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

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Chapter 12

Conclusions and Recommendations for Further Research

12.1 Conclusions of Thesis

The effects of open-loop weld path design on the stability and performance of rapid prototyping (RP) and wear replacement (WR) by the robotic GMAW process were studied. This was done by identifying a range of weld path design strategies and focussing on their effects on the geometric and thermal stability of the build process, on weld defects and on total build time. The objective was to test whether open-loop weld path design could be used to improve process stability and performance and to optimise weld path design by comparing weld path design strategies and establishing which performed best. It was found that:

1) The stability of the rapid prototyping and wear replacement by GMAW process is very sensitive to weld path design.

2) Optimised open-loop weld path design can be used to greatly improve process stability and performance.

3) The quality of an object built using the "boundary method" is very dependent on the quality of the thin wall boundaries and it was found that any overheating or melting of the thin wall boundaries by any fill welds is very detrimental to object quality and must be avoided.

4) Weld starts and stops introduce instabilities caused by arc ignitions, arc ignition failures, weld heating zones and crater filling zones and thus tend to be very detrimental to object quality. It was argued that it is very desirable to avoid such problems by avoiding weld starts and stops by using fewer individual welds per fill layer.

5) Weld path strategies that employ higher numbers of individual welds per fill layer have greater scope for thermal control, since the build process can be paused between individual welds to implement temperature control measures. Otherwise, weld pool sizes and weld bead shapes vary due to varying substrate temperatures due to continual welding, which can be a very significant source of geometric instability.

6) A balance needs to be kept in terms of the number of individual welds per layer, between introducing layer-wide thermal instability and introducing problems near weld starts and stops. The more individual welds per fill layer a path strategy uses, the more it needs to rely on special procedures to control weld starts and stops, depending on the particular application.

7) Certain path strategies tend to produce very significant geometric and thermal instabilities and weld defects at fill layer edges. A number of useful recommendations were developed for weld path design near layer edges.

8) Corners in weld paths are potentially very significant sources of thermal instability due to the welds moving through their own trailing temperature fields. This causes temporary rises in surface temperature at the weld pool and thus localised changes in weld bead shape. A number of simple yet useful recommendations were made for weld path design for minimising the instabilities introduced by corners.

9) The self-constrained welding strategy produces symmetrical, evenly formed weld beads that are not skewed and that form in their intended locations, due to each weld type being made under symmetrical constraint conditions. The self-constrained welding strategy was found to be attractive for use in rapid prototyping and wear replacement by GMAW, though there is a need to balance the parameters of the two weld types.

10) The non-constrained welding strategy produces skewed asymmetrical weld beads that form shifted away from their intended locations, due to the asymmetric constraint conditions under which the welds are made, with the direction of the skewness and the positional shift being dependent on the weld order of the weld beads. This can result in potentially grossly uneven material deposition. The non-constrained welding strategy is generally not recommended, though it may be adequate for less demanding wear replacement applications such as the surfacing of ground-engaging tools.

11) Path strategies that first fill-in the outer regions of a layer and work their way inwards towards the centre tend to promote increased heat concentration in the centre of the layer and thus extra thermal instability. Path strategies that fill-in a layer in the opposite manner do not produce such heat concentration in any region, since they deposit heat in an ever wider area.

12) The welding of new layers should begin with the weldment being at a constant temperature for all layers, otherwise weld bead shapes will vary between layers, due to inter-layer thermal instability. This is undesirable and weldment temperature control measures should be implemented between layers.

13) Slag inclusions are a common type of weld defect in rapid prototyping and wear replacement by GMAW. They are particularly common on the insides of thin wall boundaries, where they are problematic to overcome.

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

15) Improvements were made in the designs of spiral paths and equations suitable for implementation by a robot were developed to mathematically describe and generate spiral paths in rectangular and circular shapes.

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

17) The commonly used raster family of weld paths performed especially poorly when compared to other types of weld paths and is not recommended except for very undemanding applications.

18) By using one of the most recommended path strategies, rapid prototyping and wear replacement by GMAW systems can enjoy improved geometric and thermal stability and fewer problems with weld defects, simply through the choice of weld path.

19) Overall, a flexible and multi-faceted approach is required in rapid prototyping and wear replacement by GMAW. It is predicted that the most successful systems in practice will make use of a combination of technologies such as: appropriate weld path design; special welding procedures for difficult regions; controlled heating and cooling for stress and microstructure control; material removal; and some form of robust and cost effective real-time temperature and/or substrate geometry feedback control.

12.2 Recommendations for Further Research

This thesis has shown that open-loop weld path design can be used to control the stability of rapid prototyping and wear replacement by robotic GMAW and that optimal weld path design can greatly improve process stability and performance. The following further research is recommended:

1) Development of special procedures to maximise stability and minimise weld defects near arc ignitions, weld heating zones and crater fill regions and to minimise arc ignition failures.

2) Development of procedures to completely fill in the apex's of sharp corners at the edges of fill layers and to minimise weld defects in these areas.

3) Development of special procedures to minimise localised uneven deposition and thermal instability at weld path corners by varying process parameters such as travel speed, feed rate and heat input.

4) Modification or re-design of spiral paths to make them suitable for use with circular objects.

5) Study of the automatic optimisation and generation of weld paths for more complex object geometries and the effects of weld path design strategies on process stability and performance in more complex geometries.

6) Further study comparing the performance of self-constrained vs. non-constrained welding for different applications.

7) Development of practical models for the prediction of weld parameters for the two types of welding in self-constrained welding.

8) Further study of weld defects produced by weld path strategies at difficult geometries and the minimisation of slag inclusions.

9) Investigation into residual stress reduction through open-loop weld path design and the development of practical and robust guidelines on how to deal with the issue of residual stress in rapid prototyping and wear replacement applications.

10) Study of the effects of open-loop weld path design on thermal gradients and thermal cycles and their effects on the microstructures of more complex metals.

11) Development of robust and cost-effective real-time feedback control systems for controlling key process parameters such as: control of contact-tip to workpiece distance based on welding process signals; control of trough fill weld settings based on trough channel geometry in self-constrained welding; control of cooling stop duration based on weldment surface temperature; control of heat input based on surface temperature immediately ahead of the weld pool.

12) Improvement through weld path design of process stability and performance in rapid prototyping and wear replacement by the robotic GTAW process.

13) Physical modelling of the effects of weld path design on geometric and thermal stability.

14) Development of comprehensive commercially viable hybrid rapid prototyping and wear replacement systems involving deposition by welding, leveraging combinations of technologies, specifically suited for key areas of industrial application.