Paper VI

Off-Line Programming or Robots for Metal Deposition

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Abstract

Metal Deposition (MD) is a rapid prototyping technique to build parts by depositing metal in a required fashion. When a complex-shaped part is to be built, a simulation tool is needed to define robot trajectories. Three different simulation-based methods for robot trajectory generation are introduced and compared in this study. The methods are; reversed milling, adapted rapid prototyping and application programming in a computer aided robotics software. All methods were shown capable of creating robot paths for complex shapes, with the CAR software approach being the most flexible. Using this method, the geometry to be built is automatically sliced into layers and a robot path is automatically generated. The method was tentatively evaluated and appears to provide a powerful technique in the design and optimisation of robot paths for MD. Experiments showed that it is possible to manufacture fully dense parts using an Nd-Yag laser.

1 Introduction

Many of the complex-shaped components, especially those used in the aerospace and automobile industries, are manufactured by casting or forging. Components made by these processes require extensive machining and finishing operations before they can actually be used. If the production volume is low then the production cost for each component is likely to be rather high. Manufacturing by moulding is also a rather inflexible method since it is necessary to change the complete mould in order to effect a change in component geometry. The development of alternative manufacturing methods is therefore of significant interest.

One interesting alternative is metal Rapid Prototyping (RP) often referred to as Metal Deposition (MD). MD has the potential to be used to manufacture a new part, to add features to an existing part, or to repair worn parts. The technique uses a welding heat source to melt a powder or a wire material which solidifies on a surface, thus enabling a part to be built drop-by-drop. An example of such a method is the Laser-Engineered Net Shaping (LENS) process developed at Sandia National Laboratories and Stanford University [1]. In the LENS system a laser beam melts the top layer of the part in areas where material is to be added. Materials that can be used include 316 stainless steel, Inconel 625, tungsten, and titanium carbide cermets The LENS process produces fully-dense parts with functional mechanical properties. However, at present, the process can only be applied for parts with simple and uniform cross-sections.

Full flexibility and usability of the MD process technique can however be obtained if a robot is used. The robot can then either be programmed manually, or it can be programmed using Computer Aided Robotics (CAR). Manual programming is usually carried out using the teach-in method. In this method the robot arm is jogged through the program under reduced power and at reduced speed, via a joystick. The manual generation of a path in this way is very time-consuming and is a tedious task. Robot programming using computer simulation is an interesting alternative which, moreover, is necessary when complex shapes are to be built. Using this method the actual process can be simulated prior to manufacturing. There is, however, to the authors' knowledge, no commercial software currently available for the simulation and generation of robot paths for MD. Different methods could be used to develop this type of software. The aim of this paper is to introduce and compare three different possible methods.

2 Geometries

Two different part geometries were considered within this project; a solid rectangular box, see Figure 1 and a solid box with a more complex shape, see Figure 2.

The principle for off-line programming that was evaluated was the same for both namely 1) creation of a CAD model of the part, 2) slicing the CAD model into thin cross-section layers and 3) definition of geometry paths for each layer.

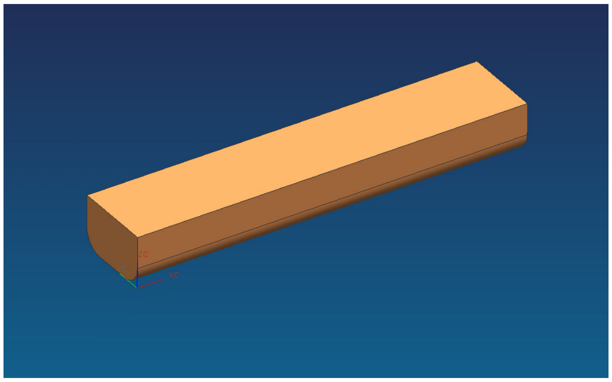

Figure 1: *A solid box.*

3 Methods for Robot Trajectory Generation

Several methods can be developed for the generation of the robot trajectory. One method is to use a CAM module in commercial CAD/CAM software. This method is, in this paper, denoted as "reversed milling" since it is based on a milling path which is mirrored.

