Composition Control in the Direct Laser-Deposition Process

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Laser-engineered net shaping (LENS) is a solid freeform fabrication process that has the capability of producing functionally graded material (FGM) components by selectively depositing different powder materials in the melt pool at specific locations in the structure during part buildup. The composition in each layer of an FGM is dependent upon the degree of dilution between the substrate (or previous layer) and powder material. A study on the effects of LENS processing parameters (laser power, travel speed, and powder mass flow rate) on dilution was conducted for deposits of H-13 tool steel and copper powder on H-13 tool steel substrates. When varying a single processing parameter while holding all others constant, the dilution was found to increase with increasing laser input power and travel speed and decrease with increasing powder mass additions into the melt pool. A method for estimating dilution in LENS deposits was developed from knowledge of LENS process efficiencies and material thermophysical properties. A reasonable correlation was shown to exist between the experimentally measured dilution and the dilution calculated from the model.

I. INTRODUCTION

THE fabrication of functionally graded materials (FGMs) for industry-related applications has been one aspect of solid freeform fabrication research.[1,2,3] Various solid freeform fabrication processes have the ability to fabricate intricately shaped components with local compositional control, resulting in unique mechanical properties throughout the graded structure. The laser-engineered net shaping (LENS) process is one such solid freeform fabrication method that has the ability to produce functionally graded structures by selectively depositing different elemental powders or premixed blends into the molten pool at discrete locations. The adaptation of multiple powder feeders in the LENS system makes this feasible. Dissimilar powder materials can be placed into separate powder hoppers. Computer software, which is integrated into the powder feed system, enables the user to vary the deposit composition as a function of position.

Although the ability to produce FGMs with the LENS process is advantageous, this advantage can only be fully exploited when methods are available for controlling the composition within each layer deposit. Previous work in the closely related process of fusion welding has demonstrated[4] that the chemical composition of the deposit can be determined through knowledge of the geometric dilution (D) between the melted substrate and deposited powder, where D is given by

$$D = \frac{A_s}{A_s + A_P} \quad [1]$$

where A_s is the cross-sectional area of melted substrate and A_p is the cross-sectional area of deposited powder. It has recently been demonstrated that determination of composition through the geometric dilution agrees very well with the composition determined through direct chemical analysis.[4,5] Figure 1 describes this in more detail.

The term "FGM" generally refers to a material in which the composition changes in a continuous manner from one target value to another. However, with a direct metal-deposition process such as LENS, which induces localized melting, it is well known that the substrate and powder thoroughly mix in the molten state to produce a homogeneous deposit.[4,5] A partially mixed zone will exist directly adjacent to the melt boundary, in which the composition varies continuously from that of the substrate to that of the homogeneous deposit. However, previous work has shown that this partially mixed zone is generally very small in relation to the deposit size.[4] Thus, any FGM produced with the LENS process will actually exhibit "stepped" changes in composition, as shown schematically in Figure 1(a). (The changes in composition, which reside within the relatively small partially mixed zone, are not shown in Figure 1(a) for clarity.) The optimal variation in dilution and concomitant composition with location will depend on the application of interest. For example, for applications in which the main objective is to smooth out mismatch in mechanical and thermophysical properties between two different materials, very gradual changes in composition with distance may be most appropriate. On the other hand, some applications may exhibit spatial limitations, in which changes in material composition are restricted within a certain spatial range. Thus, a range of dilution and composition gradients are expected to be needed to meet the potential range of engineering applications.

Use of the dilution parameter for controlling the composition of a stepped material gradient is shown schematically in Figures 1(b) and (c) for fabrication of a thin-walled component, in which the wall thickness is equivalent to the deposit width. For the first layer, the dilution is determined directly from the cross-sectional area of the melted substrate (A_s) and the cross-sectional area of the deposited powder (A_p). Since the composition is uniform throughout the deposit,[4] the concentration of any particular alloying element (i) in the first layer (denoted with a superscript 1) is

