray transfer. The current waveform is controlled by the welding power supply and the background and pulse parameters are set depending on the application [Norrish, 1992].

Controlled short-circuit, otherwise known as controlled-dip, is an "artificial" modification of the short-circuit transfer mode. In controlled short-circuit welding, the welding process is divided up into distinct sections in time and each section is given its own individually tailored voltage and current waveforms. The welding power supply monitors the instantaneous electrical signals from the short-circuit process, identifies which stage the process is in and dynamically sets the voltage and current as desired. This is done in order to remove some of the uncertainty and irregularity of the basic short-circuit transfer mode and to individually control each part of the process in an optimal manner. The advantages are a more regular welding process with less spatter than normal short-circuit welding [Norrish, 1992] [Lincoln Electric, 1998].

The actual waveform control employed during various stages in the controlled short-circuit process can vary, but there are some principles that are common. From the time the electrode initially touches the weld pool, the current is set to a low value to help create a stable contact and to reduce spatter. After a stable contact is created, the current is quickly increased to a high value to melt a section of the electrode wire and to squeeze the molten droplet from the wire tip by electromagnetic force. Just before the short-circuit is broken, the current is quickly reduced again to reduce spatter and the short-circuit is left to break through surface tension force between the droplet and the weld pool. After the short-circuit has broken, the current can be increased again to help re-establish the arc, before being brought back down to the regular arcing current [Norrish, 1992] [Lincoln Electric, 1998].

As has previously been alluded to, the diameter of the electrode wire also affects the welding process. The mechanisms through which electrode diameter affects the process vary between transfer modes. Short-circuit transfer mode occurs when the electrode wire is not melted fast enough to stop it from touching the weld pool. The larger the electrode diameter, the more electrode metal needs to be melted and the more likely that the electrode will touch the weld pool for a given welding current. Thus as the electrode diameter increases, the welding current required to produce non-short-circuiting globular transfer also increases. As has been mentioned before, when welding in short-circuit mode, it is important to set the welding parameters such that the process is as regular as possible in order to improve weld quality and reduce spatter. The detachment of metal from the electrode occurs due to resistive heating of the electrode by the briefly very high current during a short-circuit. However the larger the electrode diameter, the higher the current required to rupture it, the larger the volume of material transferred during each short-circuit and the less regular the process. If the short-circuit current is too high, this can also result in explosive metal transfer and excessive spatter [Norrish, 1992]. Thus increasing electrode diameter in short-circuit welding leads to reduced process stability. Thus smaller electrode diameters work better with short-circuit welding and are thus suited to applications that require low welding currents where deposition rate is not the primary concern.

In globular and spray transfer modes, as outlined previously, the behaviour of the molten electrode metal is governed largely by a balance between the surface tension and electromagnetic forces. Both of these are affected by electrode diameter. The larger the electrode diameter for a given welding current, the less the electromagnetic force tends to pull downwards and the more it tends to push upwards [Norrish, 1992]. The more it does this, the more it acts against the detachment of the molten droplet from the electrode tip and the closer the transfer process moves towards globular transfer. Also, the larger the electrode diameter, the larger the surface tension force acting to hold the molten droplet at the electrode tip, which also acts to prevent droplet detachment [Norrish, 1992]. Thus through both of these mechanisms, larger electrode diameters lead to larger droplet sizes and less frequent droplet detachment, thus requiring higher welding currents to achieve a given mode of transfer. Thus larger electrode diameters are best suited to applications that require high deposition rates and high welding currents.

Now, another noteworthy welding parameter is the length of the electrode wire protruding from the contact-tip, referred to as the electrode extension. The electrode extension, plus the vertical length of the welding arc (the arc length), equals the contact-tip to workpiece distance. The electrode extension controls how much electrode wire is exposed to resistive heating by the welding current. The longer the electrode extension, the greater the effect of resistive heating on the electrode. As a result, the lower the current required to melt the electrode for a given wire feed rate and the greater the allowable wire feed rate for a given welding current [Lincoln Electric, 1998]. However in GMAW, the electrode wire is stored wound-up on spools before it is fed into the welding process. It is therefore curved and not straight when it emerges out of the contact-tip and the direction of this curvature varies in time as the wire is fed. Thus the electrode tip wanders during the welding process, affecting the location of the arc and the size and location of the weld pool. The electrode extension also controls the magnitude of this lateral movement, with longer extensions translating into greater lateral movement.

Finally, the role of the shielding gas in gas metal arc welding will be discussed. The main purpose of the shielding gas is to protect the welding process from the atmosphere. However the shielding gas also influences other aspects of the process, including the characteristics of the arc and the transfer mode, the depth of penetration, as well as the shape of the weld bead. The main shielding gases are helium (He), carbon dioxide (CO_2), argon (Ar) and various mixtures of argon and other gases including helium, carbon dioxide and oxygen (O_2).

Argon has a low thermal conductivity and a low ionization potential which makes the arc and therefore the welding process relatively very stable, but it also produces a constricted arc with high current density in the centre. This constricted arc in turn deposits heat over a small area which leads to deep but narrow "finger" (or "nipple") penetration in the substrate. Argon allows spray transfer to take place when the welding current is above the threshold level, which is a positive, since globular transfer at high currents would otherwise produce more spatter and a less regular weld bead. The low ionization potential of argon also makes it easier to strike an arc. Pure argon is often used for welding nonferrous base metals [Lincoln Electric, 1998] [Praxair Technology, 2004].

Helium has a higher thermal conductivity and higher ionization potential than argon, which means that it has reduced arc stability, but it also makes the arc broader and more even. This in turn deposits heat into the substrate over a larger area, which in turn produces broader and more even penetration. Helium also provides a higher heat input for the weld pool than argon for a given welding current and arc length, which is an advantage for applications requiring maximum heat input. However helium can not support spray transfer and is limited to short-circuit and globular transfer, with increased spatter and poorer weld regularity. Also, helium is much less dense than both air and argon, therefore flow rates of two to three times that of argon are required to maintain shielding. Pure helium is typically used for welding nonferrous metals such as aluminium, magnesium and copper alloys [Praxair Technology, 2004] [Linweld, 2004] [Lincoln Electric, 1998].

Unlike argon and helium which are inert, carbon dioxide is a reactive gas. During welding it breaks down into carbon monoxide and oxygen. The oxygen reacts with the filler metal being transferred across the arc, generating a lot of slag in the weld pool and fumes. Carbon dioxide doesn't allow spray transfer to take place and can only be used with short-circuit and globular transfer modes which are erratic, unstable and generate a low of spatter. Due to the unstable welding process, carbon dioxide produces rough and irregular weld beads. However carbon dioxide is relatively inexpensive and is often used for welding carbon and low allow steels. When welding such steels, carbon dioxide produces hot and fluid weld pools, wide and deep penetration, high levels of fusion and can accommodate higher welding speeds [Praxair Technology, 2004] [Lincoln Electric, 1998].

Because of its desirable yet incomplete properties, Argon is often mixed with other gases to add to it the advantages of the other gases. Mixtures of argon and helium are often used for welding nonferrous metals such as aluminium, copper, nickel alloys, magnesium alloys, and reactive metals. The higher heat input into the substrate and broader penetration of helium is balanced with the higher arc stability of argon. Spray transfer can also be obtained if the percentage of argon in the mixture is at least 20% [Praxair Technology, 2004] [Linweld, 2004] [Lincoln Electric, 1998].

