Proceedings of the 17th World Congress
The International Federation of Automatic Control
Seoul, Korea, July 6-11, 2008

Control Design for Automation of Robotized Laser Metal-wire Deposition

Almir Heralić *, Anna-Karin Christiansson *, Kjell Hurtig *
Mattias Ottosson *, Bengt Lennartson **

* *University West, Trollhattan, Sweden (almir.heralic@hv.se)*
** *Chalmers University of Technology, Gothenburg, Sweden*

Abstract: In this paper a novel approach towards automation of robotized laser metal-wire deposition (RLMwD) is described. The RLMwD technique is being developed at University West in cooperation with Swedish industry for solid freeform fabrication of fully dense metal structures. The process utilizes robotized fiber laser welding and metal wire filler material, together with a layered manufacturing method, to create metal structures directly from a CAD drawing. The RLMwD process can also be used for repair or modification of existing components. This paper faces the challenge of designing a control system for maintaining stable process variables, such as a constant layer height and a stable component temperature, during the entire manufacturing process. Several problems are identified and discussed in the paper, e.g. the difficulty of obtaining the bead height in the weld pool environment. The case study is a repair application for stamping tools, where worn out trim edges are to be repaired. Issues regarding the control design, system identification, and the practical implementation of this application are discussed.

Keywords: Multi sensor systems, Robotics technology

1. INTRODUCTION

In the last few years there has been a growing demand for new flexible and cost effective fabrication methods that can assist or replace some of today's production applications that utilize casting. The main reason for this is the high initial cost associated with making moulds as well as the additional lead time needed for mould fabrication. Several application areas, such as prototype production, low-volume manufacturing, and high-value component repair applications, have high cost-saving potentials if the need for moulds can be minimized.

To address this problem, several new production techniques have been developed during the last years utilizing mainly laser cladding or 3D welding with GMAW (Gas Metal Arc Welding). In laser cladding, see e.g. (Milewski et al., 1998), (Atwood et al., 1998), or (Mazumder et al., 1996), a laser beam creates a weld pool into which a small stream of metal powder is injected and melted. The laser/powder system is moved across the substrate in order to form beads of the solidified powder. The beads are joined side-by-side and layer-by-layer, so that a predefined component can be formed. The deposition rate is, however, rather low as well as the catchment efficiency, i.e. the ratio between deposited and scattered powders, and milling is usually necessary due to low quality surface finish. Most of the laser cladding systems available utilize some sort of x-y-table for moving the substrate relative the laser/powder system during deposition. The x-y-table is usually enclosed in a chamber filled with a shielding gas to avoid oxidation of the component. Although very accurate, a major disadvantage with this kind of setup is the limitation in flexibility. The component size that can be manufactured is strongly limited by the x-y table's motion limits and the surrounding chamber. Repairing or modifying large-scale components is usually not possible.

In order to increase the deposition rate, 3D welding with wire using GMAW has been introduced, see e.g. (Zhang et al., 2003), (Song et al., 2005), or (Doumanidis and Kwak, 2002). The GMAW process uses DC current to create an arc between a consumable metal wire electrode (the actual filler material) and the substrate. The wire electrode is fed from a spool through a welding torch and melted by the arc to form droplets which are added to the substrate. The equipment required for GMAW systems is usually much cheeper than for laser cladding systems. However, the roughness of the produced beads is usually very high and this can introduce several problems during multi-layer deposition. Some solutions have therefore been presented where milling is applied after each deposited layer in order to enable good surface conditions for the next layer, see e.g. (Song et al., 2005). The GMAW process gives rise to high temperatures which are transferred into the substrate. This makes the GMAW technique less suitable for repair applications since any excessive heat that is introduced during deposition can lead to deformations of the original component.

To address the problems pointed out above, researchers are now looking into the possibilities of combining a high-power laser heat source with wire filler material, see e.g. (Kim and Peng, 2000a) and (Choi et al., 2001). This way the deposition rate can be increased compared to laser/powder systems but without increasing the heat input into the substrate material as with GMAW. Material properties of the components manufactured with laser metal deposition [1], using either metal wire or metal powder as the filler material, has been investigated in e.g. (Syed et al., 2005). The authors also looked at simultaneous feed of both metal wire and powder in (Syed et al., 2006). Conclusions drawn in these studies indicate better metallurgical properties when wire is used, as well as decreased surface roughness. Deposition efficiency between 30-60% for metal powder was reported in these papers while there is, in general, no material waste when metal wire is used.