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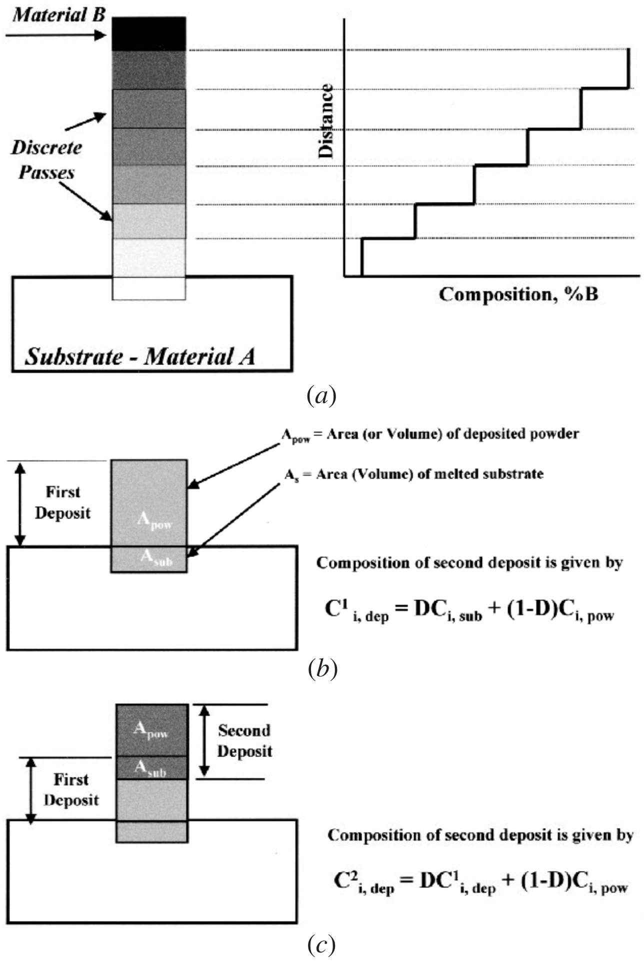


Fig. 1—(*a*) and (*c*) Schematic illustration of weld cross-sectional area for dilution measurements (A_p—deposit cross-sectional area, and A_s—melted substrate cross-sectional area).

determined from the dilution parameter by a simple rule-of-mixtures approach:

$$C^1_{i,dep} = (D^{S\&1})C_{i,sub} + (1 - D^{S\&1})C_{i,pow} \quad [2]$$

Where $C^1{}_{i,dep}$ is the concentration of element i in the first layer deposit, $C_{i,sub}$ is the concentration of element i in the substrate, $C_{i,pow}$ is the concentration of element i in the powder, and $D^{S\&1}$ is the dilution between the substrate and the first layer. When the second layer is deposited, the first layer can be viewed as assuming the rule of the substrate, and the concentration of any particular alloying element in the second layer is determined by

$$C^2_{i,dep} = (D^{1\&2})C^1{}_{i,dep} + (1 - D^{1\&2})C_{i,pow} \quad [3]$$

Where $C^2{}_{i,dep}$ is the concentration of any element i in the second layer, $C^1{}_{i,dep}$ is the concentration of that element in the first layer, and $D^{1\&2}$ is the dilution between the first and second layers. In general, the concentration of any element within a current layer (j) is given by

$$C^j_{i,dep} = (D^{j-1\&j})C^{j-1}_{i,dep} + (1 - D^{j-1\&j})C_{i,pow} \quad [4]$$

Thus, knowledge of dilution provides a method for controlling the individual deposit compositions within a stepped material gradient. As with fusion welding, the dilution is expected to vary with changes in powder feed rate, heat-source power, and heat-source travel speed.[5] Thus, relations between dilution and processing parameters are needed in order to control deposit composition. It should be noted that deposition of heavy-walled (*i.e.*, multipass) components, in which the wall thickness is greater than the deposit width, will also need to consider the relative amount of melting from adjacent passes within the same layer. Such considerations are beyond the scope of this initial investigation. The objective of this initial study is to examine the effects of LENS processing parameters on dilution in simple, single-layer deposits and to develop a method that can be used to estimate dilution from knowledge of the processing parameters. The results of this study will then form the basis of future investigations of more complex geometries.