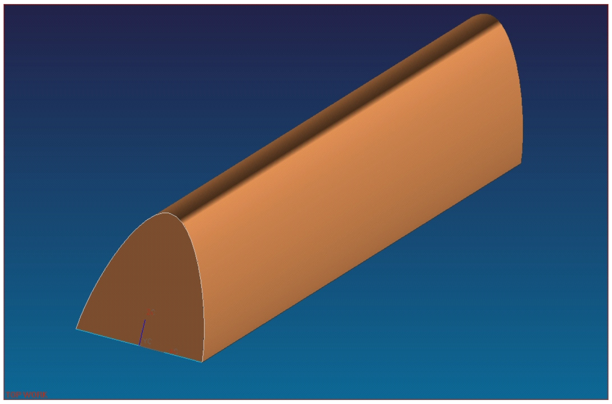

Figure 2: *Complex geometry.*

This transformation of the path is made by a developed postprocessor. An alternative method is to use software developed for the rapid prototyping of polymer parts. Since such software is developed for polymer applications, adaptations have had to be made which are further described in the section headed Adapted Rapid Prototyping, below. The final method that is evaluated is application programming in Computer Aided Robotics software (CAR). This method is, in this article, denoted as adapted CAR. In all three cases the part to manufactured is created within CAD software. All three methods also require simulation and verification of the robot path using CAR, which is why an initial brief description of this technique is necessary.

3.1 Computer Aided Robotics

Several commercial software packages for CAR are currently available (GRASP, IGRIP and RobCad etc). The procedure for the generation and simulation of robot paths using these systems can be summarized in terms of the following six steps [2, 3].

1. Modelling of the work cell
2. Work cell calibration
3. Programming of robot and other optional work cell equipment
4. Down loading of the program to the control system
5. Additional robot programming
6. Test running

The first step involves the construction of a geometrical and a kinematic model of the work cell. This geometric model can either be constructed using a CAD/CAM system, or constructed in the CAR system. In the second step a geometric calibration of the model with the real cell is performed. This step can include several sub-steps, such as tool-point, work-piece and signature calibration. [2, 4]. Tool calibration is performed to determine the tool centre point and to determine the weld torch orientation. A procedure using a measuring arrow in a fixed position in the work cell and moving the robot to this position in different directions, is usually used. The positions from the real robot cell are then uploaded to the CAR system and a "best fit" is found using regression. Calibration of the workpiece is performed similarly by moving the robot to identified positions on the workpiece. In step three the robot motion (and other possible motions) is programmed either using a high level language or a specific robot language. If a high level language is used, the program is translated to the specific robot language and downloaded (step four) to the robot controller system. The programming of the robot path is, in this study, substituted by the different methods described beneath. Usually, following the initial programming, additional equipment-specific programming is also needed (step five), which is performed manually at the robot. Validation of the program by test runs is finally performed in step six. Both IGRIP (Interactive Graphics Robot Instruction Program, Deneb Robotics) and ROBCAD (of UGS Corp.) systems were used in this study. Both a tool calibration and a workpiece calibration were performed. In Figure 3, an IGRIP snapshot from the experimental setup is shown. A more detailed description of CAR can be found in [2].

