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Process Control of Laser Metal Deposition Manufacturing – A Simulation Study

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ABSTRACT

The laser metal deposition process is a rapid manufacturing operation capable of producing functional prototypes with complex geometries and thin sections. This process inherently contains significant uncertainties and, therefore, extensive experimentation must be performed to determine suitable process parameters. An alternative is to directly control the process on–line using feedback control methodologies. In this paper, a nonlinear control strategy based on feedback linearization is created to automatically regulate the bead morphology and melt pool temperature. Extensive simulation studies are conducted to validate the control strategy.

INTRODUCTION

Laser Metal Deposition (LMD) is a novel layered manufacturing process. A laser melts metal powder (or a wire) to form a molten pool, which quickly solidifies and forms a track. This layered manufacturing process may be used to create functional prototypes and functional gradient material (FGM) metal parts. Also, parts may be repaired using the LMD process, thus, reducing scrap and extending product service life. Extensive experimentation is required to determine suitable process parameters and only near–net shape parts may be produced. Subsequent processing is required if dimensional accuracy is critical. Further, due to the variability in the LMD process, constant process parameters will often not guarantee the part will meet quality specifications in terms of mechanical properties (e.g., hardness, porosity). This variability is due to uncertainties in the process itself (e.g., changes in conduction as the part geometry changes) and from inherent disturbances (e.g., acceleration/deceleration of the table axes). This paper investigates the viability of nonlinear process controllers to regulate the melt pool temperature and track morphology.

Mazumder *et al*. (1999) described the application of multiple sensors for closed–loop feedback control of the bead height. The height controller shuts off the laser until it passes the excess built up region, thus preventing the powder from melting. Doumanidis and Skoredli (2000) established a dynamic distributed parameter model with in–process parameter identification to generate a three–dimensional surface geometry. Geometric predictions were made by a real–time model. A controller was designed to regulate the part geometry taking advantage of these predictions. Morgan *et al*. (1997) controlled the laser focal point and melt pool temperature and Li *et al*. (1987a) developed an in–process laser control loop, which is based on an algorithm involving tune currents. The later system used a microprocessor based in–process beam control unit using beam sensing via a Laser Beam Analyzer (LBA). Koomsap *et al*. (2001) presented a simulation–based design of a laser based, free–forming process controller. A simplified model called a metamodel was introduced to express the relationship between process characteristics and three process parameters: laser power, traverse speed, and powder feedrate. A dynamic metamodel was obtained and a temperature feedback controller was used to regulate the process. Derouet *et al*. (1997) measured the melt pool profile and maximum temperature and correlated this data with the melt pool depth. Using laser power and traverse speed, the melt pool depth was regulated at a constant value with a proportional plus integral plus derivative (PID) controller. Li *et al*. (1987b) developed a real time expert system and a laser cladding control system to determine the optimal operating conditions for a given requirement and for online fault diagnosis and correction. Fang *et al*. (1999) adjusted process parameters from layer–to–layer to compensate for defects using statistical process control techniques. Munjuluri *et al*. (2000) conducted simulation studies to regulate the bead profile and dilution.

These studies indicate that the quality of the laser metal deposition process may be regulated with process control technologies; however, comprehensive, systematic control strategies that account for the inherent process nonlinearities are still lacking.

PROCESS MODELING

The process model used in this paper is based on the model given by Doumanidis and Kwak (2001). Performing a mass balance of the melt pool

$$\rho\dot{V}(t) = -\rho A(t)v(t) + \mu_m m(t) \tag{1}$$

where ρ is the material density (kg/m^3) and is assumed to be constant, V is the bead volume (m^3), A is the cross sectional area in the direction of deposition (m^2), v is the table velocity in the direction of deposition (m/s), μ_m is the powder catchment efficiency, and m is the powder flow rate (kg/s). The volume and cross sectional area in the direction of deposition, respectively, are given by

$$V(t) = \frac{\pi}{6}w(t)h(t)l(t) \tag{2}$$

$$A(t) = \frac{\pi}{4}w(t)h(t) \tag{3}$$

where w is the bead width (m), h is the bead height (m), and l is the bead length (m). Performing a momentum balance of the melt pool in the direction of deposition

$$\rho\dot{V}(t)v(t) + \rho V(t)\dot{v}(t) = \rho\frac{\pi}{4}w(t)h(t)v^2(t) + \left[1-\cos(\theta)\right]\left[\gamma_{GL}-\gamma_{SL}\right]w(t) \tag{4}$$