None of the gases or gas mixtures presented thus far have been well suited to steels, with the exception of carbon dioxide. The final group of shielding gases discussed here are argon based mixtures containing carbon dioxide and/or oxygen, which are very well suited to steels and are very commonly used for the welding of steel. The addition of small amounts of oxygen to argon has the effects of further improving arc stability, reducing spatter, lowering the spray transition current, reducing undercutting and lowering heat input into the substrate. As a result, this gas mixture performs particularly well in low current short-circuit transfer for applications requiring small and shallow weld pools. The addition of carbon dioxide to argon has the effects of making the penetration broader and more even, of making the weld pool hotter and allowing the process to use higher welding speeds, though increasing percentages of carbon dioxide lead to decreasing arc stability, increasing spatter and eventually the inability to weld in spray transfer mode [Praxair Technology, 2004] [Linweld, 2004] [Lincoln Electric, 1998] [BOC Gases Australia Limited, 2004 a,b,c].

Argon based gases containing both carbon dioxide and oxygen combine all of these properties and perform well in all types of transfer modes when welding steel. As a result they are very versatile, are suitable for a wide range of steel welding applications and are very commonly used. Different blends of these three gases are available commercially, depending on the specific application. Blends containing slightly more oxygen and less carbon dioxide are especially suited for low current short-circuit applications requiring small, cool weld pools. Whereas blends containing less oxygen and more carbon dioxide are especially suited for high speed, high current, high heat input spray transfer welding, with deeper penetration and higher levels of fusion [Praxair Technology, 2004] [Linweld, 2004] [Lincoln Electric, 1998] [BOC Gases Australia Limited, 2004 a,b,c].

1.2.2 GMAW Process Monitoring and Estimation

The GMAW process is highly complex and many factors need to be balanced in order to produce a desired result. There are many welding parameters, or inputs, that have to be specified in a welding procedure. There are also many aspects of weld quality, or outputs, that have to be achieved. The final weld quality is heavily dependent on the welding procedure, yet the interaction between the inputs and outputs is highly complex in the GMAW process. Traditionally, quality welding depended heavily on the experience of the person performing the weld. Welding procedures were determined experimentally for particular welding tasks, though this necessitated the generation of new welding procedures for each new welding task. The development and testing of new weld procedures and the quality testing of the resulting welds is, however, a costly and time-consuming process [Carvalho, 1997].

For this reason much research has been carried out in the fields of GMAW modelling, process monitoring, estimation and control. Researchers have studied how various process inputs affect process outputs and automatic weld parameter selection methods have been developed [Carvalho, 1997] [Norrish, 1992]. Online weld quality monitoring systems have also been developed in an effort to improve the efficiency of weld quality testing, as well as systems for real-time control of the welding process. Doumanidis wrote that the "welder's experience with various process situations is now codified in rigorous analytical, numerical or experimental models, and his judgement during the operation is gradually superseded by real-time welding control systems" [Doumanidis, 1994]. Doumanidis also wrote that since such real-time control systems measure the welding process outputs in order to control the process inputs, they are adept at "coping with unexpected disturbances and ensuring superior joint quality and production performance" [Doumanidis, 1994]. Carvalho [Carvalho, 1997], Norrish [Norrish, 1992] and Doumanidis [Doumanidis, 1994] give information regarding weld process monitoring, estimation and control techniques.

1.2.3 Robotic Gas Metal Arc Welding

Robotic gas metal arc welding is gas metal arc welding performed by a robot instead of a human welder. A robotic gas metal arc welding cell is a welding cell consisting of all the equipment necessary for the welding process to be carried out automatically. A typical robotic welding cell may consist of the following components [Dilthey and Stein, 1991]:

- a robotic arm (actuator)
- a controller for the robotic arm
- welding power source, welding torch and other welding equipment
- a workpiece positioning system (either stationary or programmable)
- sensors for the welding process
- a computer for monitoring/controlling the welding cell
- safety devices

Dilthey [Dilthey and Stein, 1991] and Willgoss [Willgoss, 1987] provide further information about welding robots, robotic welding cells and the integration of robotic welding into computer integrated manufacturing.

Robotic welding has several advantages. Robots do not need to be qualified in welding, once given a welding program they can perform welding operations with more consistency, they have less down-time than human welders, can operate in environments that would be hazardous for humans and can perform welding operations that would be difficult or impossible to do manually.

However robotic welding also has disadvantages. Willgoss [Willgoss, 1987] stated that welding is more difficult to automate than other manufacturing processes such as milling or turning and that "the original problems of variability in welding, once catered for by a vigilant well trained welder, have come to the fore in a systematic way once mechanisation, and later automation, have been applied to the process". Since the welding is performed by a robot, the experience of a human welder is absent and control of weld quality needs to be achieved through other means. Various weld monitoring, analysis and control techniques, sometimes incorporating real-time control, may be required. The setup cost involved with a robotic welding cell can also be a disadvantage. Further information regarding the advantages, disadvantages and feasibility of automated welding is provided in WTIA Technical Note 17 [WTIA, 1986].

1.2.4 Offline Programming of Robotic GMAW

In order for a welding robot to execute a desired welding operation, the robot must be given a robot program that it can execute. There are two basic approaches to robot programming: online and offline.

Online programming involves physically moving the welding robot for which the program is intended into the required positions and saving them into the program. The robot is taken through the program step by step and taught what to do so that it can later repeat the movements. The advantages of this approach is that it is relatively simple, intuitive, requires little general programming experience from the programmer and the programmer can immediately see how the robot relates to its surroundings during program execution. The disadvantages are that this approach requires the robot to stop production while it is being taught, is usually slow and tedious and may be practically impossible for large programs that require many movements.

Offline programming on the other hand is performed away from the robot, or offline, on another system. This usually involves writing the program on a separate computer, either manually or automatically with the assistance of a suitable software package. Once the program is written it can be downloaded directly into the desired robot. There is almost no downtime associated with this approach as the robot can continue to execute the old program while the new one is being written. Writing movement instructions using a keyboard can also be quicker than physically bringing the robot to a desired position, especially when fine positioning is required. This can be made even quicker if the program is generated automatically with a software package. This is especially important when there are a large number of instructions and positions required. Libraries of old programs can also easily be created and new programs can borrow previously written code, thus further speeding up the programming process.

Offline programming does have disadvantages, however. More general programming experience is required from the programmer and the process may involve various software packages such as CAD packages, which have to be purchased, installed and tested and which require experience to use. Another serious disadvantage is that the programmer is entirely removed from the reality of the welding cell and may have little idea how the program will perform in real life. This can be a safety issue for both operators and equipment and can result in productivity losses if programs are tested on the robot and found to be incorrect. Thus the simulation of the welding cell may be required using special software packages in order to test the robot program in virtual reality.

Positional calibration is also a problem with offline programming. During the course of a welding procedure the welding robot must interact with other objects in the welding cell, such as the weldment. Determination of the precise positional coordinates of such objects relative to the robot's coordinate system may be difficult in offline programming. Such positional coordinates may need to be measured using the robot directly, through online programming. However once the positional data of a stationary object is known, the same data can then be used in other programs.

A detailed treatment of offline programming of robotic welding operations is given by Carvalho [Carvalho, 1997]. An example of research in the area of automatic computer assisted offline programming for robotic GMAW is also given by Legoff [Legoff and Hascoët, 1998].