The Robotized Laser Metal-wire Deposition (RLMwD) technique, described in this paper, is being developed by the welding research group at the University West in Sweden, in close cooperation with the Swedish industry. The RLMwD process is carried out using a 6-axis industrial robot arm utilizing fiber laser welding and wire filler material. The usage of metal wire, rather than metal powder, will ensure high deposition rates and low environmental impact (due to a much cleaner process and no material waste). A high-power fiber laser is chosen to provide enough energy to ensure material integrity, and at the same time, maintain low heat input into the base material. The RLMwD process can also make use of all the benefits that modern fiber laser welding is offering. It is e.g. rather easy to modify the beam spot size and shape.

The RLMwD system is intended to be as modular as possible, allowing for different types of robots, laser sources, and materials. This means that the RLMwD system has the great advantage of utilizing existing standard welding equipment, rather than specially made high-cost equipment traditionally associated with laser cladding, and can thus be used both for metal deposition and industrial welding applications. Furthermore, the usage of an industrial robot arm, rather than an x-y-table, introduces a new level of flexibility concerning the size and the shape of the components that can be manufactured or repaired.

Automation of related systems is discussed in Section 2, and a detailed description of the RLMwD system is given in Section 3. A suitable application for the RLMwD system, involving repair of worn-out trim edges in stamping tools, is described in Section 4. Experimental system modeling of the metal deposition (MD) process is discussed in Section 5, and issues regarding control design and experiment results are given in Section 6.

We are focusing on both repair applications of large-scale stamping tools, used e.g. within the car industry, and new production techniques within the aerospace industry. Due to this, tool steel and titanium, correspondingly, are considered in the experiments presented in this paper.

2. AUTOMATION IN RELATED SYSTEMS

In order to enable high deposition rates it is of utmost importance to maintain stable process variables. To ensure this, the RLMwD system will be fully automated. This involves measuring and controlling variables such as the height, the width, and the temperature of each bead that is laid. To date only a few papers are directly referring to automation of metal deposition. For example, within laser cladding with powder, Mazumder and his colleagues developed a phototransistor-based height detector for use in a closed-loop direct metal deposition process, see (Mazumder et al., 2000). The feedback signal from the height detector was used to turn the laser beam on and off for specific durations, and thereby control the height of the built-up component. When the laser is turned off the powder is scattered rather than deposited. In (Bi et al., 2006a), the infrared temperature signal emitted from the melt pool was investigated for closed-loop control of laser cladding with powder. The influence of the main process parameters on the infrared temperature signal was studied by cladding single tracks. As a result, correlation between the measured infrared signal and dimensions of the clad could be found. A closed-loop process control was then investigated by deposition of thin walls, (Bi et al., 2006b). The weld pool temperature was controlled by regulating the laser power, and as a result, improved homogeneity of the microstructure and better dimensional accuracy of the deposited samples was achieved. In (Fearon and Watkins, 2004), a non-feedback layer height controlling process was described. The method limits deposited layer height by abruptly limiting the availability of powder in the vertical plane at a fixed distance from the powder feed nozzle. This is possible due to the shape of the powder streams emitted from a specially designed feed nozzle.

The closed-loop height control system described e.g. by Mazumder in (Mazumder et al., 2000) uses process-specific properties such as the catchment efficiency of the metal powder. This means that similar approach cannot be applied in the case of metal wire deposition, since all wire that is fed into the process must always be deposited. In any other case the component will be destroyed. Thus, prior to the control design, a good understanding of the relation between the wire feed rate and laser power, and the resulting geometrical properties of the beads, must be obtained. This will give upper and lower limits for the control system to work within. The influence of the component temperature on the resulting beads must also be investigated. Few attempts to describe the weld pool shape, and the solidification of the beads, in metal wire deposition have been reported in the literature, e.g. (Kim and Peng, 2000b), and (Hung and Lin, 2004), but these are calibrated to other conditions and materials than in this project. Instead, an empirical approach towards describing the relations between the process parameters, and the resulting bead properties, around an operating point, seems more feasible, see e.g. (Li et al., 2003) for a laser metal powder system, or (Doumanidis and Kwak, 2002) for a GMAW system.

3. RLMWD - SYSTEM OVERVIEW

The RLMwD system can be divided into three main parts; Preparation of weld paths and corresponding process parameters, actual metal deposition, and final scanning for geometry validation. First, a preparation of weld paths and process parameters based on a CAD drawing for a given component must be made. This is done using an Off-Line Program (OLP) which slices up the model in layers with uniform thickness. For each layer, the OLP generates robot paths along which the beads should be

[1] In the reminder of this paper, the general term *metal deposition* (MD) will be used for describing a laser cladding process with wire filler material.