where θ is the wetting angle (rad), γ_{GL} is the gas to liquid surface tension parameter, and γ_{SL} is the solid to liquid surface tension parameter. Performing an energy balance of the melt pool

$$\begin{aligned}\rho c_l\dot{T}(t)V(t) + \rho\dot{V}(t)\left[c_s\left(T_m-T_0\right)+h_{SL}+c_l\left(T(t)-T_m\right)\right] = -\rho\frac{\pi}{4}w(t)h(t)v(t)c_s\left(T_m-T_0\right)+ \\ \mu_Q Q(t) - \frac{\pi}{4}w(t)l(t)\alpha_s\left(T(t)-T_m\right) - \frac{\pi}{\sqrt[3]{2}}\left[w(t)h(t)l(t)\right]^{\frac{2}{3}}\left[\alpha_G\left(T(t)-T_0\right)+\varepsilon\sigma\left(T^4(t)-T_0^4\right)\right]\end{aligned} \tag{5}$$

where T is the average melt pool temperature (K), c_s is the solid material specific heat ($J/(kgK)$), T_m is the melting temperature (K), T_0 is the ambient temperature (K), h_{SL} is the specific latent heat of fusion–solidification (J/kg), c_l is the molten material specific heat ($J/(kgK)$), μ_Q is the laser efficiency, Q is the laser power (W), α_s is the convection coefficient (W/m^2K), α_G is the heat transfer coefficient (W/m^2K), ε is the surface emissivity, and σ is the Stefan–Boltzmann constant (W/m^2K^4). Using the steady–state solution for the conductive temperature distribution in a material subjected to an energy source moving at a constant velocity, the bead width–length relationship at the average temperature is given by the following elliptical relationship

$$l(t) = X(t) + 0.25\frac{w^2(t)}{X(t)} \quad with \quad X(t) = \max\left[\frac{w(t)}{2} \quad \frac{\mu_Q Q(t)}{2\pi k\left(T(t)-T_0\right)}\right] \tag{6}$$

where k is the thermal conductivity constant ($W/(mK)$). The steady–state and dynamic numerical solution to equations (1), (2), and (4)–(6) is addressed in Boddu *et al*. (2003).

DESIGN OF FEEDBACK LINEARIZATION CONTROLLERS

Two LMD process controllers, based on feedback linearization, are presented in this section. The first controller is utilized to regulate the track width. Combining equations (1)–(3)

$$\dot{V}(t) = -\frac{1.5v(t)}{l(t)}V(t) + \frac{\mu_m}{\rho}m(t) = f_1 + g_1 m(t) \tag{7}$$

The state variable is track volume and the input variable is powder mass flow rate. The output equation is

$$y_1(t) = w(t) = \frac{6}{\pi h(t) l(t)}V(t) \tag{8}$$

While the state equation is linear in the state variable, the system has time–varying parameters that are known and, thus, may be canceled. Therefore, a feedback linearization control scheme is utilized. Since $\frac{\partial y_1}{\partial w} g_1 \neq 0$, the system has a relative degree of one and the following control law may be used

$$m(t) = \frac{a\left[w_r - w(t)\right] - f_1}{g_1} \tag{9}$$

where w_r is the reference track width (m) and a_1 is the controller parameter (s^{-1}). The control law in equation (9) cancels the time–varying dynamics and replaces them with first–order, time–invariant linear dynamics. The closed–loop system now has a time constant of a^{-1}, which may be selected by the designer.

The second LMD process controller is utilized to regulate the melt pool temperature. Combining equations (1) and (5), the temperature nonlinear state equation is

$$\begin{aligned}\dot{T}(t) = &-\frac{1}{\rho c_l V(t)}\left[\mu_m m(t) - \rho A(t) v(t)\right]\left[c_s\left(T_m - T_0\right) + h_{SL} + c_l\left(T(t) - T_m\right)\right] \\ &-\frac{\pi}{4 c_l V(t)} w(t) h(t) v(t) c_s\left(T_m - T_0\right) - \frac{\pi}{4\rho c_l V(t)} w(t) l(t) \alpha_s\left(T(t) - T_m\right) \\ &-\frac{\pi}{\sqrt[3]{2}}\frac{1}{\rho c_l V(t)}\left[w(t)h(t)l(t)\right]^{\frac{2}{3}}\left[\alpha_G\left(T(t)-T_0\right) + \varepsilon\sigma\left(T^4(t) - T_0^4\right)\right] + \frac{1}{\rho c_l V(t)}\mu_Q Q(t) = f_2 + g_2 Q(t)\end{aligned} \tag{10}$$