II. EXPERIMENTAL PROCEDURE

The LENS 750 Directed Metal Deposition System, manufactured by Optomec Design Company (Albuquerque, NM), was used to deposit H-13 tool steel and copper onto grit-blasted H-13 tool steel substrates under the matrix of processing parameters presented in Table I. The process-parameter range was chosen to obtain a wide range of processing conditions. Single-pass deposits were made in order to simplify the layer-additive process, so that the effects of process variables could be extensively explored in a simplistic manner. To measure dilution, the deposits were cross sectioned using an abrasive cutoff wheel, polished to a 1 μm finish, and etched using 2 pct Nital. A quantitative image-analysis system was used to measure the cross-sectional area of deposited powder material and the cross-sectional area of melted substrate, as shown schematically in Figure 1.

III. BACKGROUND

As described in more detail in Section IV, knowledge of LENS process efficiencies is required to develop relations between parameters and dilution. Process efficiencies (laser-energy-transfer efficiency (η_a), melting efficiency (η_m), and deposition efficiency (η_d)) were previously measured as a function of laser power, travel speed, and powder mass flow rate under the same set of processing parameters used in this study. The results of these measurements are explained in detail in Reference 6, but are also briefly summarized in

Table I. Experimental Test Matrix of Processing Parameters used to Deposit H-13 Tool Steel and Copper Powder on H-13 Tool Steel Substrates for Dilution Measurements

Powder Material	Laser Power (W)	Travel Speed (mm/s)	Powder Flow Rate (g/s)
H-13 tool steel	125 to 500	5 to 35	0.08 to 0.33
Copper	250 to 500	5 to 35	0.11 to 0.22

the following text, as they are important for developing relations between dilution and LENS parameters.

A. *Laser-Energy-Transfer Efficiency*

The Laser-energy-transfer efficiency represents the fraction of laser output energy that is actually absorbed by the workpiece. The η_a parameter is important, because the absorbed energy can be significantly different than the output energy, and the absorbed energy will strongly affect the amount of substrate and powder that is melted in the deposit. The transfer efficiency of the LENS process has been measured using a Seebeck envelope calorimeter for H-13 tool steel and copper powder deposits on H-13 tool steel substrates. Previous studies on this gradient-layer-type calorimeter method have shown this to be an accurate method for measuring energy-transfer efficiency for arc and laser welding processes.[7–11] From the range of processing parameters tested, the resulting laser-energy-transferefficiency measurements ranged between 30 and 50 pct, as can be seen in Figure 2. The energy-transfer efficiency is plotted as a function of heat input for varying powder mass flow rates of H-13 tool steel and copper deposits. No trend was observed that would suggest any influence of powder additions on laser-beam absorption. The type of powder material deposited, H-13 tool steel or copper, also has no effect on the laser-energy-transfer efficiency, and an average transfer efficiency of 0.40 can be used to provide a good estimate of the actual laser energy absorbed by the workpiece.

B. *Melting Efficiency*

The laser energy absorbed by the workpiece is generally utilized in two ways—a fraction of the energy is utilized for melting, while the major fraction of remaining energy escapes to the surrounding unmelted area *via* thermal conduction. The melting efficiency represents the fraction of absorbed energy which is actually utilized for melting. The melting efficiency is strongly affected by processing parameters and

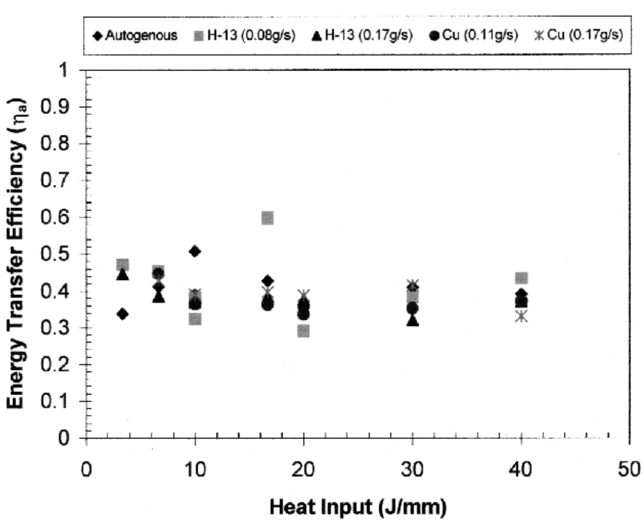


Fig. 2— Plot of energy transfer efficiency as a function of heat input for varying powder mass flow rates.