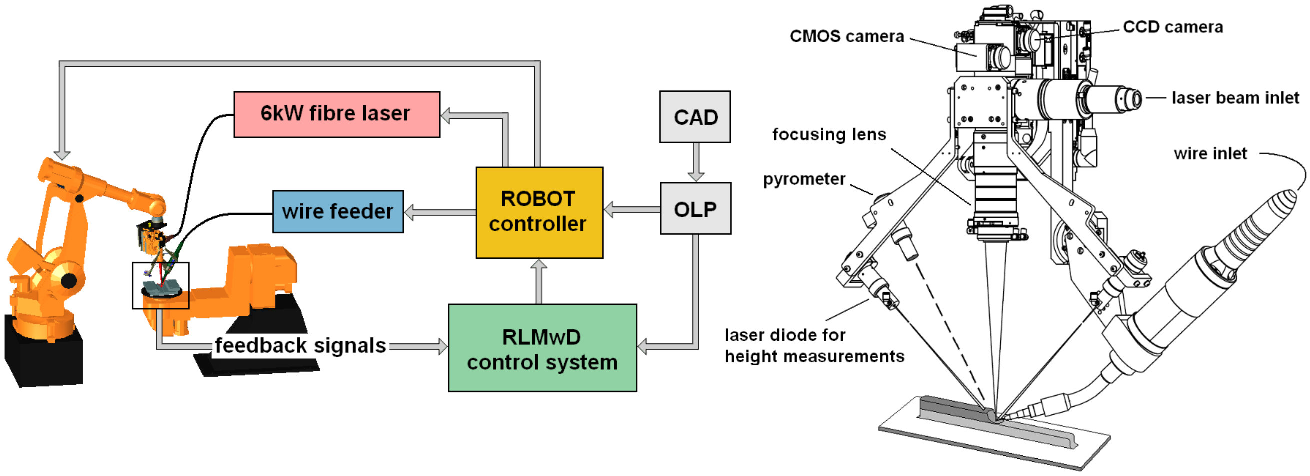

Fig. 1. Left: The principle of the RLMwD system. Right: The welding tool used for deposition of metal wire.

formed. This is described in more detail in (Ericsson et al., 2005). A schematic picture of the RLMwD system is given in the left part of Fig. 1 and the details around the data acquisition system are given in (Heralić et al., 2007). Prior to deposition, the robot motions are tested using a robot simulation software in order to detect any errors in the code or collisions during motion. Once the correct robot paths are generated and tested in simulation, the component is built up by using a 6-axis robot arm and conventional welding equipment, utilizing a 6kW fiber laser. During deposition, metal wire is melted by the laser and added to the base plate as beads, side-by-side and layer-by-layer, in accordance to the OLP, until the entire component is manufactured. Deposition must be performed in a closed room, without any operators present, due to the high-power laser being used. Adequate process information must therefore be presented to an operator outside the welding room.

3.1 Sensor data acquisition

Within this project a measurement system is developed to enable an operator to monitor and control the welding process solely outside the welding room. Information such as the weld parameters (laser power, wire feed, and weld speed), the temperature of the component, the oxygen level in the surrounding atmosphere, the robot position, and the weld pool images are continuously updated and presented to the operator. This information is also stored for subsequent experiment evaluation. If necessary, the operator can easily manipulate the process parameters online, directly from the control board. In order to gain full traceability of each individual run, any corrections that are made during deposition (by the operator or the future control system), are also recorded by the measurement system.

3.2 Weld tool

The welding tool used in this project is a seam tracker manufactured by Permanova Lasersystems in Sweden illustrated in the right part of Fig. 1. It consists of a set of optic components for laser beam focusing, a CCD camera for seam tracking, a CMOS camera for weld pool imaging, and a wire feeder. The optic system is attached to a servo positioning mechanism for sideways corrections of the laser beam position. The servo mechanism is used in seam tracking applications where the laser beam should follow a seam during welding (which can deviate from the nominal path). The CCD camera is mounted on top of the last mirror in the optics, through which it is viewing the seam in front of the weld pool. A fast image processing software detects a red laser stripe projected on the seam, and by examining the curvature of the projected stripe the seam position is detected, see (Lindskog, 2002) for more details. The CCD camera, and the CMOS camera, can view the scene around the melt pool due to a semi-transparent mirror placed in the optics. The mirror is highly reflective to the fiber laser wavelength but it transmits several wavelengths within the visible light region. In other words, the mirror reflects the high-power fiber laser light down on the melt pool, through the focusing lens, and at the same time, it transmits the visible light reflected from the process through the focusing lens up to the cameras.