The state variable is melt pool temperature and the input variable is laser power. The output equation is

$$y_2(t) = T(t) \tag{11}$$

The state equation is highly nonlinear and has time–varying parameters that are known and, thus, may be canceled. A feedback linearization control scheme is again utilized. Since $\frac{\partial y_2}{\partial T} g_2 \neq 0$, the system has a relative degree of one and the following control law may be used

$$Q(t) = \frac{b\left[T_r - T(t)\right] - f_2}{g_2} \tag{12}$$

where T_r is the reference melt pool temperature (*K*) and *b* is the controller parameter (s^{-1}). Again, the control law in equation (12) has canceled the time–varying dynamics and replaced them with first–order, time–invariant linear dynamics and the closed–loop system has a time constant given by b^{-1}, which may be selected by the designer.

SIMULATION STUDIES

A series of simulations are now conducted to analyze the feedback linearization controllers. The following parameters are taken from Doumanidis and Kwak (2001): ρ = 7200 kg/m^3, μ_m = 0.92, μ_Q = 0.58, T_0 = 292 *K*, $\theta = 90^0$, c_l = 780 *J*/(*kgK*), $h_{SL} = 2.45*10^5$ *J*/*kg*, T_m = 1673 *K*, α_s = 183 *W*/(m^2K), $\sigma = 5.67*10^{-8}$ *W*/(m^2K^4), α_G = 24 *W*/(m^2K), and ε = 0.53. To achieve the same simulation results presented in Doumanidis and Kwak (2001), the following parameters were found by trial and error: *k* = 6.5 *W*/(*mK*), $\gamma_{GL}-\gamma_{SL}$ = –0.00036, c_s = 1250 *J*/(*kgK*),

The reference bead width is 4.5 *mm* and the reference melt pool temperature is 1773 *K* for all the simulations. In the first three simulations, the bead width controller given by equation (9) is implemented for three different values of the parameter *a*, the laser power is 1200 *W*, and the table velocity is 5 *mm*/*s*. The results are shown in Figures 1–3. For *a* = 0.2 and 0.5, the powder flow rate was decreased to perfectly track the reference bead width. As expected, the speed of response was smaller for the larger controller gain. However, for *a* = 1, the controller was unstable. The powder mass flow rate increased exponentially, the bead width went towards zero, and the bead height became unreasonably large. In the simulation, the minimum melt pool temperature is the ambient temperature since the LMD system cannot take energy out of the melt pool. The results demonstrate that the speed of response cannot be arbitrarily small. Also, it is interesting to note that the reference temperature was not tracked. This is to be expected since an arbitrary value of laser power was selected.

The next set of simulations are shown in Figures 4–6 where the melt pool temperature controller, given by equation (12), is implemented for *b* = 0.2, 0.5, and 24, respectively. The powder flow rate and the table velocity are constant values of 25 *g*/*min* and 5 *mm*/*s*, respectively. Again, the reference melt pool temperature was tracked in the steady–state and the speed of response decreased as the controller gain increased. However, the speed of response is limited as the system went unstable for *b* = 25 (not shown). Again, the reference bead width is not tracked since the powder flow rate was an arbitrary value.

In the next set of simulations, shown in Figures 7 and 8, the bead width controller and the melt pool temperature controller are implemented simultaneously. In the first simulation, *a* = *b* = 0.5 and the table velocity is a constant 5 *mm*/*s*. In the next simulation, *a* = *b* = 0.2, the table is accelerated for part of the period, and the table is decelerated for part of the period. The exact table velocity and acceleration profiles are shown in Figure 8. Note that in implementation, the powder flow rate is calculated first since the laser power needs this value in its calculation. The controllers, when utilized together, are able to simultaneously regulate the bead width and melt pool temperature. The entire effect of the table acceleration does not appear in the differential equations and, thus, is not completely taken into account by either controller. However, the controllers are able to maintain the desired references after the table reaches a new constant velocity. Also, the table acceleration is seen to have much more impact on the bead dimensions than on the melt pool temperature.