1.2.5 Adaptive Control of Robotic GMAW

Adaptive control of robotic welding involves the incorporation of a sensory and feedback control capability into a welding cell. However a robotic welding program is generated, it may sometimes be necessary to adapt the program in real time during the welding operation in order to cope with unpredictable disturbances. Roedsted wrote that such disturbances may be caused by "inaccuracies during prefabrication, errors with positioning and deformation during welding, and they lead to inconsistent weld quality" [Roedsted and Koch, 1987].

Typical parameters that may be controlled in real time are torch position and weld path, contact-tip to workpiece distance (also referred to as standoff) and weld process parameters such as heat input, travel speed and wire feed rate [Middle and Goh, 1987]. Adaptive control of robotic welding is dealt with by Dilthey [Dilthey and Stein, 1991] and Carvalho [Carvalho, 1997].

1.3 Rapid Prototyping and Wear Replacement

1.3.1 Rapid Prototyping

Rapid prototyping is the manufacturing of objects or machine parts through use of highly flexible generic manufacturing techniques that can efficiently produce arbitrarily shaped products with minimal set-up time. Rapid prototyping is concerned with manufacturing one-off objects or objects needing only small production runs, in a much faster and more cost effective manner than is possible with conventional manufacturing techniques. It is thus valuable for reducing product development times since it is able to quickly produce prototypes of products, as well as being an economical way of producing small numbers of specialised parts. Rapid prototyping is also commonly known as "solid freeform fabrication", "layered manufacturing", "desktop manufacturing" as well as "rapid tooling" when applied to the manufacture of tooling for other manufacturing processes. The term "rapid prototyping" (RP) is used in this thesis and for the purposes of this thesis all these above terms are considered interchangeable.

Rapid prototyping is a large and rapidly growing industry with many different processes commercially available or undergoing research. These processes offer fast and flexible production of objects from a wide range of materials. They vary from being able to produce prototypes for visualisation purposes only, through to being suitable for low and medium volume production of finished products in the desired materials and with the desired engineering properties.

Most rapid prototyping processes involve the "slicing" of the desired object design into thin "slices" and the subsequent manufacturing of the object layer-by-layer until the manufactured object approximates the design. This can be done either by material addition, material removal or by a combination of material addition and removal processes. This type of methodology is central to the success of rapid prototyping since it allows for generic style manufacturing processes that do not require part-specific tooling or fixturing [Kovacevic, 1999]. More information regarding the rapid prototyping industry is provided by Conley [Conley and Marcus, 1997], Link [Link, 1999], NCMS [National Center for Manufacturing Sciences, 1998], Ramaswami [Ramaswami, 1997] and Rosochowski [Rosochowski and Matuszak, 2000].

Some of the more common rapid prototyping processes are briefly described below. These include Stereolithography (SLA), Selective Laser Sintering (SLS), Fused Deposition Modelling (FDM), Laser Engineered Net Shape (LENS), Shape Deposition Manufacturing (SDM).

Stereolithography (SLA): Stereolithography was the first commercially available and most common rapid prototyping process and relies on a laser selectively curing a liquid epoxy or plastic resin [Conley and Marcus, 1997] [Link, 1999] [Ramaswami, 1997]. The laser builds the object layer-by-layer by scanning the surface of the liquid resin and solidifying new material on top of previously solidified material. After the object is completed, it is removed from the unused liquid, cleaned and post-cured using ultraviolet light [Kietzman, 1999]. Stereolithography is thus limited to creating objects made from special photocurable resins [Conley and Marcus, 1997], however objects thus produced can be coated with metal and may be suitable for various rapid prototyping applications [Link, 1999]. Figure 1.5 shows a diagram of the stereolithography process.

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Figure 1.5: The stereolithography process [Rosochowski and Matuszak, 2000]

Selective Laser Sintering (SLS): The selective laser sintering process forms an object by fusing powder together using a laser [Kietzman, 1999]. After the laser solidifies a thin layer of powder, a roller distributes a new powder layer on top of the old and the process is repeated until the object is completed. After the object is completed, it is removed from the powder bed and any excess powder is removed [Link, 1999]. To reduce thermal stresses and laser power, the powder is kept heated at just below melting temperature so that only a small change in temperature by the laser is required to fuse the powder [Link, 1999]. An attractive feature of SLS is that the powder bed acts as a support for the solidified object layers making it easy to build overhanging or free-floating objects. Selective laser sintering can also be used for a range of applications and even though the powder used is usually a polymer, some limited success can be achieved with metal-based powders [Link, 1999]. Figure 1.6 shows a diagram of the SLS process.

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Figure 1.6: The selective laser sintering process [Castle Island Co., 2001]

Fused Deposition Modelling (FDM): FDM uses a thermoplastic wire that is fed into a heated nozzle and gets deposited on a substrate in long continuous lines to form an object [Ramaswami, 1997]. The thermoplastic filler wire gets heated to just above its melting temperature and the semi-solid wire solidifies immediately after deposition, welding itself to the substrate [Rosochowski and Matuszak, 2000]. The nozzle moves relative to the substrate and the object is formed layer-by-layer with the nozzle being moved upwards in between layers [Wenbiao and Jafari, 2000]. Usually polymers and waxes are used for the filler wire, though polymer-based metallic and ceramic mixtures are also used [Bouhal, Jafari, et al., 1999] [Conley and Marcus, 1997] [Kietzman, 1999]. The FDM process is illustrated in Figure 1.7.

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Figure 1.7: The fused deposition modelling process [Wenbiao and Jafari, 2000]

Laser Engineered Net Shape (LENS): The LENS process uses a laser to melt metal powder. The laser is focused on a point on a substrate forming a weld pool into which is blown a metal powder, causing the metal powder to melt and thus form a weld [Hensinger, Ames and Kuhlmann, 2000]. The process is also shielded from the atmosphere by a gas, which is usually argon, helium or nitrogen [Lewis and Schlienger, 2000]. Layers are formed by welding overlapping weld beads next to each other and the object is built up layer-by-layer resulting in a fully dense metal object [Lewis and Schlienger, 2000]. It is possible to use multiple metal powders such as stainless steel alloys, titanium alloys or tool steel alloys, to either deposit different metals in different regions of the object, or to create specialised alloyed objects [Hensinger, Ames and Kuhlmann, 2000] [Lewis and Schlienger, 2000]. The process results in high quality material properties and small metallic grain sizes [Hensinger, Ames and Kuhlmann, 2000]. Since LENS produces fully dense metal objects, it can be used to directly manufacture machine parts or tools for other manufacturing processes [Link, 1999]. Figure 1.8 shows a diagram of the LENS process.

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Figure 1.8: The laser engineered net shape process
[Hensinger, Ames and Kuhlmann, 2000]

Shape Deposition Manufacturing (SDM): Shape deposition manufacturing is a rapid prototyping process that involves both material deposition and removal [Ramaswami, 1997]. The deposition can be carried out by welding-based processes such as laser welding, microcasting, extrusion or casting and the material removal is usually carried out by CNC milling [Cooper, 1999] [Kietzman, 1999]. The deposition and milling operations alternate during the build process as required [Kietzman, 1999]. Stress relief may also be employed during the object build process [Merz, Prinz, et al., 1994]. Microcasting employs a modified GMAW welding torch that establishes an arc between a filler wire and the torch itself, so that the filler wire melts and large molten metal droplets detach and free-fall to the substrate [Amon, Beuth, et al., 1998].