3.3 Height and width measurements

When the welding tool is used for metal deposition, the servo system is turned off and the laser stripes are then used for height measurements of the last laid bead, see Fig. 2. The original idea was to measure the actual height before the weld pool in order to create an appropriate control signal, and at the same time, measure the height shortly after the weld pool in order to evaluate the result. However, due to the high temperature of the melt pool the laser stripe initially available in this project cannot be seen unless placed around 15 mm behind the melt

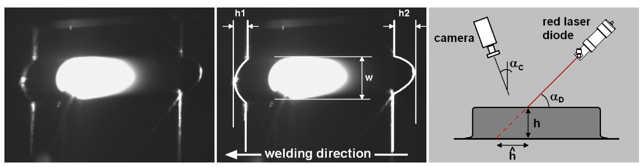

Fig. 2. Left and Middle: A weld pool image captured by the CCD camera. The projected laser stripes used for measurements are clearly seen in the image. See the text for more explanation. Right: The height is calculated by using the triangulation principle.

pool. This imposes several problems which are discussed in Section 6. The image processing software available with the seam tracker is reprogrammed to calculate the horizontal distance between the starting point of the laser stripes and the point of the most sideways deviated bright pixel, corresponding to the highest point on the intersection between the laser stripe and the bead, (*h1* and *h2* in the middle part of Fig. 2). The calculation of the actual height h is made by using the triangulation principle, utilizing the known angle α_d of the projected laser stripe according to: $h = \hat{h} \cdot \tan \alpha_d$, where $\hat{h}$ is the measured horizontal deviation of the projected laser stripe (*h1* or *h2* in Fig. 2). However, in order to avoid direct reflections of the high-power laser light back into the optics, the focusing lens is somewhat tilted in respect to the vertical axis (in the sagittal plane). This means that the viewing angle of the CCD camera is also tilted, see the right part of Fig. 2. In that case the height is calculated using:

$$h = \hat{h} \cdot \frac{\tan(\alpha_d + \alpha_c)}{\cos \alpha_c (\tan \alpha_c \tan(\alpha_d + \alpha_c) + 1)} \qquad (1)$$

with angles defined in the right part of Fig. 2. The width of a newly formed bead is obtained by simply extracting the width of the weld pool in the acquired image (w in middle part of Fig. 2).

3.4 Temperature measurements

Experience has shown that the temperature of the component is very much affecting the final shape of the deposited beads and the material properties of the same. Problems like cracks between different layers may occur if certain temperature requirements are not fulfilled for all times during deposition. Other problems like total collapse of the component may happen when e.g. smaller features are manufactured at high deposition rates. The heat from the high-power laser is then concentrated around a small volume which easily reaches the melting temperature. These problems call for automation with a temperature feedback signal. For this purpose, a pyrometer is added to the welding tool, as shown in the right part of Fig. 1, in order to measure the temperature of the last laid bead. If the temperature increases in the component, the laser power can e.g. be decreased in order to restore the original condition. The temperature feedback can also cause the robot to pause if necessary, or by contrast, to shorten any preprogrammed pauses in order to maintain a stable component temperature. At this point in the project, the temperature signal is only used to control the duration of the preprogrammed pauses.

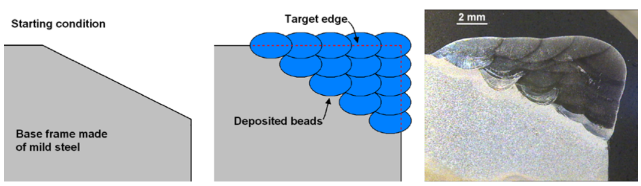

Fig. 3. A cross-section view of the built-up edge. Left: The starting condition. Middle: A schematic representation of the deposited beads. Right: Cross-section of a real specimen.

4. HARDFACING USING RLMWD

A possible application area for the RLMwD system, currently under investigation at the University West, is hardfacing of worn-out trim edges in stamping dies. Hardfacing is a repair technique where abrasion resistant metal is applied on the surface of softer material in order to increase wear properties. Today such repair is usually done manually by skilled welders using TIG (Tungsten Inert Gas) welding. Several layers of hard tool steel material is deposited on a base frame made of mild steel. The final die is obtained after machining. However, the quality of the manual welds vary from time to time, and it is also relatively time consuming. It is not unusual that too little material is deposited or too much which then creates extra milling time. Furthermore, maintaining correct working temperature to ensure good material properties (e.g. no cracks or adhesion problems between layers) can be hard to obtain in manual weld. If the task can be automated, a considerable quality improvement of the welds can be achieved. The experiments on hardfacing are briefly described below.