SUMMARY, CONCLUSIONS, AND FUTURE WORK

This paper presented a nonlinear, multivariable control method to regulate the bead width and melt pool temperature in an LMD process. The controllers were applied to a simulation of the LMD process. The results demonstrate that the bead width and melt pool temperature can be regulated simultaneously, but there is a limitation on the closed–loop system's speed of response. If the controller gain is too large, instability will occur. Also, it was shown that table acceleration had a dramatic effect on the bead dimensions but not the melt pool temperature. Future work will be to validate the controllers experimentally and analytically determine their stability limits.

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REFERENCES

Boddu, M.R., Thayalan, V., and Landers, R.G., 2003, "Modeling for the Control of the Laser Aided Manufacturing Process (LAMP)," in *Fourteenth Annual Solid Freeform Fabrication Symposium*, Austin, Texas, August 4–6.

Derouet, H., Sabatier, L., Coste, F., and Fabbro, R., 1997, "Process Control Applied to Laser Surface Remelting," *Proceedings of ICALEO*, Sec. C, pp. 85–92.

Doumanidis, C. and Kwak Y–M., 2001, "Geometry Modeling and Control by Infrared and Laser Sensing in Thermal Manufacturing with Material Deposition," *ASME Journal of Manufacturing Science and Engineering*, Vol. 123, No. 1, pp. 45–52.

Doumanidis, C. and Skoredli, E., 2000, "Distributed–Parameter Modeling for Geometry Control of Manufacturing Processes with Material Deposition," *ASME Journal of Dynamic Systems, Measurement, and Control*, Vol. 122, No. 1, pp. 71–77.

Fang, T. and Jafari, M.A., 1999, "Statistical Feedback Control Architecture for Layered Manufacturing," *Journal of Materials Processing and Manufacturing Science*, Vol. 7, pp. 391–404.

Koomsap, P., Prabhu, V.V., Schriempf, J.T., Reutzel, E.W., 2001, "Simulation–Based Design of Laser–Based Free Forming Process Control," *Journal of Laser Applications*, Vol. 13, No. 2, pp. 47–59.

Li, L., Hibberd, R.H., and Steen, W.M, 1987a, "In–Process Laser Power Monitoring and Feedback Control," *4th International Conference of Lasers in Manufacturing*," pp. 165–176.

Li, L., Steen, W.M., Hibberd, R.H., and Weerasinghe, V.M., 1987b, "Real–Time Expert Systems for Supervisory Control of Laser Cladding," *Proceedings of ICALEO*, pp. 9–15.

Mazumder, J., Schifferer, A., and Choi, J., 1999, "Direct Materials Deposition: Designed Macro and Microstructure," *Materials Research Innovation*, Vol. 3, pp. 118–131.

Morgan, S.A., Fox, M.D.T., McLean, M.A., Hand, D.P., Haran, F.M., Su, D., Steen, W.M., and Jones, J.C., 1997, "Real–Time Process Control In CO_2 Laser Welding and Direct Casting: Focus and Temperature," *International Congress on Applications of Lasers and Electro–Optics*, Sec. F, pp. 290–299.

Munjuluri, N., Agarwal, S., and Liou, F.W., 2000, "Process Modeling, Monitoring and Control of Laser Metal Forming," *Eleventh Annual Solid Freeform Fabrication Symposium*, Austin, Texas.