As well as depositing the material that makes up the object, SDM also deposits a sacrificial support material during the build process that surrounds the object and is removed at the end of the process by either melting or etching [Ramaswami, 1997]. Instead of using very thin layers of material to build an object, the use of a support material and CNC milling allows SDM to use adaptive near-net-shape material layers or "compacts" with sloping sides to approximate the object [Kietzman, 1999] [Ramaswami, 1997]. This enables the manufacture of complex geometric features such as undercuts and conformal cooling channels [Link, 1999]. Shape deposition manufacturing has the ability to produce fully dense objects from a wide variety of materials and it can be used to directly manufacture machine parts or tools for other manufacturing processes. A picture of the SDM process is shown in Figure 1.9.

Please see print copy

Figure 1.9: The shape deposition manufacturing process [Kietzman, 1999]

Further information about these and the many other rapid prototyping processes in existence is given by Amon [Amon, Beuth, et al., 1998], Conley [Conley and Marcus, 1997], Cooper [Cooper, 1999], Kietzman [Kietzman, 1999], Link [Link, 1999], Merz [Merz, Prinz, et al., 1994], Ramaswami [Ramaswami, 1997] and Rosochowski [Rosochowski and Matuszak, 2000].

1.3.2 Rapid Prototyping by Robotic GMAW

Rapid prototyping by robotic gas metal arc welding (GMAW) is a rapid prototyping process that uses gas metal arc welding to deposit molten weld metal where it is needed in order to form an object. A robot guides the welding torch along a substrate, depositing weld beads on top of other previously deposited weld beads as required. Because the GMAW process involves local remelting of the substrate and the addition of molten filler metal, rapid prototyping by GMAW has the ability to create dense objects and is suitable for direct manufacturing of metal parts. Gas metal arc welding is also a widely researched and well established process and rapid prototyping by GMAW can be performed using various metals and using readily available equipment. Some illustrations of the rapid prototyping by GMAW process and its applications are shown in Figures 1.10 to 1.15.

Please see print copy

Figure 1.10: The RP by GMAW process [after: Ribeiro, 1999]

Please see print copy

Figure 1.11: Close-up of the RP by GMAW process
[Skordeli and Doumanidis, 1999]

Please see print copy

Figure 1.12: Photograph of the RP by GMAW process [Ribeiro, 1999]

Please see print copy

Figure 1.13: Photograph of a welded object [Ribeiro, 1999]

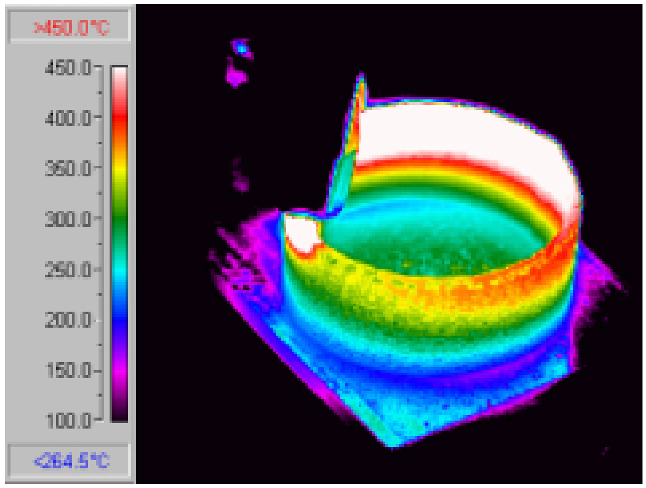

Figure 1.14: Thermal image of the welding of a hollow cylinder

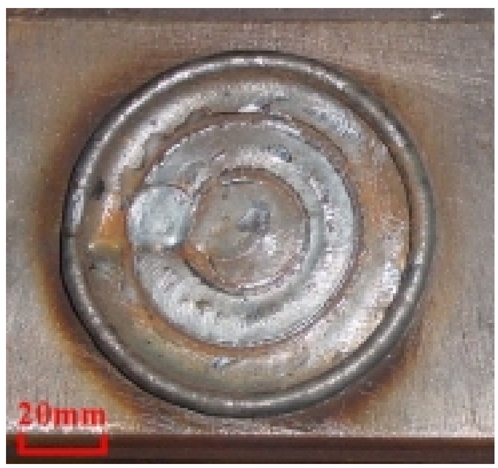

Figure 1.15: Photograph of a layer of a solid cylinder

The advantages of rapid prototyping by GMAW are that it:

- Creates fully dense metal parts with full metallurgical bonding
- Is suitable for direct manufacturing of fully functional metal parts
- Uses gas metal arc welding which has been widely investigated and is well established
- Uses readily available off-the-shelf equipment
- Can achieve high speed [Kovacevic and Beardsley, 1998]
- Is relatively low cost [Kovacevic, 1999]
- Produces very little waste of material

The disadvantages of rapid prototyping by GMAW are:

- High substrate temperatures, residual stresses and warpage
- Relatively poor dimensional accuracy and surface quality
- Thermal and geometric instability
- High potential for weld defects and unfilled voids
- Metal deposition coupled to heat deposition and process relatively difficult to control

Early rapid prototyping by robotic welding and the related process of cladding by robotic welding can be traced back as far as the 1940's [Carpenter and Kerr, 1947] [Harter, 1942]. Investigation into these processes continued through the 1960's and 1980's, when they acquired names such as "shape melting" and "shape welding", notably by companies such as Krupp, Thyssen, General Electric, Hitachi, Boeing and especially Sulzer and Babcock & Wilcox [Dickens, Pridham, et al., 1992] [Kussmaul, Schoch, et al., 1983] [Pacheco, 1993] [Dekumbis, Marsden, et al., 1992] [Geisseler, 1987] [Ludwig, 1981] [Ayres, Edmonds, et al., 1988] [Doyle and Ryan, 1989] [Doyle, Edmonds, et al., 1989] [Edmonds and McAninch, 1988] [Malone, McAninch, et al., 1990]. Most of this research was directed at the creation or modification of large rotationally symmetrical objects. Rapid prototyping by welding of arbitrarily shaped asymmetrical objects of any size first appeared in the early 1990's, most notably in the Sulzer patent by Schneebeli which presented the key concepts of the modern process, but also through the work of other researchers such as Dickens [Schneebeli, Braun, et al., 1993] [Dickens, Pridham, et al., 1992].

Dickens [Dickens, Pridham, et al., 1992] and Spencer [Spencer and Dickens, 1995] [Spencer, Dickens, et al., 1998] researched various aspects of RP by GMAW, including various effects that weld path generation can have on weld and object quality. They investigated object surface quality, weld temperatures and the residual stresses caused by the welding process. They showed that RP by GMAW requires high quality regular welds and investigated the effects of varying various weld parameters on weld and object quality. They performed mechanical and material testing on objects produced by this process and showed that in the absence of weld defects such as voids and lack of penetration, "parts produced by the 3-D welding process have good structural integrity and property levels which would allow them to be exploited in service conditions" [Dickens, Pridham, et al., 1992].

The role of welding parameters in rapid prototyping by GMAW and the mechanical properties of objects produced with this process were also researched by Jacono and De Boer, who concentrated on welding with mild steel [De Boer, Jacono, et al., 2000] [Jacono, 1999]. Jacono found a range of welding parameters that could be successfully used to produce high quality single weld thickness walls, but also found that this range is narrow and that such walls are very sensitive to the weld parameters used. He also proved that if weld defects are not present, the mechanical properties of welded objects are just as good as those of the parent filler wire metal.

Another noteworthy form of rapid prototyping by welding that should be mentioned at this point is rapid prototyping by gas tungsten arc welding (GTAW). This form of rapid prototyping is the same as rapid prototyping by GMAW, except that is uses the GTAW welding process. The GTAW process is similar to GMAW, except that the arc is created between the workpiece and a non-consumable tungsten electrode, instead of a consumable electrode like in GMAW. A filler wire is then fed directly into the weld pool by a separate wire feeding mechanism, such that the wire is always fed in front of the moving arc.