material thermophysical properties.[10] The melting efficiency for each processing condition was determined by

$$\eta_m = \frac{V_p \Delta H_p + V_s \Delta H_s}{\eta_a P t} \qquad [5]$$

Where η_a is the laser transfer efficiency, P is the laser power, t is the deposition time, and V_p and V_s are the total volume of the deposited powder and melted substrate, respectively. The parameters V_p and V_s were determined by multiplying the cross-sectional area of the deposited powder and melted substrate by the deposit length. The ΔH terms directly adjacent to V_p and V_s correspond to the melting enthalpy for the powder and the substrate, respectively. For the H-13 tool steel powder deposited on the H-13 tool steel substrate, the melting enthalpy (which is the energy required to raise the temperature of the material above its melting temperature and supply the latent heat of fusion) of the powder and the substrate are the same, since they are of the same material (10.5 J/mm^3).[12] In cases where copper was deposited onto the H-13 tool steel substrate, the melting enthalpy of copper[12] was used for ΔH_p, (5.9 J/mm^3).

A dimensionless-parameter model that has been used to predict melting efficiency through knowledge of process variables and material thermophysical properties was used to estimate the melting efficiency for the LENS deposits. This approach has been described in detail elsewhere[6,9,13] and will be briefly reviewed here. The model uses dimensionless parameters to correlate the weld size to processing parameters, and they are defined as follows:

$$Ry = \frac{\eta_a P S}{\alpha^2 \Delta H_m} \qquad [6]$$

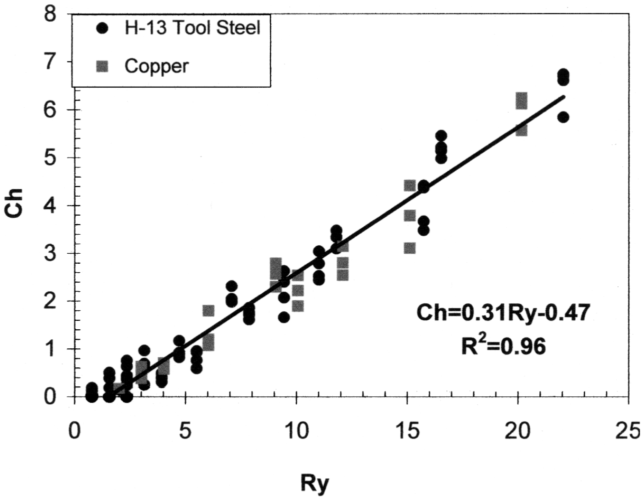
$$Ch = \frac{S^2 A}{\alpha^2} \qquad [7]$$

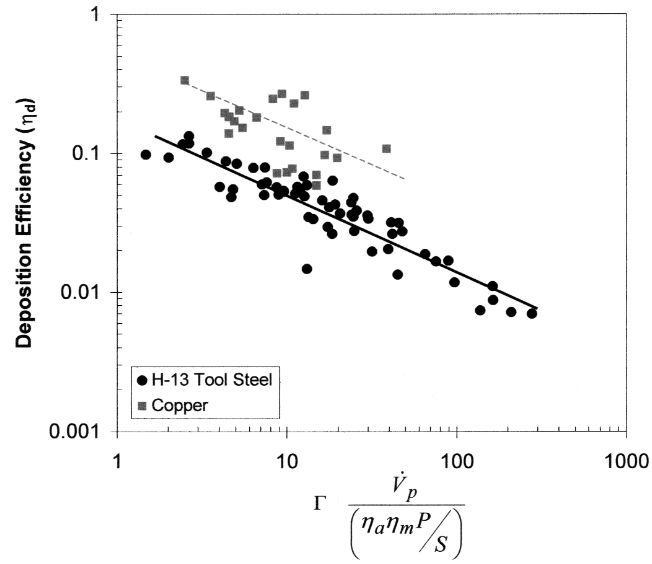
Where S is the heat-source travel speed, α is the thermal diffusivity of the substrate at the liquidus temperature, ΔH_m is the melting enthalpy, and A is the total deposit cross-sectional area. The ratio of Ch to Ry yields the melting efficiency:

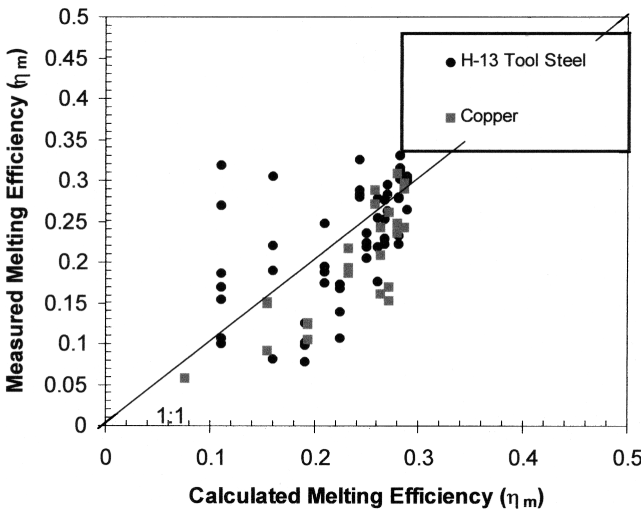
$$\eta_m = \frac{Ch}{Ry} = \frac{S A \Delta H_m}{\eta_a P} \qquad [8]$$

(Equation [8] is simply an alternative expression to Eq. [5], in which the energy required for melting ($A\Delta H_m$) and the actual absorbed energy ($\eta_a P/S$) are defined per unit length of deposit). As shown in Figure 3(a) and consistent with the original approach to this dimensionless-parameter model,[9,13] a correlation between Ch and Ry has been developed. This correlation allows melting efficiency to be determined solely as a function of the dimensionless parameter (Ry) for the materials used in this study. The melting efficiency can be determined through the Ry parameter by

$$\eta_m = 0.31 - \frac{0.47}{Ry} \qquad [9]$$


H-13 Tool Steel
Copper
Ch=0.31Ry-0.47
R^2=0.96
Ch
Ry


H-13 Tool Steel
Copper
Deposition Efficiency (η_d)
$\Gamma \quad \frac{\dot{V}_p}{\left(\eta_a \eta_m P/S\right)}$


H-13 Tool Steel
Copper
1:1
Measured Melting Efficiency (η_m)
Calculated Melting Efficiency (η_m)

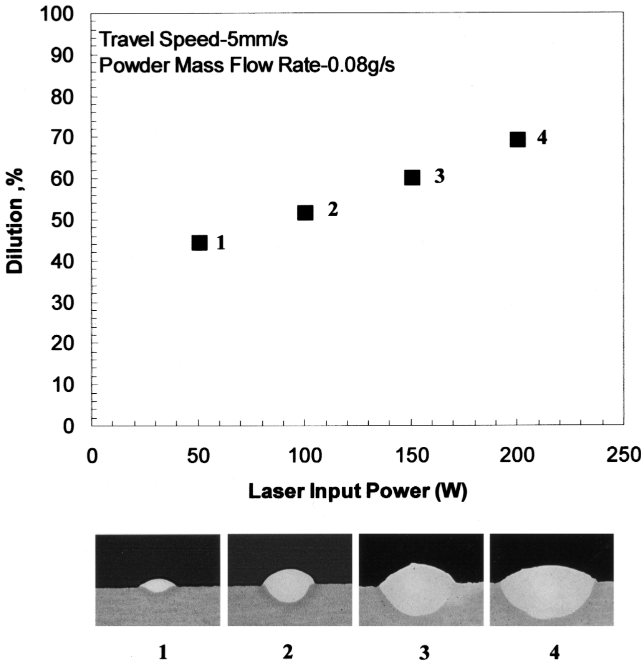


Fig. 5—Dilution as a function of laser input power for fixed travel speed and powder mass flow rate for direct deposition of H-13 powder onto H-13 substrates.