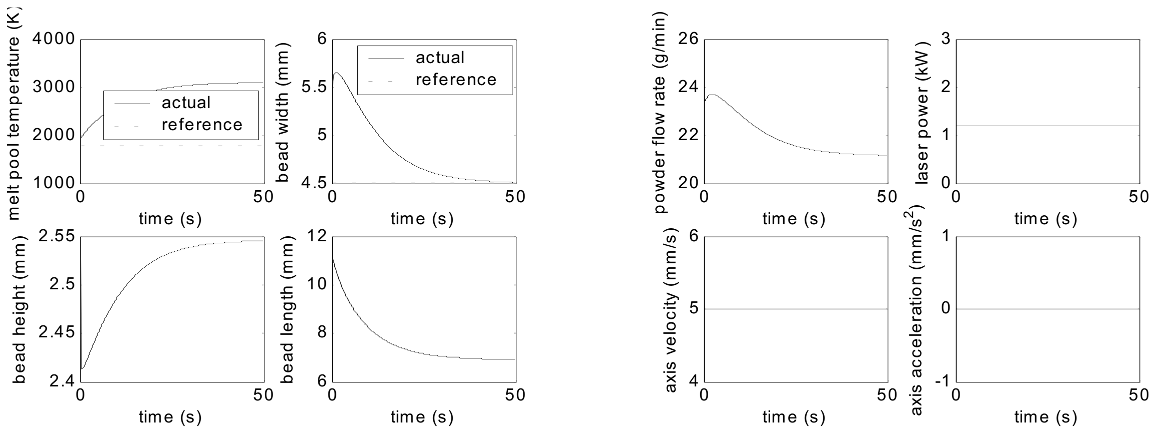

Figure 1: Bead Width Control with *a* = 0.2.

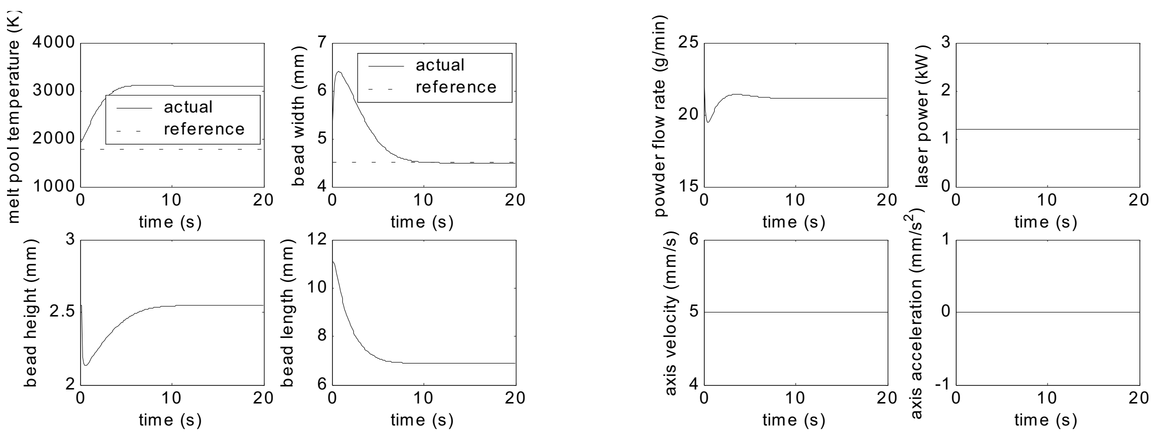

Figure 2: Bead Width Control with *a* = 0.5.

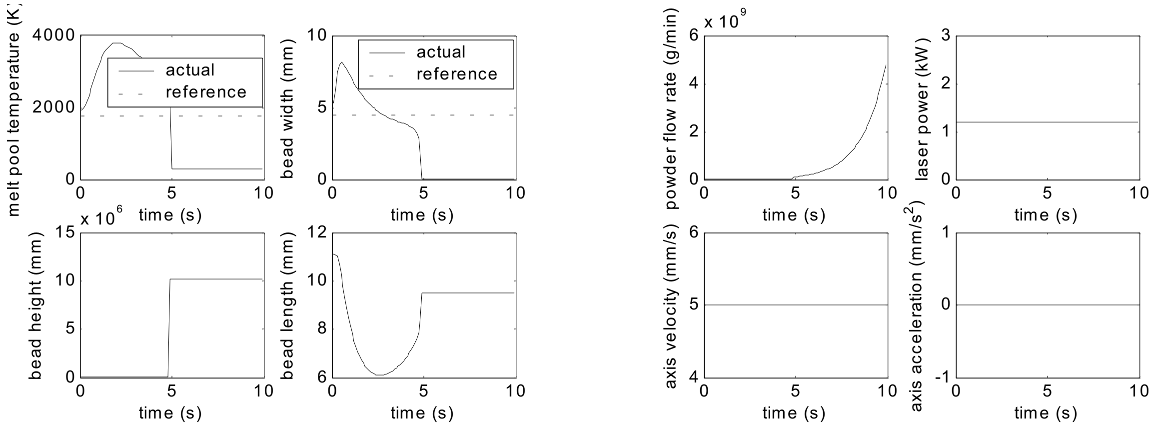

Figure 3: Bead Width Control with *a* = 1.