The GTAW process has a number of advantages over the GMAW process that can be very useful for rapid prototyping. The GTAW process is inherently more stable and easier to control than the GMAW process, because the position and shape of the electrode tip do not vary and because heat deposition is decoupled from material deposition [Kovacevic, 2001]. As a result, it can produce higher quality weld beads to a higher level of precision and is commonly used for high quality welding applications [Advantage Fabricated Metals, Inc., 2003] [Kovacevic, 2001]. GTAW is also particularly good at performing low heat input, low temperature welding and can produce welds with low levels of distortion [Advantage Fabricated Metals, Inc., 2003]. As well as this, GTAW can also be used to weld more exotic metals than GMAW and does not produce slag or spatter [Advantage Fabricated Metals, Inc., 2003]. However disadvantages of robotic GTAW are that it is slower than GMAW and requires more complex and more expensive equipment [Advantage Fabricated Metals, Inc., 2003] [TM Technologies, 2004] [Kovacevic, 2001].

Rapid prototyping by GTAW has been under investigation in parallel to rapid prototyping by GMAW and the two processes share many of the same problems and challenges. Rolls Royce investigated the direct manufacture of aircraft engine parts made of nickel and titanium based alloys using rapid prototyping by both GMAW and GTAW, in conjunction with Cranfield University in the 1990's [Dickens, Pridham, et al., 1992] [Norrish, 2004]. Direct manufacture through rapid prototyping was looked at in order to reduce the levels of waste of the expensive alloys compared to conventional material processing techniques. The feasibility of this approach was initially proven by Brian Benn and Tony Pratt, of Rolls Royce and by John Norrish, John Saville and Antonio Fernando Ribeiro, of Cranfield University [Norrish, 2004] [Ribeiro, 1998] [Ribeiro and Norrish, 1997]. Subsequently this process was developed to the point of industrial application at Cranfield University by Stephen Blackman and John Saville [Norrish, 2004]. Recently, Rolls Royce have been continuing their research into rapid prototyping by both GMAW and GTAW in conjunction with Nottingham University, under Richard Harvey and Graham McCartney [Knight, 2003] [McCartney, 2004]. Rolls Royce use the process to produce parts for its Trent 800 engine for the Boeing 777 and claim that it can drastically cut production time compared to conventional techniques [Knight, 2003].

The specific research of Antonio Fernando Ribeiro was aimed at the welding of objects by GMAW whose cross-sections are only one weld bead in thickness [Ribeiro, 1998] [Ribeiro and Norrish, 1997]. Ribeiro developed a completely automated RP by GMAW cell for the welding of such objects. As part of this welding cell he developed an automated weld path and robot program generation system. As well as this, he carried out work on weld parameter prediction and also found that the quality of objects produced is highly dependent on the weld parameters used. However Ribeiro's work was only applicable to the welding of thin-walled objects and is not transferable to the welding of objects with thicker cross-sections.

A weld path and weld parameter generation system suitable for the rapid prototyping of thick objects by GMAW was developed by Zhang [Zhang, Li, et al., 2002]. Zhang's software system could analyse CAD drawings of objects and automatically generate weld paths and weld parameters intended for the welding of the object. Zhang also investigated some problems associated with weld paths, such as what happens at weld corners and weld starts and he proposed some solutions.

Kovacevic undertook research directed at improving the predictability and control of the GMAW metal transfer process, in an effort to produce smoother and more regular weld beads as is required in rapid prototyping by GMAW [Kovacevic, 1999] [Kmecko, Hu, et al., 1999]. He also used finite element modelling to analyse temperatures and weld penetration in rapid prototyping by GMAW and discussed the roles of heat input, weld temperatures, cooling cycles, microstructure and weld bead dimensions [Kovacevic and Beardsley, 1998]. Kovacevic also investigated the control of heat input in rapid prototyping by GTAW when welding in regions of a substrate with localised variations in heat transfer conditions, such as edges and corners, in order to produce consistent weld bead geometry [Jandric and Kovacevic, 2001].

The effects of heat input on residual stresses and object deformation were also investigated by Matthes [Matthes and Alaluss, 2001]. Matthes used finite element modelling to analyse temperature, stress and deformation in straight line bead on plate welds that had been welded on top of each other. Matthes confirmed the findings of previous researchers, concluding that residual stresses can be very large and problematic in RP by GMAW and can lead not only to deformation but also cracking.

Rapid prototyping by GMAW in a slightly different form has been researched by Karunakaran [Karunakaran, Shanmuganathan, Jadhav, et al., 2000] [Karunakaran, Shanmuganathan, Roth-Koch, et al., 1998], Song [Song, Park, et al., 1998] [Song, Park, et al., 1999], as well as Kmecko and Kovacevic [Kmecko, Hu, et al., 1999]. These researchers developed a rapid prototyping system based on a combination of GMAW and CNC milling. The system is both additive: material is added on top of previously deposited material using the GMAW process; and subtractive: unwanted material is machined away. The milling capability has the particular advantage of being able to produce high surface and dimensional quality independently of the welding process. Song also investigated how various welding parameters affect his RP system, including some effects on hardness and microstructure. Karunakaran, on the other hand, also investigated the application of adaptive slicing for his RP system.

Researchers at Tufts University have developed control systems which guide the welding process in real time, for GMAW and for GTAW. Doumanidis developed the "scan welding" process, which uses a control system and temperature feedback to control the temperature field in a substrate in real-time by controlling the welding torch motion and heat input in real-time [Doumanidis, 1994] [Doumanidis and Fourligkas, 1997]. He successfully applied this system to rapid prototyping by GMAW, achieving real time weld path and temperature control.

Doumanidis and Skordeli also developed a system for real time weld path control for RP by GMAW based on geometric modelling [Doumanidis and Skordeli, 2000] [Skordeli and Doumanidis, 1999]. They developed a 3D geometry model of a surface being generated by droplet-based deposition processes. The model treated droplets of deposited material as spheres and estimated deposited surface geometry using summations of spherical elements. This model was used to develop a real time control system for the regulation of surface geometry in real time through control of the torch motion and wire feed rate. They successfully used this system for RP by GMAW and controlled the welding process as required to bring the deposited surface to the desired geometry.

1.3.3 Wear Replacement

Wear replacement is the repair of worn metallic components or machine parts. Wear replacement uses a welding process to deposit metal onto the surface of a part to build up the surface of the part until it reaches the desired geometry. In this way, material that had been missing from the surface of the part through wear or other damage is replaced by new material from the welding process.

However this technique is not restricted to just replacing missing material from old parts. It is also used to give parts, both new and old, various surface properties not found in the base material. Specially selected welding processes, consumables and welding procedures can be used to control surface composition and microstructure in order to give the components greater resistance to wear, corrosion, heat and other forms of damage [Sun and Ang, 2002]. Such techniques are often referred to as surfacing, cladding, hardfacing, reclamation, repair welding, as well as wear replacement. However for convenience, the term wear replacement is used in this thesis and is taken to encompass all of these techniques and applications. Research into the customisation of surface properties of a component through wear replacement, is however outside the scope of this thesis.

