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Adaptive control of thermal processes: laser welding and additive manufacturing paradigms

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Abstract

In Laser-based Manufacturing, the configuration of process parameters aims to maintain quality measures within specific boundaries and it is obtained through experimentation. The idea developed and presented in this paper concerns the prediction of the performance of adaptive control policies, based on process modeling. Two examples of Laser-based Manufacturing are deployed in order to verify the response of adaptive control algorithms through empirical design, Laser welding and Laser-based Additive Manufacturing processes. The penetration depth has been utilized as the quality criterion of the adaptive control loop for both processes. The solidification phase has also been examined.

Keywords: Laser-based manufacturing; Adaptive control; Process modeling; Penetration; Solidification phase

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1. Introduction

The use of flexible manufacturing techniques such as laser processing, should be extended and established in modern manufacturing [1]. It is essential that high-reliability, high-precision and/or high-productivity laser-based processes be created by taking advantage of laser features. Therefore, in-process monitoring and adaptive control, they are of outmost importance and necessary for their production results to be kept in deterministic boundaries [2]. However, the lack of established quality or adaptive control systems has been the problem for laser welding and laser cladding and although the machines by SLM Solutions are equipped with a thermal sensor, used for monitoring the temperature of the melt pool, the data received is not utilized for the alteration of the process parameters accordingly (adaptive control) [3]. Several studies, demonstrating efforts for the development of adaptive control systems, have been published, while model-based (experimental or numerical) adaptive control approaches are very rare even in proving the concept level.

Indicatively, authors in [2], have suggested a new procedure for in-process monitoring and adaptive control for laser micro-spot welding. Laser pulse duration and peak power were controlled every 0.15 ms interval, during the process, on the basis of the heat radiation signal, detecting the through-hole. On the other hand, an adaptive control system of laser cutting has been developed in [4], aiming at the improvement of productivity and cut quality. The control strategy is based on a set of parameters, which have an effect on the quality of the cut. The authors have selected one of these parameters, namely the striations on the cut surface. Cutting experiments, using this technique, have shown that the improvement of the cut quality is feasible. The paper presented in [5], has integrated an empirical model to describe the process dynamics and correlate the Laser Aided Metal Deposition process parameters with the specimens' quality. Based on a multi-sensor monitoring system, the authors were in a position to develop a closed loop control for the process and showed that the data, provided by the system, enabled the improvement of the process control, through an adaptive process controller. Effects of some controller parameters on material processing were also investigated. A statistically designed experimental matrix was used for this study. Another experimental based feedback control scheme was developed in [6], with respect to the process conditions of arc welding (weld speed and wire feed). A multivariable adaptive control system, based on a generalized one-step ahead regulation algorithm, was established and validated experimentally. Applications of such

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a bead profile regulation were explored in multi-pass weld joining, coating hardening and rapid manufacturing methods. More adaptive control techniques are cited in [7] mainly for robotic applications. The lack of numerical based adaptive control methods is evident though, in literature and different approaches for the control algorithms that govern such systems. The authors of the particular paper, in the past, investigated into the effect of process control on data handling, while an evaluation of the type of the controller and its performance for thermal based processes has been extensively performed within the paper. The energy efficiency has been also considered for the evaluation of the control performance of thermal processes, and its investigation into the way that this criterion could affect the design procedure of the controller along with the level up to which this fact could modify control strategies, developed for that purpose [8].

The study performed in this paper aims at demonstrating the adaptive control feasibility potential in laser processing and specifically, in laser conduction welding, laser keyhole welding and Additive Manufacturing (AM). A model-based approach (numerical) was developed for investigating the melting, solidification and cooling down phases of the processes. Empirical calibration of control laws has been utilized, while the changing parameter was the power besides the quality criteria being the depth and the width of the melt pool.

2. A model-based adaptive control approach for thermal processes

2.1. Method

The method developed and described herein, presents a model-based adaptive control approach, considering as criteria specific quality measures of the laser-based processes. The algorithm deployed for the purposes of the paper, calculates min and max values of the criteria selected. The values are provided by the numerical model developed and implemented within the algorithm (see section 2.2). As far as the chosen criteria are concerned for assessment during adaptive control, the melt-pool geometry was found to be the most crucial measure, related to the quality of both laser welding and AM processes, during the melting phase [9], [10]. However, different approaches have been followed in the solidification phase of the laser welding paradigm and the cooling down phase of AM process. For laser welding, the solidification front position is estimated and the velocity of the boundary, as the melt pool is getting smaller, is maintained within the values extracted from the study in [11]. On the other hand, as the cooling down phase is vital in AM, due to the thermal stresses that may appear and lead to part quality issues, the authors intended to maintain the temperature within specific values. The values were obtained from the corresponding material phase change diagrams. The process parameter altered, each time, was that of the laser power.

In the next step, according to the state of the examined criteria, the algorithm either adjusts the provided laser power value or checks if the process is finished. In the first case, the current temperature rate is being validated while the constraint not to exceed the boiling temperature of the material is constantly monitored. The empirical control law is then applied by enforcing changes in the laser power. The flowchart below depicts the afore mentioned algorithm's steps, deployed in this paper.

As it has been referred above, the control algorithm, depending on the phase of the process (melting, solidification, cooling down) investigates whether the corresponding criteria have been met. If this has not been achieved, the control law is applied, depending on the temperature region. The relation that determines the way the power will be modified, is chosen on the basis of the temperature region and has been established empirically (through successive approximations and in general trial-and-error). Additional constraints, such as those not reaching the boiling point, set the maximum allowed temperature that the control algorithm should maintain during the process, especially in laser conduction welding applications. The figure below presents the temperature regions that have been integrated for the estimation of the changes in the power values and the corresponding empirical relations of the control law. It is noted that the constants a_n can either be positive or negative.

Finally, it has to be mentioned that the governing relation for the adaptation of the power between two states has been carefully designed in order for issues and inaccuracies to be avoided during the numerical solution. A (not frequent) smooth transition of the power values, through the control law, ensures the retrieval of good results (figure below).

2.2. Process Modelling

Process modelling can be separated into two phases, namely those of the heating and the melting. Regarding the heating phase, the governing equation that describes thermal problems is the diffusion equation (1) [12].

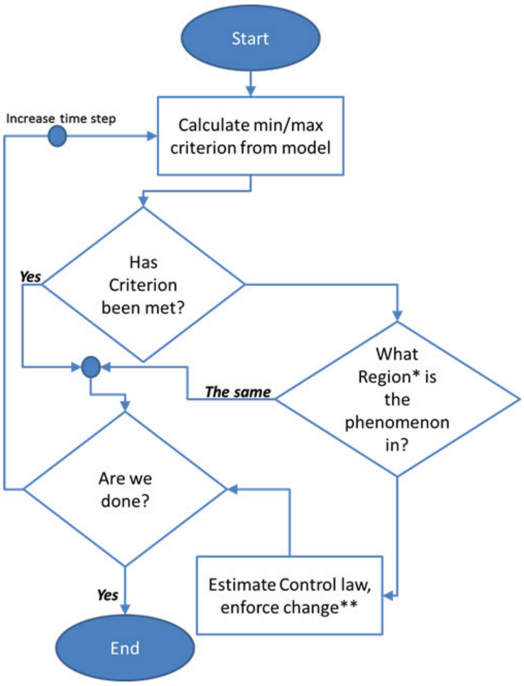

Fig. 1: Adaptive control algorithm flowchart. (*) Regions are illustrated in Fig. 2 (**) Changes are smooth as indicated in Fig. 3.