4.1 Worn-out trim edge reproduction

The starting condition is shown in the leftmost part of Fig. 3, and the final shape obtained after deposition is shown in the rightmost part of Fig. 3. The first bead is laid in the lower right corner of the base material and the subsequent layers are deposited from right to left, see the middle part of Fig. 3. Here tool steel wire is deposited on a softer mild steel base. The rightmost part of Fig. 3 indicates that the volume of the deposited material is somewhat excessive compared to the target edge. This because an extra layer was deposited in order to ensure that enough material was available for a sharp edge to be machined within this experiment. However, the difference between the deposited shape and the target edge must in future be much smaller in order to ensure cost effectiveness.

To test the flexibility of the RLMwD system, a circular base frame was chosen, as shown in Fig. 4. At most, eight layers were deposited at the outer edge of the base frame. The process was supervised and manually controlled by an operator using the measurement system described earlier. The non-straight shape of the trim edge imposed no problems for the RLMwD process. The hardness of the new edge was measured and the results for one set of measurements are given in Fig. 5. The vertical axis of the graph in Fig. 5 represents the Vickers

Fig. 4. Left: A circular mild steel plate with the original chamfered edge seen on the left half of the plate, and the deposited tool steel material on the right half. Right: The same plate with the new sharp edge, obtained after machining.

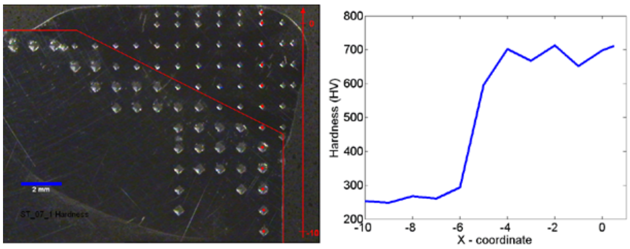

Fig. 5. Hardness measures are performed to examine the result. The red-dot marked measures are plotted in the graph in the right part of the figure.

hardness of the measured points. The hardness profile in the transition region between the deposited material and the softer substrate is satisfactory since the mixture zone between these two materials is rather small. This means that only a few layers of tool steel material need to be deposited before saturation in hardness is reached. However, despite the fact that saturation in hardness is reached in this experiment, the maximum hardness obtained at the surface is somewhat lower than what was originally estimated based on the material specification of the tool steel wire used. This calls for further investigation regarding the process parameters used during deposition, such as the laser power and welding speed as well as the temperature of the welds. Some pores have been found in the sample but these are considered harmless for the intended application.

5. EXPERIMENTAL SYSTEM MODELING

During deposition, an operator can modify three process parameters; the laser power, the wire feed rate, and the welding speed. Here we will look at the effect of varied laser power and wire feed rate (at constant welding speed) on the resulting geometrical properties of the beads. In the remainder of this paper, units according to Table 1 are used.

Notation		Units
P	Power	Watt
v_w	Welding speed	mm/s
v_f	Filler wire rate	mm/s
E	Energy per weld length	Ws/mm
V	Wire volume per weld length	mm^3/mm
w, h	Width, height of last laid bead	mm
T_r, T_s	Response time, sample time	s

Table 1. Units used in the experiments.

5.1 Static gains

In order to investigate how the wire feed rate, v_f, and the laser power, P, for a given weld speed, v_w, affects the geometrical properties of the deposited beads, several bead-on-plate experiments are made during which the height and the width of the beads are measured and recorded. The samples are also cut-up to determine if there are any pores in the beads or lack of fusion between the beads and the substrate. Within this project mainly two cases are investigated; tool steel wire deposited on mild steel substrate and titanium wire deposited on titanium substrate. During the experiments the welding speed is maintained constant. However, in order to generalize the results for any given weld speed, the laser power is converted into energy per weld length, and the filler wire rate is converted into wire volume delivered per weld length:

$$E = \frac{P}{v_w} \quad \text{and} \quad V = \frac{v_f}{v_w}\pi r^2 \tag{2}$$

where E is the energy per weld length given in (Ws/mm), v_f is the wire feed rate in (mm/s), r is the wire radius in (mm), and V is the wire volume delivered per weld length given in (mm^3/mm).