Wear replacement is a complex process requiring careful selection of welding process and consumables and careful development of the welding procedures in order to achieve the desired outcomes. Nevertheless, the cost savings gained by repairing used parts instead of replacing them and extending their service life by giving them more desirable surface properties, are significant [WTIA, 1996 b] [Drews and Cordes, 1990]. Thus wear replacement is widely used in industries that experience extreme surface conditions, such as mining [WTIA, 1996 b] and power generation.

Examples of research into the welding repair and surfacing of turbines and other power generation equipment are Doumanidis [Kwak and Doumanidis, 1999], Lau [Lau, Lau and Poon, 1996], Magnier [Magnier and Segura, 1999], Tinkler [Tinkler, Fihey, et al., 1991] [Tinkler, McNabb, et al., 1987] and Yushchenko [Yushchenko and Savchenko, 2000]. A photograph of a nuclear steam turbine half joint repaired using wear replacement is shown in Figure 1.16.

Please see print copy

Figure 1.16: A nuclear steam turbine half joint repaired using wear replacement [Lau, Lau and Poon, 1996]

Wear replacement is thus similar to rapid prototyping in that a flexible, generic manufacturing technique is used to "create" material. Only in wear replacement, the material is created on top of previously existing material to modify an existing object, rather than creating a wholly new object. Also, while rapid prototyping can be performed in a wide spectrum of materials and using a wide spectrum of processes, wear replacement is more restricted. Wear replacement needs to create material that is dense, with full metallurgical bonding, that is ready for service conditions.

A wide range of welding processes can be used for wear replacement applications. While just about any fusion welding process can be used, the most common processes are [Sun and Ang, 2002] [WTIA, 1996 b]:

- Manual metal arc welding (MMAW)
- Gas metal arc welding (GMAW/MIG/MAG)
- Flux cored arc welding (FCAW)
- Gas tungsten arc welding (GTAW/TIG)
- Submerged arc welding (SAW)
- Plasma arc welding
- Laser beam welding

More information regarding the various welding processes that are used for wear replacement, including their advantages and disadvantages, characteristics and typical applications, is given by Sun [Sun and Ang, 2002] and by WTIA Technical Note 4 [WTIA, 1996 b]. More information about wear replacement using laser welding is given by Alam [Alam, Harris, et al., 2002], while further information about FCAW is given by Aloraier [Aloraier, Ibrahim, et al., 2002] [Shehata, Aloraier, et al., 2002].

1.3.4 Wear Replacement by Robotic GMAW

Wear replacement by robotic GMAW is wear replacement performed automatically by a robot using the gas metal arc welding process. The GMAW process is economical and has a high deposition rate, compared to the MMAW and GTAW processes [Sun and Ang, 2002] [WTIA, 1996 b]. It can weld in all positions and is good for general purpose wear replacement applications [WTIA, 1996 b]. Compared to the other processes, the GMAW process is also particularly suited to automation, with most industrial arc welding robots being designed to work with GMAW [Sun and Ang, 2002] [WTIA, 1996 b].

However, a major issue in wear replacement in general is the need for improvement in deposited surface regularity and the need for high geometrical precision. The required surface quality depends on the application; for example a high surface quality is required for machine parts, whilst for ground engaging tools a relatively rough surface finish is often acceptable. A problem in wear replacement by GMAW is that the GMAW process is not naturally suited to high geometrical precision and it tends to produce ridges and valleys in the deposited surfaces, which can reduce the mechanical properties of components [Sun and Ang, 2002].

Automating the wear replacement process has been an attractive field of development for some time [Drews and Cordes, 1990] [Kwak and Doumanidis, 1999] [Magnier and Segura, 1999] [Tinkler, Fihey, et al., 1991] [Tinkler, McNabb, et al., 1987]. Automated wear replacement has significant advantages over manual wear replacement and its continuing development is being pushed by the demands of industry [Sun and Ang, 2002]. Automatic wear replacement has the advantage of being able to produce higher quality products with higher consistency, has higher productivity and removes the hazards associated with manual welding in difficult and dangerous conditions [Drews and Cordes, 1990] [Sun and Ang, 2002] [Tinkler, Fihey, et al., 1991].

1.3.5 Rapid Prototyping and Wear Replacement by Robotic GMAW

Rapid prototyping and wear replacement by robotic GMAW are very similar processes. Both involve the deposition of weld metal on top of previously deposited weld metal in order to fill a desired volume and create a shape out of fully dense metallurgically bonded metal. Both use the same welding process as the means of depositing new metal and fusing it to the previously deposited metal and both are automated and use robots to perform the welding.

The main difference between the two processes is that rapid prototyping usually starts with a flat metal base plate on top of which a new part is created. Also, rapid prototyping can include the creation of finer, more geometrically complex shapes since it is used to create new parts that may have small and complex features. On the other hand, wear replacement starts with an existing part that is almost always not flat, on top of which material is added to modify the part. Thus automated wear replacement needs to include some sensing mechanism through which the existing part geometry can be measured, before the shape to be deposited can be determined [Drews and Cordes, 1990].

The similarities between rapid prototyping and wear replacement by robotic GMAW often allow these two processes to be investigated together. Improvements in shape deposition intended for one process can often be applied to the other process. For convenience, the term rapid prototyping will be used throughout the rest of this thesis. However, it is intended to encompass the creation of shapes using weld metal deposited by the robotic GMAW process for both rapid prototyping and wear replacement.

1.3.6 Automatic Weld Path Generation

Both rapid prototyping (RP) and wear replacement (WR) by robotic GMAW require the generation of weld paths that the welding torch can follow. By its nature, the GMAW process can be regarded as a point source of material and heat, which welds by moving relative to a workpiece along desired weld paths. In manual welding, the manual welders choose the weld paths intuitively. However robotic GMAW requires the generation of precise weld paths and welding programs, complete with welding parameters, that a welding robot can understand.

In order for the RP and WR by robotic welding processes to be truly automatic, the weld paths complete with welding parameters need to be generated automatically. However, the analysis of a particular object that is to be produced and the generation of the welding procedures that are to be used by the robot can be a highly complex task. It is also a very important task, since as Sarma states, "the geometric and functional properties of the end product are dependent on the trajectory of the tool" and "the trajectory dictates the accuracy of the end product and the time taken to manufacture the product" [Sarma, 2000]. For an automatic RP or WR system to be viable, weld path generation needs to be carried out in a manner that is efficient, practical, robust and requires as little operator input as possible.

Automatic weld or tool path generation in general is not new. Automatic cutting tool path generation and optimisation in CNC machining has been investigated extensively. Tool path generation in other forms of RP, such as fused deposition modelling and LENS, has also been well investigated. Examples of these investigations include: Cooper [Cooper, 1999]; Dong [Dong, Kao, et al., 1999]; Hensinger [Hensinger, Ames, et al., 2000]; Horváth [Horváth, Vergeest, et al., 1998]; Kamarthi [Kamarthi, Bukkapatnam, et al., 2000] [Kamarthi, Pittner, et al., 1997]; Kao [Kao and Prinz, 1998]; Langrana [Langrana, Qiu, et al., 2000]; Nickel [Nickel, Barnett, et al., 2001]; Pang [Pang, Joneja, et al., 2001]; Rajan [Rajan, Srinivasan, et al., 2001]; Ramaswami [Ramaswami, 1997]; Tai [Tai, 1997]; Tangelder [Tangelder, Van Den Belt, et al., 1995]; Tarabanis [Tarabanis, 2001]; Tse [Tse and Chen, 1997]; Vosniakos [Vosniakos and Papapanagiotou, 2000]; Wah [Wah, Murty, et al., 2002]; and Wenbiao [Wenbiao and Jafari, 2000].