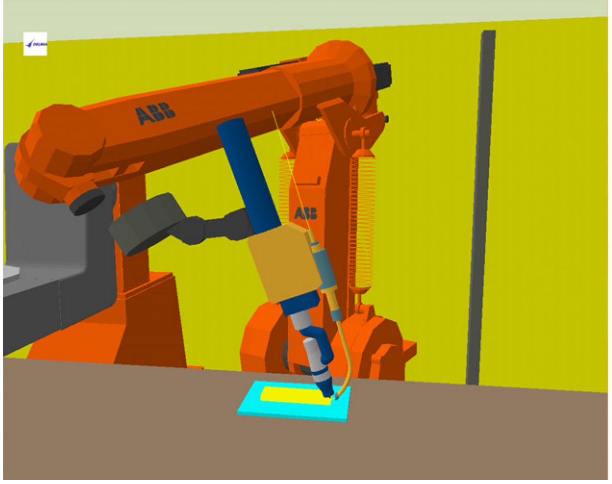

Figure 3: *Snapshot from IGRIP.*

3.2 Robot Path Generation through Reversed Milling

Unigraphics (UG), of UGS Corp. is a 3-D graphical tool for computer-aided design (CAD).The software is available in both Microsoft Windows and UNIX versions. A specific Computer Aided Manufacture (CAM) module is available. It is used to define up to five axis milling paths, a so called NC-code. In this study the NC code was instead used to generate robot paths for MD. The procedure is based on three steps. The first of these is the generation of the robot path in the CAM module. The slicing of the part is made at this initial stage and a robot path is constructed for each layer. The second step is the importation of the path to the CAR software, where a robot simulation of the path is made. Finally, in the last step the robot motion is downloaded to the physical robot where MD is performed, see Figure 4.

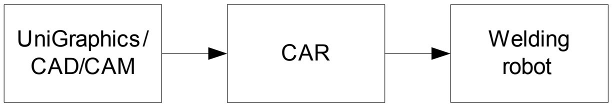

Figure 4: *Schematic principle of the "reversed milling" procedure.*

The CAM module generates an NC code which is easy to understand for a person familiar with NC machines. The code mainly consists of coordinates and tool data. Since it is developed for milling, it describes how to remove material. In the MD process, material is added. Thus the need here is to reverse the path so that the last coordinates in the NC code actually become the start coordinates for the MD process. This mirroring can either be performed by introducing a fictive surface located at the upper surface on the part to be manufactured, or by the development of a postprocessor that automatically makes this transformation. This latter method was the approach taken in this study. In the CAR software this transformed path is verified. A simulation is also performed, verifying the robot orientation and thus ensuring that no collisions between the welding torch and the part occur. A typical robot path for one layer of a rectangular shape is shown in Figure 5. The deposition is started from the lower right corner and a zig-zag movement up to the upper left corner has been defined. While performing experiments it was shown that it is a major advantage if the starting point for each layer could be varied, and if an individual thickness could be defined for each layer. The advantages with individual layer thicknesses and different starting points for each layer agree with the findings of [5]. The start location for each layer and individual layer thicknesses could, however, not be automatically varied. This makes the path generation more cumbersome. Another drawback with this method was that a counter support path was needed for each layer in order to maintain the shape of the part. This counter path also had to be defined manually for each layer. These drawbacks, notwithstanding, the method was shown capable of creating complex 3D shapes, thus enabling robot paths for the test geometries to be constructed.

3.3 Adapted Rapid Prototyping

The term rapid prototyping (RP) refers to a class of technologies that can automatically construct physical models from CAD data [6]. Although several RP techniques are available, all seem to employ the same procedure. The steps to create a path can be summarized as [6]:

1. Creation of a CAD model of the design

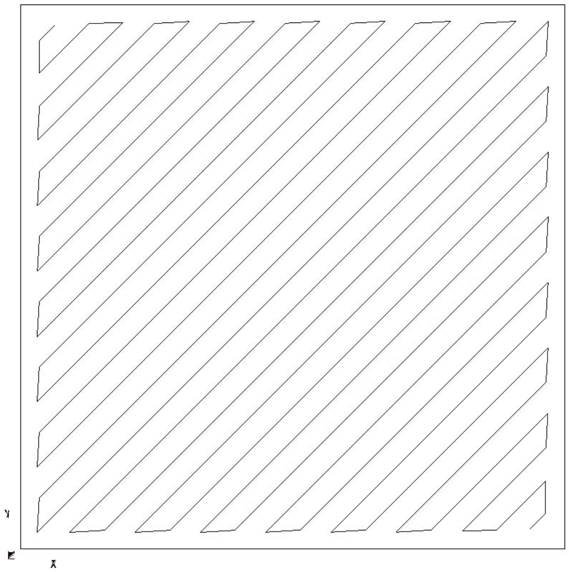

Figure 5: *Robot path for one layer.*

2. Conversion of the CAD model to STL format
3. Slicing the STL file into thin cross-sectional layers

One example of RP equipment manufacturer that employs this procedure is Stratasys, of Eden Prairie, MN, a company that has developed a number of different RP machines. The machines can create complex-shaped 3D polymer prototypes directly from a CAD-drawing. The CAD-drawing is pre-processed in Stratasys' own Insight software which imports a STL-file [5], which is the most commonly used file format that in RP. The STL-files can be generated by most of the commercially available CAD software. Insight automatically slices the geometry in layers and then creates tool paths for a specific machine. The tool paths are rotated for each layer i.e. starting each layer in a new corner as desired. Since the path is generated for a specific machine and for additive polymers only thin layers (0.03-0.1 mm) can be defined. When metal RP is to be applied, a larger part dimension is necessary and a scaling procedure is thus needed. Another adaptation that has to be made is that the Insight software exports not coordinates, but pulses to the machine. These pulses must subsequently be translated to coordinates. A specific translator had therefore to be developed. A postprocessor was created that automatically translates the instructions in the SML-file (Insight file format) to Rapid (ABB robot language). The program also ensures the rotation of the starting point for each layer. In order to obtain the same tool orientation for each layer, transformations also had to be made to some of the tool paths. The path generated by this program is thereafter imported to the CAR software where the robot motion is simulated and collision checks are made. An advantage in using the adapted RP method compared to the "reversed milling" method is that counter paths are automatically generated using this method. Drawbacks using this method are that constant layer thicknesses are generated and that the scaling procedure could be a possible cause of errors. It is necessary that the operator knows what scale factor to use, and this can vary from part to part. A common drawback between this method and the reversed milling method is that two different software systems are needed; one software system for robot path generation, and another for robot simulation. The final method of the three suggested alternatives uses the same software for both purposes.

3.4 Adapted Computer Aided Robotics

The most interesting solution for the generation of robot trajectories is to make sole use of CAR software, see Figure 6.

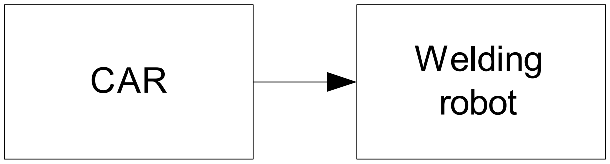

Figure 6: *Robot path generation and simulation using computer aided robotics.*

The major advantage with this method is that, compared to the reversed milling and adaptive RP methods, it gives the operator a better overview of the whole process. The major disadvantage, though, is the lack of automatic path generation. Application programming is thus necessary, both for slicing the part into layers, as well as for the creation of the movement in each layer. The program has to calculate robot paths in a general way, independent of part geometry. Two different ways of generating paths were evaluated. In the case of simple geometries a standalone program was suggested that interactively asks the operator for geometry information such as component height and width and position i.e. the location where the part is to be manufactured. For cases where more generalized shapes are to be made, such as the example in Figure 2 above, the path is preferably generated by implementing functions directly in the CAR software. Information about the weld path, as well as information about the welding parameters, is then exported to the physical robot. An example of a side view showing the robot path coordinate systems is shown in Figure 7.