The results indicate that the built width w is more or less linearly related to the energy per weld length E. The height h, however, depends both on wire volume per weld length V and the energy per weld length E. This is due to the fact that any change in energy changes the width of the beads, and by that, also the shape of the cross-section area of the beads. The height is then non-linearly related to the width. However, if the width is constant, i.e. constant energy input, the height change of the bead is more or less linear to change in V. The estimated linear relations between E and w, and V and h during quasi stationary conditions can then be expressed as:

$$w = K_{Ew}E + C_{Ew} \tag{3}$$

$$h = K_{Vh}V + C_{Vh} \tag{4}$$

Thus, the static gains for the transfer functions, energy to width ($G_{Ew}(s)$) and wire volume to height ($G_{Vh}(s)$), are K_{Ew} and K_{Vh} respectively. Even though the gain K_{Vh} is different for different energy inputs, only one gain needs to be known, i.e. the gain corresponding to the nominal energy input. The OLP will slice up the component uniformly, and by that, require constant width and height of the beads throughout the deposition. If there is a change in the input energy, e.g. due to the component being heated up, which then results in change

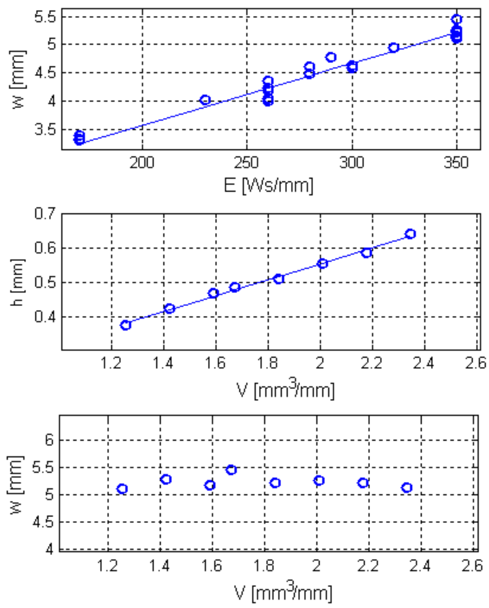

Fig. 6. Tool steel wire deposited on mild steel substrate. Top: Bead width as a function of E. Middle*: Bead height as a function of V. Bottom*: Bead width as a function of V. The lines in the graphs are the linear approximations of the data. *(E=350 Ws/mm).

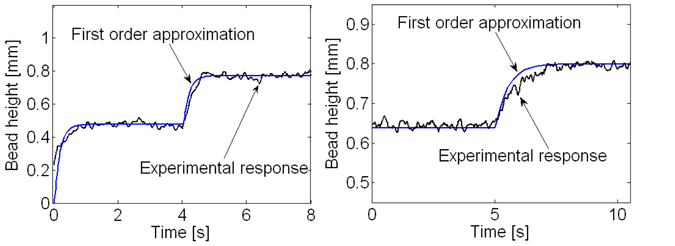

Fig. 7. Experimental and first order model open-loop response of bead height to a step change in V. Left: Tool steel wire deposited on mild steel substrate. Right: Titanium wire deposited on titanium substrate.

of the width, the controller will automatically decrease the laser power in order to maintain constant width. This means that the K_{Vh} will remain constant, or at most in the near vicinity of its original value, at all times during deposition. Fig. 6 shows a set of process parameters and the corresponding geometrical data for the tool steel material. Similar linearities are obtained for titanium as well.

5.2 Transfer functions $G_{Ew}(s)$ and $G_{Vh}(s)$

The dynamics of the RLMwD process is investigated through a set of step response experiments. Single beads are deposited on thick plates to maintain stable thermal conditions. First, a bead is deposited until geometric steady state of the bead profile is reached. At this point, one of the two process inputs (E or V) is perturbed by a step change, and the response of the two outputs (w and h) are recorded. Fig. 7 shows the response of the bead height after a positive step change in V for tool steel material and titanium. The results indicate that the dynamics of the system can be approximated by first order transfer functions (also shown in Fig. 7). The time constant, T_r, is then estimated from the experimental data, and the static gains, K_{Ew} and K_{Vh}, are previously obtained in Section 5.1. Given the time constant and the static gains, the transfer function from energy to width or from wire volume to height can be formulated as:

$$G_x(s) = \frac{K}{1 + sT_r} e^{-sT_s} \tag{5}$$

where $G_x(s)$ is either $G_{Ew}(s)$ or $G_{Vh}(s)$ and K is the corresponding static gain, K_{Ew} or K_{Vh}. In the current measurement system the sampling interval is T_s=0.05 s.

6. CONTROL DESIGN

For design purpose there is a need to know what design criteria are most vital, and in the RLMwD-process it is considered to be vital to keep the width and the height at constant values despite process disturbances. As a first approach, a PI-controller is proposed with transfer function $F(s) = K_p + \frac{K_i}{s}$. Initially SISO (single-input single-output) loops are designed, such that the width is controlled by the laser power, or the energy per weld length, and the height is controlled by the wire volume per weld length, as discussed in Section 5. The design criteria have been to keep the process values constant without excessive control activity during changes in the reference signal and/or disturbance. The criterion is therefore a combination of keeping the sensitivity ($S(s)$), complementary sensitivity ($T(s)$), and control sensitivity ($F(s)S(s)$) functions within certain limits, and at the same time, have as much integral action as possible in the controller, in order to get error-free output, see e.g. (Goodwin et al., 2001) for details. The discrete time transfer functions $G_{PIw}(z)$ and $G_{PIh}(z)$ are defined as:

$$G_{PIx}(z) = K_{px} + K_{ix}\frac{T_s}{z-1} \tag{6}$$

where x is either h or w, for the height and width respectively. The transfer function (6) corresponds to the discrete-time difference equation:

$$u(t_k) = u(t_{k-1}) + K_{px}e_x(t_k) + (K_{ix}T_s - K_{px})e_x(t_{k-1}) \tag{7}$$

where e_x is either the error in measured height (e_h) or measured width (e_w), and u is the control signal, either ΔV or ΔE correspondingly. However, certain limitations in the current measurement approach have been identified that need to be solved before a closed-loop height controller can be implemented. For example, errors caused by the rear height measure delay must be reduced using a Smith predictor or similar, see e.g. (Smith, 1957). However, the system will still not be able to handle disturbances that are shorter than the distance between the rear laser stripe and the weld pool, which is not acceptable. Furthermore, with this setup the CCD camera needs to overlook a relatively large area due to the necessary shift of the rear laser stripe. This gives less measurement accuracy and more noise sensitivity. One way of reducing disturbances in the measurements is to ensure good contrast between the laser stripes and the surface. This involves finding appropriate illumination and suitable camera filters. Simply increasing the exposure time of the camera will introduce an error in the width measurements due to the blooming affect of the bright weld pool caused by the long exposure time.

The practical issues presented above were not foreseen at the beginning and must be dealt with before both SISO loops can be implemented simultaneously. However, initial

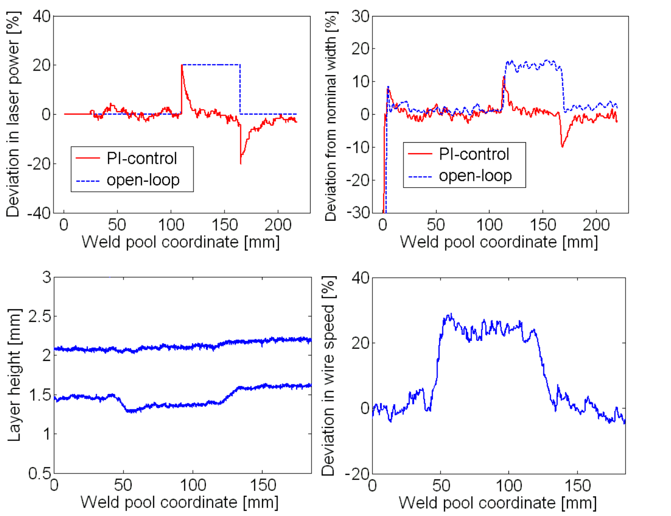

Fig. 8. Top: Compensation of 20% disturbance in laser power using a PI-controller in comparison with the open-loop result. Bottom: A disturbance in wire speed is introduced to create a cavity. On the subsequent layer a feed-forward compensator restores the correct height.

trials with only closed-loop control of the width have been carried out successfully, see the top part of Fig. 8. The height control, on the other hand, has only been tested using a feed-forward compensator. Here the field of view of the camera is narrowed to only include the front laser stripe in order to increase the measurement accuracy. The obtained height signal is delayed the time it takes the robot to move the distance between the weld pool and the front laser stripe. The control signal is calculated using the inverse of the static gain, i.e. $\Delta V = e_h/K_{Vh}$. The result is shown in the bottom part of Fig. 8. First a disturbance in wire speed is introduced during deposition to create a cavity. On the subsequent layer the cavity is successfully detected and compensated for by increasing the wire speed appropriately. The experiments presented in Fig. 8 are made using titanium wire deposited on titanium substrate.

7. CONCLUSION

The ideas and results presented in this paper indicate promising steps towards a fully automated RLMwD-system. Standard industrial welding equipment is used implying that the concept can be further adopted for several applications. The paper discusses issues regarding non-contact sensors, modeling for control, and relevant applications for the system. A number of important practical constraints are overcome, but there are still issues to be refined during planned experiments followed by integration with a novel OLP-software (however outside this paper). The application investigated considers hardfacing repair of trim edges in a stamping tool. Further, the close cooperation with industry ensures that the project addresses adequate problems.

ACKNOWLEDGEMENTS

The work presented in this paper is performed in close cooperation with the Swedish manufacturing industry and financed by the Swedish MERA (Manufacturing Engineering Research Area) - programme.