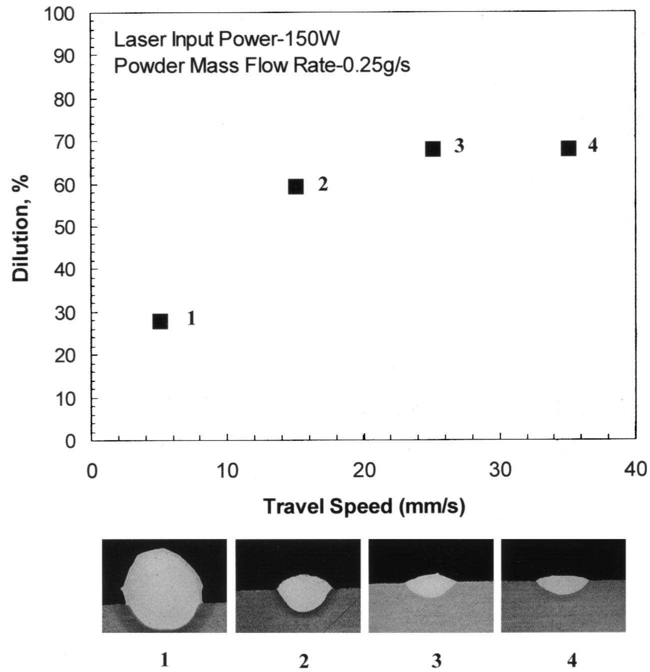


Fig. 6—Dilution as a function of travel speed for fixed laser input power and powder mass flow rate for direct deposition of H-13 powder onto H-13 substrates.

size of the deposit and melted substrate both increase with increasing laser-input power. However, since the powder mass flow rate is constant in this condition, the melted substrate area increases more than the deposit cross-sectional area when the laser-input power is increased. This, in turn, causes an increase in dilution.

The dilution was observed to initially increase and then saturate as the travel speed increased, for a constant laser-input power and powder mass flow rate (Figure 6). There are two primary factors that can cause this behavior. First, the amount of deposited powder material will be affected by the travel speed, as evident through the following expression:

$$A_p = \frac{\eta_d \dot{V}_p}{S} \quad [12]$$

Where A_p is the cross-sectional area of deposited filler material, η_d is deposition efficiency, $\dot{V}_p$ is the volumetric filler-metal feed rate, and S is the travel speed. Equation [12] shows that the deposit cross-sectional area is dependent upon the ratio of the volumetric powder-material feed rate to the travel speed. As the travel speed increases, there is less powder delivered to the melt pool, resulting in a decrease in deposit cross-sectional area. This is evident when examining the corresponding micrographs for the data points in Figure 6. The micrographs clearly depict a decrease in the deposit cross-sectional area as the travel speed increases.

The dilution will also be affected by the melting efficiency. As the melting efficiency increases, more of the incoming laser power is available for melting the underlying substrate and incoming powder. If the powder feed rate is held fixed (as was done for Figure 6), then the powder melting rate (and, therefore, A_p) is not expected to change significantly. Thus, the major effect would be to increase the amount of melted substrate, which would, in turn, increase dilution. It is well known[4,8,9] that the melting efficiency initially increases with increasing travel speed and then saturates at higher travel speeds. Such behavior may account for the leveling of dilution shown in Figure 6 with the higher travel speed. (It should be noted, however, that there is no limit to the dilution that can be obtained with this process. For example, a dilution value near 100 pct is easily obtained by simply reducing the powder feed rate. In fact, the dilution reaches 100 pct when the powder feed rate is zero.)

Dilution was also observed to decrease with increasing powder mass flow rate when the laser input power and travel speed are held constant (Figure 7). This effect can also be explained from Eq. [12]. From this equation, it is apparent that when the travel speed is constant, an increase in the volumetric powder-material feed rate will result in an increase in the deposit cross-sectional area. Examination of the micrographs in Figure 7 shows this trend as well. As more powder is delivered to the melt pool, a greater amount of energy is utilized to melt the incoming powder flux, leaving a lesser amount of energy to melt the underlying substrate.[4] When this occurs, the melted substrate cross-sectional area decreases. Thus, the deposit is comprised of a larger fraction of deposit material. Dilution, therefore, decreases as the powder mass flow rate increases.