4 Experiments

Experiments were performed using both a robotised TIG welding cell and a Nd-YAG laser cell. The TIG cell consists of a six-axis robot ABB IRB 1400 with a torch from Binzel AB (thoriated tungsten electrode) which is connected to a TIG Commander 400 AC/DC, from Migatronic Inc. Argon gas was used on the top side to avoid oxidation of the component. The laser welding experiments were carried out with 2.3 kW Nd:YAG laser cw2500 from , Rofin, German witch was linked to the IRB 4400 robot. The material used was stainless

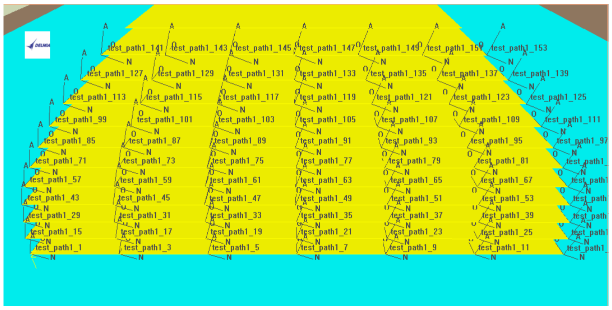

Figure 7: *Complex geometry with robot poses.*

steel 316L. Figure 9 shows a snapshot from the TIG process. An arc of plasma is formed between the electrode and the base plate. The process was shown to be rather sensitive with regard to the process parameters needed to obtain the desired shape of the deposited metal. The weld torch had to be inclined 20 degrees from the vertical axis. The deposit direction is from left to right in Figure 8. The base plate had to be clamped very firmly to a fixture in order to avoid deformation and to enable efficient heat transportation.

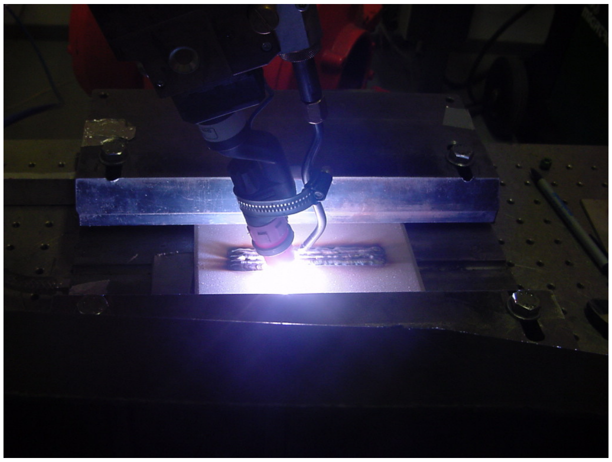

Figure 8: *Metal Deposition by TIG welding.*

In the TIG experiments Automatic Voltage Control (AVC) was used to maintain an optimum electrode distance of 1.5 mm. The process parameters used for the welding operation can be listed as follows:

- Weld speed : 3.0 mm/s
- Wire feed : 1.1 mm/s
- Weld current : 120 Amp

Experiments in which a rectangular solid box was manufactured, were performed line by line. The part to be manufactured was 40.6 mm wide, 100 mm long and 18mm high. It was initially made by 14 layers without any overlap of the weld seam i.e. the distance between the centres of each seam was chosen to be equal to the width of the seam. It was, however, shown that an overlap between seams is necessary. New deposit trials were performed by taking a weld seam overlap of 2.7mm. The number of seams and layers was reduced to five and four respectively. Better results were achieved this time as the layers were attached to each other and no discontinuities were observed. It was, however, observed that at some locations of the deposit the seams were not straight but deviated in a zigzag fashion. It was shown that the process was sensitive to slight deviations in the wire feed angle. Another observation was that edges occurred at the boundaries of the seams, Figure 9. This was shown to be due to partial oxidation of the deposited metal and hence the adjacent seams did not join perfectly.

Experiments were then performed using the Nd-Yag laser cell. Figure 10 shows the solid box part. Each layer had an individual starting corner and a zig-zag movement from this corner had to be performed. A counter path was also used for each layer. It was also shown that it was necessary to adjust the wire feed rate and the laser power continuously during the deposit. A sensor-based control system would be necessary to be able to fully automate the process. Figure 11 illustrates the necessity of these continuous adjustments where a rectangular shape has been made. The left shape was performed without any adjustments of the process, whilst the right shape was performed with continuous manual adjustments.