However such research into tool or weld path generation for other processes does not consider the particular characteristics and limitations of RP and WR by the robotic GMAW process and is not directly transferable. RP and WR by robotic GMAW has intrinsic properties that differ significantly from other RP processes and these greatly affect the performance of the process and the task of weld path generation. Particular features of the RP and WR by GMAW process such as high substrate temperatures, residual stresses and warpage, relatively poor dimensional accuracy and surface quality, thermal and geometric instability, high potentials for weld defects and unfilled voids, metal deposition being coupled to heat deposition and the process being relatively difficult to control, all make weld path generation more difficult.

Kovacevic wrote that most research into tool path generation (prior to 1999) "focused on developing software to transfer CAD data into instructions for positioning systems" and that "the importance of understanding and controlling the metal transfer process in GMAW was not recognized as one of the key issues in controlling the quality of the resultant weld and/or generated layer of metal for rapid prototyping" [Kovacevic, 1999].

Comprehensive automatic weld path generation systems for RP and WR by robotic GMAW that consider all the various characteristics and limitations of the process pertinent to weld path design have not yet been developed. More research into path generation that takes into consideration the complexities of the deposition system and its relationships with the properties of the final product is required. This was recognised by Sarma who states that further research is required into the effects of deposition paths on "the geometric properties" and "the functional properties of the manufactured shape" for various forms of RP [Sarma, 2000].

Weld path generation, complete with weld parameters, for RP and WR by robotic GMAW can be highly complex. This is due to the many complex and inter-related phenomena that occur during the object creation process, all of which affect the geometric, mechanical, microstructural and other properties of the finished object. The weld procedures that are used during the object building process affect all of these phenomena and the final object properties. While much is known about the GMAW process when applied to materials joining, this knowledge does not suffice for weld path generation for the rapid prototyping process, since the criteria for high quality joint welding differ from the criteria for high quality rapid prototyping [Kovacevic, 1999].

The weld paths used to build an object affect the geometry and regularity of every single weld created and can contribute to the presence of weld defects in every weld. As well as affecting the properties of individual welds, they also affect the geometry, regularity and surface smoothness of the object as a whole and can lead to poor mechanical properties if weld defects or voids are present.

The heating and cooling history at different points in the object also depend on the geometric and thermal aspects of the weld paths. In turn, thermal conditions within the object affect the level of remelting of previously deposited metal and fusion with newly deposited metal, thermal stresses, weld defects and the surface temperatures prior to later weld bead deposition. The surface temperatures of the previous weld bead affect the way in which a new weld solidifies and the time it takes to solidify, the shape of the weld bead, the likelihood of weld defects occurring and the surface smoothness of the object. The thermal conditions and history that material at various locations within the object is subjected to also affect material microstructure, residual stress and the object's mechanical properties. Finally, the weld paths also determine the total length of time it takes to build the object.

Examples of weld procedures producing inadequate properties of objects rapid prototyped by robotic GMAW are shown in Figures 1.17-1.19.

Please see print copy

Figure 1.17: Cross-section of rapid prototyped object showing lack of fusion [Jacono, 1999]

Please see print copy

Figure 1.18: Cross-section of rapid prototyped object showing excessive remelting and loss of geometric accuracy [Jacono, 1999]

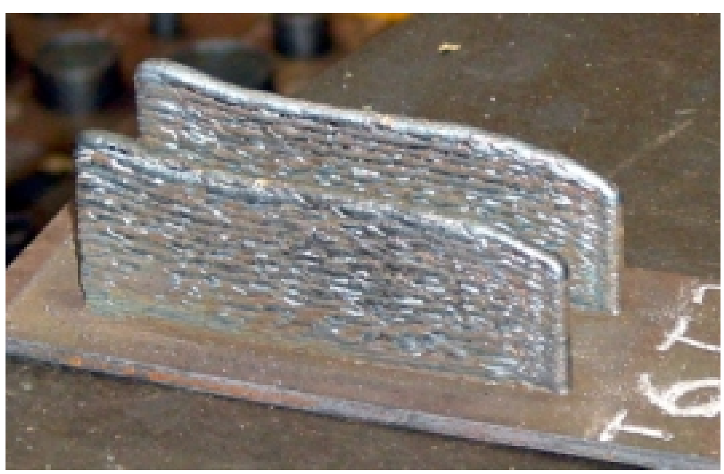

Figure 1.19: Rapid prototyped thin metal walls showing irregular geometry and poor surface regularity

1.3.7 Geometric and Thermal Stability Problems in Rapid Prototyping by GMAW

A major problem with rapid prototyping by the GMAW process has been found by previous researchers to be geometric and thermal instability. It was found that as the build procedure of an object progresses and more and more layers of weld metal are deposited, the geometric accuracy and precision as well as the thermal conditions within the object deteriorate. These are major problems because they reduce the quality of the finished object and make weld path design and process control more difficult.

Dickens found that "heat build up due to the welding process can cause earlier welding passes to remelt and cause part distortion or collapse of the structure" [Dickens, Pridham, et al., 1992]. He also found 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" [Dickens, Pridham, et al., 1992]. He added 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, Pridham, et al., 1992].

These findings relating to geometric and thermal instability were echoed by Spencer, who wrote that as an object was being built "excess residual heat not only affected surface finish [of the object] but also the bead height, due to delayed solidification" resulting in "large amounts of porosity, poor surface finish and increased material flow" [Spencer, Dickens, et al., 1998]. Spencer also recognised that the contact-tip to workpiece distance varies undesirably during a build procedure, due to variations in weld bead height caused by retained heat and that this causes losses in weld and object quality [Spencer, Dickens, et al., 1998].

The presence of geometric instability in RP by welding was also reported by Song. Song stated that dimensional accuracy in RP is very important, describing it as a "critical issue…for the currently used rapid tooling techniques" [Song, Park, et al., 1998]. He described the deterioration of dimensional accuracy as an object progresses through the build process, 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].

Kmecko stated that poor geometrical qualities are a result of "small defects in the previous layer that become more and more amplified in subsequent layers" [Kmecko, Hu, et al., 1999]. In an effort to reduce weld irregularities that would then accumulate into large defects, Kmecko investigated metal transfer control for RP by GMAW in order to produce more regular welds. However he reported that despite this research, "the rapid prototyping process based on 3-D welding alone does not provide satisfactory dimensional accuracy and surface quality" [Kmecko, Hu, et al., 1999]. He concluded that "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].

Finally, similar problems associated with geometric and thermal stability were also observed during preliminary welding trials performed by the author at the University of Wollongong.

To overcome or control some of the problems stemming from this geometric and thermal instability, past researchers have adopted various research directions, as previously outlined in the introductory section on rapid prototyping by robotic GMAW in this thesis. Dickens and Spencer investigated the effects of various weld settings as well as weldment temperature on object quality [Dickens, Pridham, et al., 1992] [Spencer and Dickens, 1995] [Spencer, Dickens, et al., 1998]. Zhang investigated the effects of weld settings, developed a strategy where weld paths from stacked weld layers are rotated to help reduce the effects of error accumulation and identified that regions near weld starts and weld ends are particularly prone to errors and defects and proposed some solutions [Zhang, Li, et al., 2002].