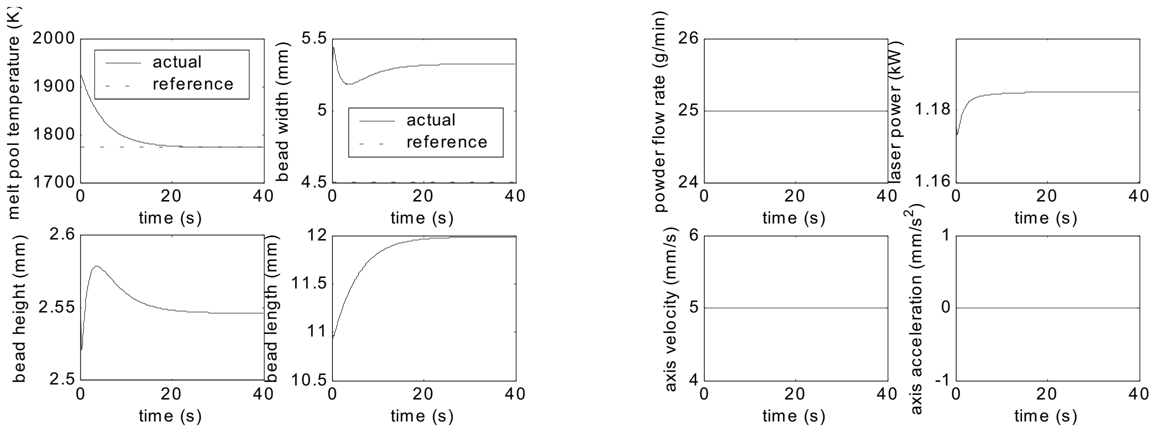

Figure 4: Melt Pool Temperature Control with *b* = 0.2.

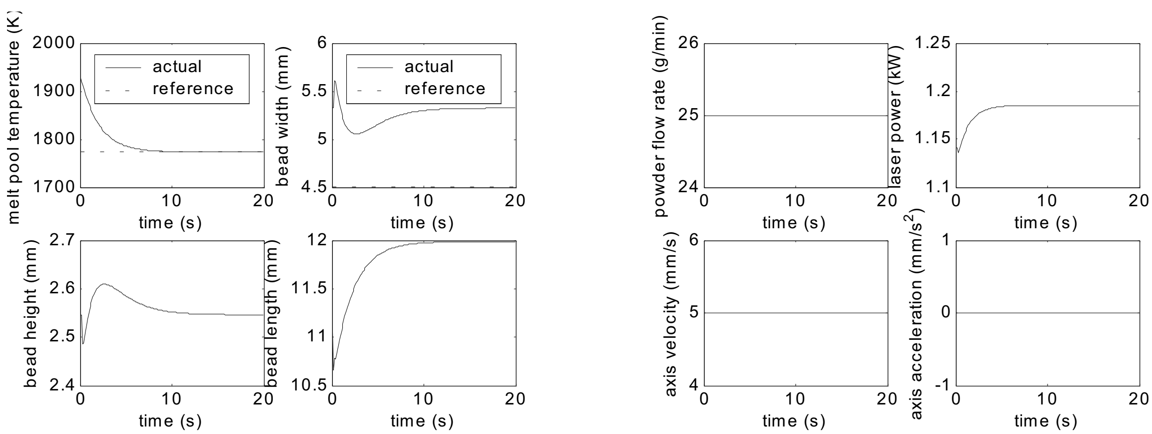

Figure 5: Melt Pool Temperature Control with *b* = 0.5.