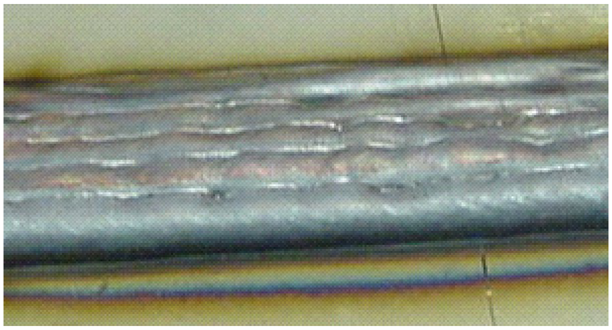

Figure 9: *Edges along the seam after four layers.*

Visual inspection of the cross-section revealed a fully dense material without any pores, Figure 12. Further work is planned to develop a process window in which a stable process is ensured. Microstructure evaluations and the mechanical testing of material properties with the aim of securing the functional performance of the parts are also planned.

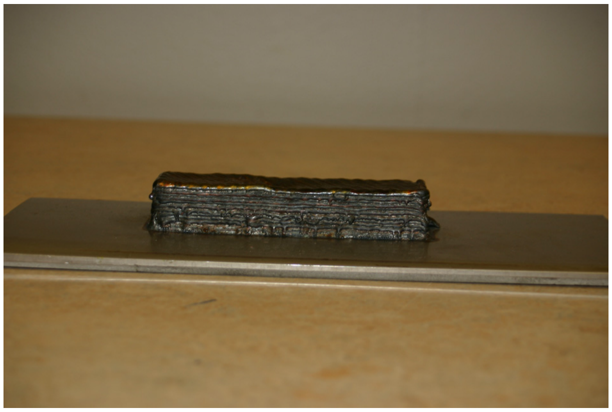

Figure 10: *The solid box geometry manufactured using a Nd-Yag laser cell.*

Figure 11: *Deposit without continuous process control (left) and with continuous process control (right).*

Figure 12: *Cross section of the solid box geometry.*

5 Summary and Conclusion

Three different methods for the off-line programming of robot paths were evaluated in this paper. Two different geometries were considered; a rectangular solid box and a more complex geometry. Computer programs were developed to generate optimal robot paths for these geometries. All three methods were shown to be capable of generating the paths for the geometries. The major drawback encountered in the use of a CAM module for path generation is that the software has been developed for milling, which means that its functionality for Metal Deposition is limited. Individual paths for each deposit are needed, thus making the method more time-consuming for complex parts. The method using polymer Rapid Protyping software had a higher functionality since different starting points for each layer were automatically defined. A drawback with this method, though, was that individual layer thicknesses could not be defined and that scaling procedures were found to be necessary. The most flexible method seems to be the adaptation of Computer Aided Robotic (CAR) software. Using this method, a fully automated path generation seems possible, even for complex-shaped parts. Another advantage with this solution is that only one system is needed for both path generation and for robot simulation. Further work is however needed to evaluate the use of the method for more complex-shaped parts. The welding experiments showed that it was possible to manufacture fully dense parts, although the continuous control of process parameters is a requirement. Development of a sensor-based control system is therefore under way. The present study seems to provide an efficient way of manufacturing parts by means of the process of metal deposition. The final quality of the product in terms of accuracy, finish and mechanical properties can be improved further by examining different aspects of the process, such as heat transfer and microstructure, thus enabling more optimized weld parameters. The development of a simulation tool that can predict part temperature and distortion during deposition would also be a worthwhile innovation. Optimal robot speeds, and trajectories related to shrinkage and distortion can thus be automatically defined. Such a simulation tool software system can by accomplished by linking the CAR software with Finite Element software in the same manner as was done in previous work regarding welding [7].

6 Acknowledgement

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