B. *Estimating Dilution in LENS Deposits*

A method of predicting dilution levels for arc welding processes as a function of processing parameters has previously been proposed.[4] The model is based upon a power-balance

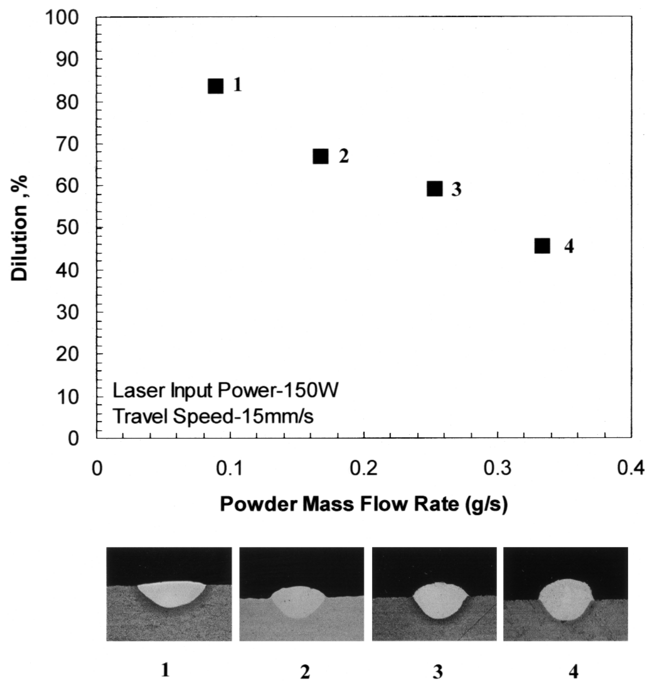


Fig. 7—Dilution as a function of powder mass flow rate for fixed laser input power and travel speed for direct deposition of H-13 powder onto H-13 substrates.

approach across the heat source, where the total energy available for melting is set equal to the energy required to melt the filler and substrate materials. The power balance is given by

$$\eta_a \eta_m P = \eta_d \dot{V}_p \Delta H_p + \dot{V}_s \Delta H_s \quad [13]$$

Where the left-hand side of the equation ($\eta_a \eta_m P$) represents the power available for melting. The right-hand side of the equation has two terms that represent the power required to sustain the volumetric melting rates of the deposited powder and substrate. In arc welding processes where a filler wire is used, the deposition efficiency is, essentially, unity. However, as previously shown, only a small fraction of the incoming powder actually fuses to the deposit in the LENS process. The deposition efficiency (η_d) is incorporated into Eq. [13] in order to account only for powder that is fused to substrate. Since the energy-transfer and melting efficiencies can be estimated, rewriting Eq. [13] in terms of the only unknown variable ($\dot{V}_s$) yields the following:

$$\dot{V}_s = \frac{\eta_a \eta_m P - \eta_d \dot{V}_p \Delta H_p}{\Delta H_s} \quad [14]$$

As previously shown,[4] Eq. [1] can be rewritten in terms of volumetric melting rates of the powder and substrate. Rewriting this in another form results in the following:

$$D = \frac{\dot{V}_s}{\dot{V}_s + \eta_d \dot{V}_p} = \left(1 + \frac{\eta_d \dot{V}_p}{\dot{V}_s} \right)^{-1} \quad [15]$$

Substituting Eq. [14] into [15] yields an expression for dilution as a function of melting power, volumetric filler-metal feed rate, and melting enthalpy of the substrate and powder materials:

$$D = \left(1 + \frac{\eta_d \dot{V}_p \Delta H_s}{\eta_a \eta_m P - \eta_d \dot{V}_p \Delta H_p} \right)^{-1} \quad [16]$$

Equation [16] provides a method to estimate dilution, since the energy-transfer efficiency is known and the melting efficiency can be estimated from the dimensionless-parameter model described previously. The results of the laser-energy-transfer efficiency measurements show that the laser-energy-transfer efficiency was relatively insensitive to the range of processing parameters used in this study. Therefore, an average η_a value of 0.4 was used in all calculations.