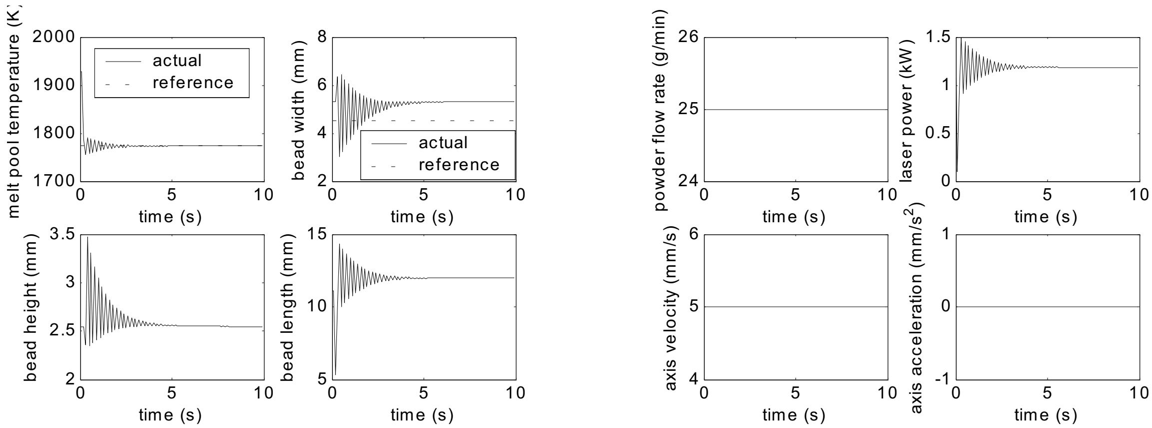

Figure 6: Melt Pool Temperature Control with *b* = 24.

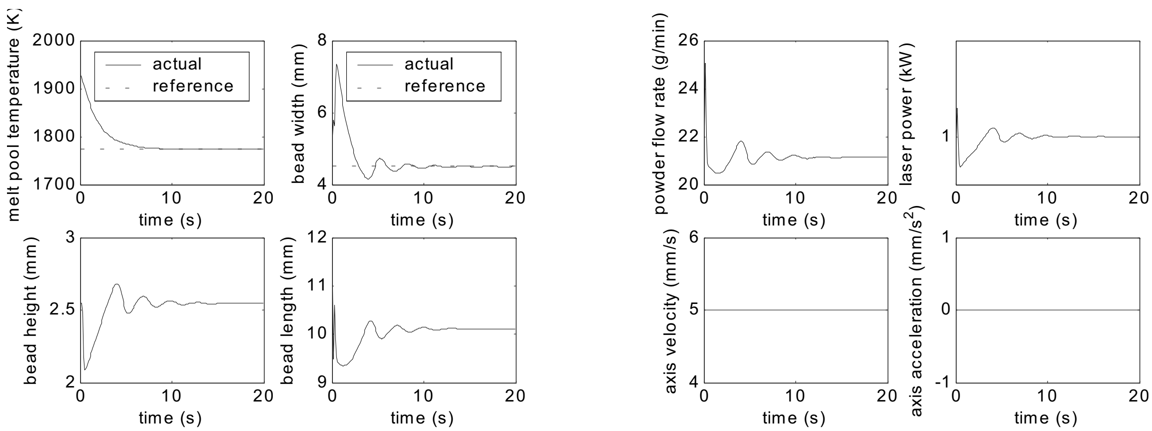

Figure 7: Temperature and Bead Width Control with Constant Table Velocity (*a* = *b* = 0.5).

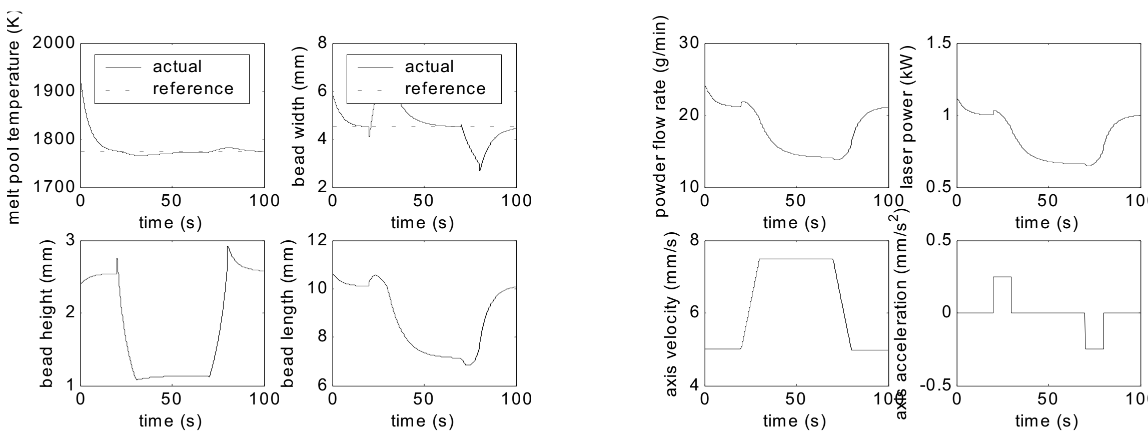

Figure 8: Temperature and Bead Width Control with Constant Table Acceleration (*a* = *b* = 0.2).