De-Skilling Industrial Laser Process Development

Ming Y. Huang, Hussein A. Abdullah and Chris R. Chatwin
Manufacturing Systems and Informatics Research Group, Department of Mechanical Engineering, University of Glasgow, Glasgow, Scotland

A knowledge-based adaptive control environment is constructed to enhance the cost performance of a laser manufacturing system, this decreases the dependence on a skilled technician and reduces process development lead time. The control environment consists of two shells: a pre-process knowledge-based management system (KBMS) expert shell and an adaptive process controller. Experimental results are presented which show how effectively the adaptive control system improves process quality.

Keywords: Adaptive control; Knowledge based systems; Laser materials processing

1. Introduction

The laser cutting process is a highly nonlinear process and consequently very difficult to analyse or predict analytically. Many researchers have investigated laser cutting phenomena in order to establish an appropriate cutting model to describe and control the laser cutting process. Based on an energy balance method, a simple cutting model was proposed by Chryssolouris and Choi [1] and Steen [2]. Using a cylindrical source model, relationships between the incident power density per unit thickness and the laser beam feedrate in terms of the thermal properties of the target material were established by Bunting and Cornfield [3]. Using stability analysis of the melt flow over the transient cut surface, a thin film flow cutting model was presented by Schuocker [4], Vicanek et al. [5] and Tsai and Weng [6]. Through the investigation of the dynamic behaviour of these thin film flow patterns they characterised the thickness of the thin layer and predicted the striation frequency range for stable cutting processes. Many models of laser cutting processes have been developed [7-9]. However, formulae and data generated by one researcher are often not of use to other researchers as these models are frequently system and set-up dependent.

A hierarchically-structured control algorithm that integrates a knowledge-based expert shell and an adaptive process controller has been developed to provide a system-independent and a set-up-unrelated environment for controlling the laser cutting process. Knowledge of laser cutting is organised and exploited using a rule-based system for process optimisation. Cutting feedrate and stand-off height are optimised through an adaptive controller by monitoring the magnitude of the irradiance emitted from the cut front.

2. Knowledge-Based Adaptive Control Environment: System Description

A knowledge-based adaptive control environment is constructed to enhance the cost performance of 1.2 kW Ferranti MFKP CO2 laser manufacturing system, 10.6 \( \mu \)m wavelength. This control environment decreases the dependence on a skilled technician and reduces the time taken in finding the optimal laser operating parameters. The control environment consists of two shells: a pre-process KBMS expert shell and an adaptive process controller.

The process knowledge and initial optimal operating parameters are stored in the knowledge base. A rule-based backward chaining inference engine and least-square parameter estimation are used to relate material selection to operating parameter evaluation. When a cutting query for a particular material is made, the initial optimal operating parameters are deduced from the knowledge-based expert shell and fed back by the operator via the graphical user interface (GUI). When the cutting process is initiated, the adaptive controller is activated. Optimum operating parameters, reasoned from the expert shell, are transferred to the control actuator unit. Settings of the laser power mode (i.e. pulsed or CW) and power range are then downloaded to the laser pulser unit. Settings of cutting feedrate and stand-off height are also downloaded to the Heidenhain TNC controller unit. The cutting process is then initiated by the TNC controller unit. Irradiance emitted from the cut front during the laser cutting process is sampled, by a photodiode, and fed back to the process adaptive controller which provides optimal control of the cutting process based on this irradiance measurement. The system diagram is illustrated in Fig. 1.
3. Pre-Process KBMS Expert Shell

3.1 Knowledge-Based Structure: Laser-Material Interaction Analysis

Knowledge relating to laser cutting processes can be classified into two categories: structured knowledge and heuristic knowledge. Structured knowledge represents the conceptual understanding of laser cutting phenomena, such as laser cutting models. Heuristic knowledge contains factual data, which can be represented in an IF-THEN form, such as relationships between the cutting process quality and laser operating parameters, and relationships between material characteristics and laser processing suitability.

3.1.1 The Structured Knowledge

This type of knowledge is obtained from fundamental research into laser cutting behaviour. Such as why the cut is formed and how it is formed. Through analysis of the cutting phenomena, based on physical laws, mathematical equations are formulated that describe and explain the interaction phenomena. The mathematical equations that describe the behaviour of the system are termed the laser cutting models. These models originate from two main sources: theoretical analysis and experimental deduction (statistics) leading to empirical models.

Knowledge from Theoretical Analysis. As mentioned in the previous section, many models have been developed to explain the laser cutting phenomena. Models that are suitable for online process control must give a reasonably accurate process prediction and also be sufficiently simple that they can be computed in real-time. Only then is real-time control possible.

The Simple Cutting Model proposed by Chryssolouris and Choi [1] and Steen [2] was adopted as one of the reference models. They assumed that all the energy enters the melt and is removed before significant conduction can occur. Hence using a heat balance in the cutting region gives a simple mathematical equation that describes the cutting process:

\[ \frac{P}{tV} = \frac{w}{\eta} \left( C_{p} T + L_{f} + m' L_{v} \right) \]  

where

- \( C_{p} \) = thermal conductivity
- \( \eta \) = coupling coefficient
- \( L_{f} \) = latent heat of fusion
- \( L_{v} \) = latent heat of vaporisation
- \( m' \) = fraction of melt vaporised
- \( P \) = incident laser power
- \( \rho \) = density
- \( t \) = thickness
- \( V \) = cutting speed (feedrate)
- \( w \) = average kerf width

Knowledge from Experimental Deduction (Statistics). Using regression analysis, data collected from experiments can be used to establish useful experimentally based empirical models for the cutting processes. Table 1 represents a set of feedrate data for mild steel (BS1449-CR4) and stainless steel (S304) of different thicknesses. A graphical representation is given in Fig. 2.

Using least-square regression on the feedrate data, experimental models for the laser cutting process of these materials were obtained. For example, take the feedrate-thickness relationship data of mild steel (high power) from Table 1, by using least-square regression the cubic equation below is obtained:

\[ V = 9040.0 - 4872.9t + 1054.8t^{2} - 78.056t^{3} \]  

Where experimental data, such as equation (2) is available from the knowledge base it is used in preference to the simple cutting model given by equation (1). Equation (2) is quite accurate but specific to a particular material; whereas, equation (1) is general but gives only a first approximation, this is useful when no experimental data is available. The system