As shown in Figures 2 and 3, η_a and η_m are not sensitive to changes in the powder composition within the range of dilution values produced for these single-pass deposits. However, in cases where multiple layers are deposited and more significant composition and geometry changes are produced, η_a and η_m may change more appreciably. For example, η_a is expected to be lower for deposition on pure copper due to the relatively low absorptivity of copper from the Nd:YAG laser. Thus, with the deposition of additional layers of copper, the copper concentration will gradually increase and the η_a value may be reduced beyond that shown in Figure 2. The value of η_m will depend on component geometry and thermal diffusivity.[4,8] Consider again the case of copper deposition onto steel. Complete construction of a tall, thin wall of copper onto the steel will eventually produce a local increase in thermal diffusivity and a change in heat-transfer condition from three dimensional (which occurs when deposition takes place near the thick substrate) to two dimensional (when the thin wall becomes high enough so that the substrate no longer forms an effective heat sink). The localized increase in thermal diffusivity may have the effect of reducing η_m, while the shift in heat transfer from three dimensional to two dimensional may increase η_m. These additional factors may need to be taken into account by adjusting η_a and η_m with deposition conditions and will be evaluated in more detail in future studies.

Figure 8 shows a comparison of the measured and calculated dilution values. The results indicate that there is reasonable correlation between measured and calculated dilution values at high dilution values, and there is more scatter at lower dilution values. As previously discussed,[4] the deviation between measured and calculated values at low dilution levels results from the difficulty in predicting η_m when the melting efficiency is low. At low values of melting efficiency, small increases in the laser power and/or heat-source travel speed produce relatively large changes in the melting efficiency. As a result, changes in melting efficiency with variations in processing parameters are difficult to predict accurately when η_m is low. As the melting efficiency increases, η_m asymptotically approaches the maximum value of 0.37[8] (for three-dimensional heat-flow conditions), and η_m does not change significantly with even large changes in laser power and/or travel speed. Under these conditions, the melting efficiency and dilution can each be predicted with reasonable accuracy.

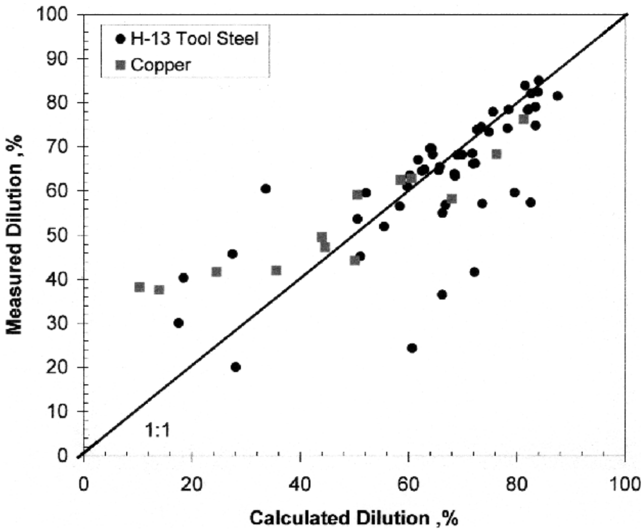


Fig. 8—Comparison between measured dilution and calculated dilution for H-13 tool steel and copper powder deposits on H-13 tool steel substrates.

V. CONCLUSIONS

A study has been conducted on dilution in the LENS solid freeform fabrication process. The following conclusions can be drawn from this work.

1. Dilution increases with increasing laser power and travel speed and decreasing powder mass flow rate.
2. The previous dilution model, developed to predict dilution for arc welding processes, was shown to be applicable for the LENS process when a deposition-efficiency term is incorporated, in order to account only for powder which was incorporated into the melt pool.
3. The dilution model provides reasonable estimates of deposit dilution, particularly at high dilution levels. Inaccuracies at low dilution levels are attributed to difficulty in accurately predicting the melting efficiency when the melting efficiency is low.

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