REFERENCES

C.L. Atwood, M.L. Griffith, M.E. Schlienger, L.D. Harwell, M.T. Ensz, D.M. Keicher adn J.A. Romero, and J.E. Smugeresky. Laser engineered net shaping (LENS): A tool for direct fabrication of metal parts. In *Proceedings of ICALEO'98*, 1998.

G. Bi, A. Gasser, K. Wissenbach, A. Drenker, and R. Poprawe. Identification and qualification of temperature signal for monitoring and control in laser cladding. *Optics and Lasers in Engineering*, 44(12):1348–1359, 2006a.

G. Bi, A. Gasser, K. Wissenbach, A. Drenker, and R. Poprawe. Characterization of the process control for the direct laser metallic powder deposition. *Surface and Coatings Technology*, 201(6):2676–2683, 2006b.

D.S. Choi, S.H. Lee, B.S. Shin, K.H. Whang, Y.A. Song, S.H. Park, and H.S. Jee. Development of a direct metal freeform fabrication technique using CO2 laser welding and milling technology. *Journal of Materials Processing Technology*, 113:273–279, 2001.

C. Doumanidis and Y.-M. Kwak. Multivariable adaptive control of the bead profile geometry in gas metal arc welding with thermal scanning. *International Journal of Pressure Vessels and Piping*, 79(4):251–262, 2002.

M. Ericsson, P. Nylén, F. Danielsson, and H. Carlsson. Off-line programming of robots for metal deposition. In *7th International Conference on Trends in Welding Research*, May 2005.

E. Fearon and K.G. Watkins. Optimization of layer height control in direct laser deposition. In *23rd International Congress on Applications of Lasers & Electro-Optics (ICALEO 2004)*, 2004.

Graham C. Goodwin, Mario E. Salgado, and Stefan F. Graebe. *Control system design.* Prentice Hall, Upper Saddle River, NJ ; London, 2001.

A. Heralić, A-K. Christiansson, M. Ottosson, K. Hurtig, and B. Lennartson. Automation of robotized laser metal-wire deposition. In *IASTED International Conference on Control and Applications*, pages 80–85, 2007.

C-F. Hung and J. Lin. Solidification model of laser cladding with wire feeding technique. *Journal of Laser Applications*, 16(3):140–146, 2004.

J-D. Kim and Y. Peng. Plunging method for Nd:YAG laser cladding with wire feeding. *Optics and Lasers in Engineerng*, 33(4):299–309, 2000a.

J-D. Kim and Y. Peng. Melt pool shape and dilution of laser cladding with wire feeding. *Journal of Materials Processing Technology*, 104(3):284–293, 2000b.

Y. Li, H. Yang, X. Lin, W. Huang, J. Li, and Y. Zhou. The influence of processing parameters on forming characterizations during laser rapid forming. *Materials Science and Engineering A*, 360:18–25, 2003.

A. Lindskog. Seam tracking laser welding tool. In *European Automotive Laser Applications Conference, (EALA'02)*, 2002.

J. Mazumder, J. Koch, J. Nagarthnam, and J. Choi. Rapid manufacturing by laser aided direct deposition of metals. *Advances in Powder Metallurgy and Particulate Materials*, 4(15):107–118, 1996.

J. Mazumder, D. Dutta, N. Kikuchi, and A. Ghosh. Closed loop direct metal deposition: art to part. *Optics and Lasers in Engineering*, 34:397–414, 2000.

J.O. Milewski, G.K. Lewis, D.J. Thoma, G.I. Keel, R.B. Nemec, and R.A. Reinert. Direct light fabrication of a solid metal hemisphere using 5-axis powder deposition. *Journal of Materials Processing Technology*, 75:165–172, 1998.

O.J.M. Smith. Closer control of loops with deadtime. *Chemical Engineering Progress*, 53:217–219, 1957.

Y-A. Song, S. Park, D. Choi, and H. Jee. 3d welding and milling: Part ia direct approach for freeform fabrication of metallic prototypes. *International Journal of Machine Tools and Manufacture*, 45(9):1057–1062, 2005.

W.U.H. Syed, A.J. Pinkerton, and L. Li. A comparative study of wire feeding and powder feeding in direct diode laser deposition for rapid prototyping. *Applied Surface Science*, 247:268–276, 2005.

W.U.H. Syed, A.J. Pinkerton, and L. Li. Combining wire and coaxial powder feeding in laser direct metal deposition for rapid prototyping. *Applied Surface Science*, 252:4803–4808, 2006.

Y-M. Zhang, P. Li, Y. Chen, and A.T. Male. Weld deposition-based rapid prototyping: a preliminary study. *Journal of Materials Processing Technology*, 135 (2-3):347–357, 2003.