As mentioned previously, Kovacevic and Kmecko investigated the GMAW metal transfer process in an effort to reduce geometric instability by producing more regular welds [Kovacevic, 1999] [Kmecko, Hu, et al., 1999]. They [Kmecko, Hu, et al., 1999], as well as Karunakaran [Karunakaran, Shanmuganathan, Jadhav, et al., 2000] [Karunakaran, Shanmuganathan, Roth-Koch, et al., 1998] and Song [Song, Park, et al., 1998] [Song, Park, et al., 1999], also investigated a modified form of rapid prototyping that relied on the GMAW process for metal deposition and the CNC milling process for material removal, so that the material removal process could remove the effects of the geometric instability. Also, Jandric and Kovacevic researched the control of weld bead dimensions through control of the weld settings when welding in regions with localised differences in heat transfer conditions [Jandric and Kovacevic, 2001].

Finally, Doumanidis and Skordeli took a very different approach. Instead of relying on regular welds, open-loop weld path design, or on machining, they investigated various on-line control systems that could control the welding procedure and guide the welding torch in real time [Doumanidis, 1994] [Doumanidis and Fourligkas, 1997] [Doumanidis and Skordeli, 2000] [Skordeli and Doumanidis, 1999].

1.3.8 Effects of Weld Path Strategies on Stability of Rapid Prototyping by GMAW

This thesis adopts a different approach to addressing the geometric and thermal stability problems with rapid prototyping by GMAW. It focuses on the role played by weld path design strategies by studying how they affect the stability of the process. The thesis tests the effects that weld path design can have on process stability and examines the usefulness of open-loop weld path design as a tool for improving process stability and performance. The improvement of process stability through weld path design is investigated by testing and comparing a range of weld path design alternatives.

Material removal such as CNC milling is not considered and is assumed not to be a part of the rapid prototyping process. This is in order to focus on improving the deposition process, which in turn could be used to improve rapid prototyping both with and without material removal. Thus even though it is not considered, this research is also applicable to rapid prototyping that uses a combination of welding and machining, where it could be used to reduce the amount of material removal required. According to Jandric, a disadvantage of the rapid prototyping by welding and milling process is its relatively slow speed [Jandric and Kovacevic, 2001]. However, Jandric also stated 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 could be eliminated" [Jandric and Kovacevic, 2001].

Real-time process sensing, feedback control, adaptive programming and real-time welding torch motion control are also not considered in order to focus on improving the process stability through open-loop weld path design. A better understanding of how open-loop weld path design affects process stability would improve rapid prototyping systems that do not employ real-time control. However knowledge of the open-loop behaviour would also help to improve the control of closed-loop systems if closed-loop control is deemed to be desirable.

1.4 Thesis Objective

The objective of this thesis is to study the effects of weld path design strategies on the stability of rapid prototyping (RP) and wear replacement (WR) by the gas metal arc welding (GMAW) process, in order to test whether open-loop weld path design can be used to improve process stability and part quality. The hypothesis adopted here is that improved geometric and thermal stability should be possible if the material and heat input are optimised by control of the weld path through open-loop weld path design. This is to be done by firstly identifying and cataloguing the open-loop tool path design strategies adopted for the RP and WR by GMAW process that appear in literature. Secondly, by trialling various weld path design strategies and investigating aspects of their performance, in order to ascertain the usefulness of open-loop weld path design as a tool for improving process stability and performance. Then finally, by testing and comparing a selection of alternative weld path design strategies to further investigate their effects on stability and to establish which strategies perform best.

An empirical approach is adopted for the study of the effects of open-loop weld path design on process stability. This approach was adopted in order to avoid the complexities associated with physical modelling and finite element analysis in order to perform a broad study encompassing a range of weld path design strategies tested under a range of conditions. Restricted finite element analyses of the RP and WR by GMAW process are highly complex, whereas broad analyses encompassing the many phenomena involved are nearly impossible [Kovacevic and Beardsley, 1998]. A broad study is deemed to be necessary in order to make a substantial contribution to the success of the RP and WR by GMAW process in general.

The weld path design strategies were tested and compared against the following criteria:

- Geometric stability of welds and weld layers
- Thermal stability of welds and weld layers
- Minimisation of weld defects such as porosity, inclusions, lack of fusion and unfilled voids
- Minimisation of build time

Geometric stability is defined in this thesis to mean the uniformity and predictability of the shape of deposited weld beads and weld layers. It is directly linked to the dimensional accuracy and surface quality of objects produced, both of which are vital to the success of the RP and WR by GMAW process. The geometric stability of every single weld produced affects the stability of every subsequent weld bead. These in turn affect the geometric stability of all weld layers and thus the stability of the whole object. Geometric stability can also affect weld defects such as unfilled voids and porosity.

Thermal stability is defined in this thesis to mean the uniformity and predictability of the weldment surface temperatures on top of which welds are made. As welds are made, the surface temperatures at different points on the substrate change. Thermal stability is related to geometric stability since surface temperature affects weld bead shape, the amount of remelting of previously deposited weld metal and the surface smoothness of the object. Thermal stability also affects the depth of penetration of weld beads and weld defects such as inclusions and lack of fusion.

Weld defects need to be minimised since they reduce the mechanical properties of the object and reduce its functionality. Minimisation of weld defects is thus necessary if rapid prototyping and wear replacement by GMAW is to be viable. Yet care needs to be taken when designing weld paths, since the potential for weld defects is high.

The final criteria considered is build time, since it is desirable to speed up the build process by minimising the time taken to build a single weld layer or a whole object.

The measurement, comparison and optimisation of residual stresses is not considered and is outside the scope of this thesis. Open-loop weld path design would naturally affect residual stresses, however this would be a topic for further research. For the purposes of this thesis, it is thus assumed that any residual stresses in the objects produced can and should be removed after the build process is complete by heat treating the entire object.

The welding and base plate material is limited to plain carbon steel. Plain carbon steel is used in order to avoid complexities arising from complex microstructures and heating cycles. The measurement, comparison and optimisation of metal microstructure and the effects of multiple and varied heat cycles are considered to be outside the scope of this thesis and a topic for further research. For the purposes of this thesis, it is assumed that microstructure can be adequately controlled through heat treatment of the entire object after the build process is complete. The outcomes of this research may be extended to welding metals other than plain carbon steel on the condition that the same assumption can be made.

The mechanical properties of objects produced, such as tensile strength and toughness, are not measured or compared. Previous research has shown that objects rapid prototyped by robotic GMAW have similar mechanical properties to the electrode wire metal and are suitable for service conditions, as long as they are defect-free [Dickens, Pridham, et al., 1992] [Jacono, 1999]. Thus the presence of weld defects is used in this thesis as an indicator of mechanical properties, where an absence of defects signifies adequate mechanical properties.

1.5 Thesis Outline

The introduction to the thesis is given in Chapter 1.

Chapter 2 is the literature survey, wherein is presented past research into the areas of geometric and thermal instability in RP and WR by GMAW, as well as various styles and methodologies of open-loop weld and tool path design.

Chapter 3 rationalises and catalogues different weld path design strategies that can be applied to RP and WR by GMAW, illustrates and describes them and indicates which ones will be tested in this thesis.

A description of the experimental hardware and software used in this thesis is given in Chapter 4.

Chapters 5 to 7 present the preliminary path strategy sensitivity experiment which trials various weld path strategies, examines some of their effects on process stability and performance and ascertains the usefulness of open-loop weld path design as a tool for improving process stability and performance.

Chapters 8 to 10 present the weld path strategy comparison experiment which tests and compares a selection of alternative weld path strategies in order to further investigate their effects on stability and to establish which strategies perform best.

The outcomes of the thesis are discussed in Chapter 11 and the conclusions and suggestions for further research are presented in Chapter 12.

The references are given after Chapter 12, followed by the appendices.