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Height variation in scanned hot-wire laser surfacing processes

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Abstract

The use of hot wire in laser cladding can raise the energy efficiency and the deposition rate of the process drastically. This study shows that when using hot wire, the process faces stronger restrictions to one of the process parameters, the wire nozzle height. A change of three millimeters in wire nozzle height can double the dilution. This is because of the impact of stick out length on the wire heating. But not only the heating has an effect when changing the height, it also changes the wire positioning, a parameter which is sensible for the process stability.

Keywords: height variation; hot-wire; laser cladding; heating power; process stability

1. Introduction

Laser cladding is a very precise process in terms of dilution with the drawback of not being energy efficient. This disadvantage can be reduced by adding resistive heating of the wire by electric current. Hinse-Stern et al. developed this technique and called it laser hot wire cladding [1]. The temperature of the wire depends on the stick out, which again is influenced by the wire nozzle height, the vertical distance of the wire nozzle to the work piece. Although this process can only be used with NC controlled handling systems, there are many reasons for wire nozzle height deviations during the process or when changing process parameters. The most obvious reason is a work piece that is not flat and a NC system that does not perfectly follow its surface. A less obvious reason for deviations can be seen when looking at the stick out, which is the extension of the wire from the wire nozzle. Usually, this extension is defined as the distance from the wire nozzle to the work piece. Hagqvist et al. [2] worked with this definition in order to use resistance measurements for a height control

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system. In a control system, this approach works, since the aim is to obtain a constant height. In this paper the stick out is defined as the distance between the wire nozzle and the current work piece surface, measured along the wire axis. This definition considers both, the work piece surface as well as the surface of the melt-pool. The reason for this definition is the cross sectional area of the electrical conductor. Only a small cross sectional area of the conductor leads to desired heating effect, due to its high resistance. This means that if the wire has contact to the melt pool, which is on a higher level than the work piece surface, the stick out is reduced (Fig. 1 right side). In this case the seam height gains an influence on the heating power. The seam height again can be influenced by process parameters. Feed to propagation speed ratio has a great effect on the height, but also the laser power has an influence [3-5].

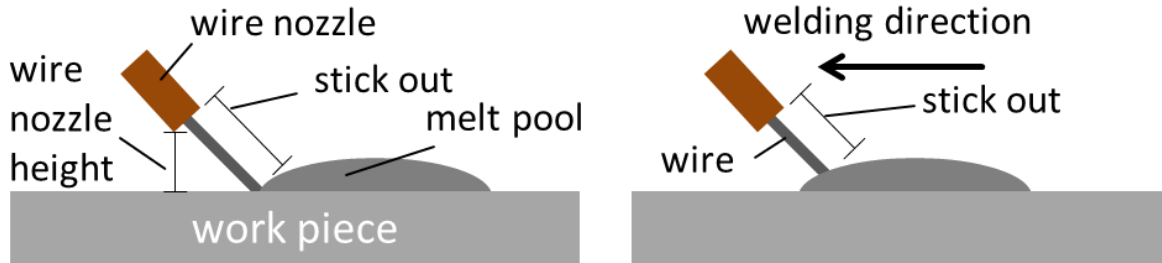


Fig. 1. Wire positioning on the work piece (left), wire positioning on the melt pool (right)

2. Materials & Methods

The experimental setup (Fig. 2) consists of a Laserline diode laser emitting 1800 W radiation at a wavelength of 1025 nm, which is guided to the processing head by a 400 μm diameter fiber. A two axis scanner system is used to deflect the laser beam 4.9 mm perpendicular to the welding direction with a symmetric triangular function on the work piece surface. The chosen traverse speed of 310 mm/min is fast enough to minimize the raise of dilution due to substrate heating [3]. The surfacing material, a martensitic chrome silica steel (X45CrSi9-3) with a diameter of 0.8 mm is delivered at 3.6 m/min together with 8 l/min Argon shielding gas by a Dinse hot-wire feed system. Welding has been done in dragging direction with the wire at 57° from the surface normal.

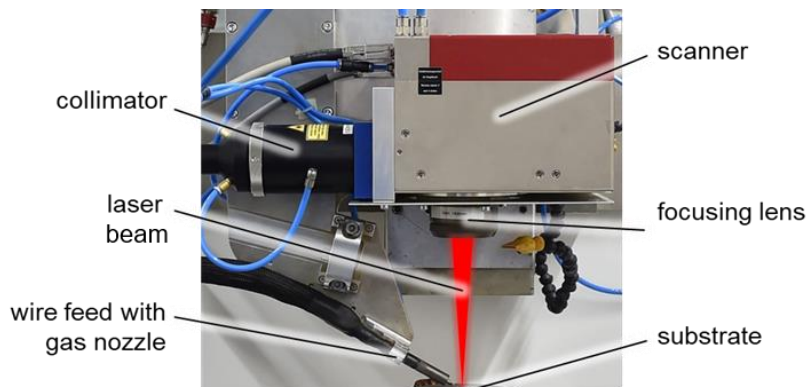


Fig. 2. Experimental setup for laser hot-wire surfacing

Four height settings, which are evenly spaced 1 mm apart, have been chosen for the experiments. The focus diameters in these four distances have been measured using the FocusMonitor system by Primes. Within these four height settings, the measured focus diameter varies from 1.75 mm to 1.78 mm and can therefore be assumed as constant, as this change is only 1.71%.

To calculate the heating power by current of the hot-wire source, the wire stick out and the temperature dependent electrical resistivity of the material have to be considered. Since there is no data available for the hard-facing material X45CrSi9-3, data was estimated from other materials that have similar physical properties. The most important factor taken into account was the specific electrical resistivity at ambient temperature of $0.9 \mu\Omega\text{m}$. Fig. 2 [6] shows plots of high alloyed steels which are in the same range.

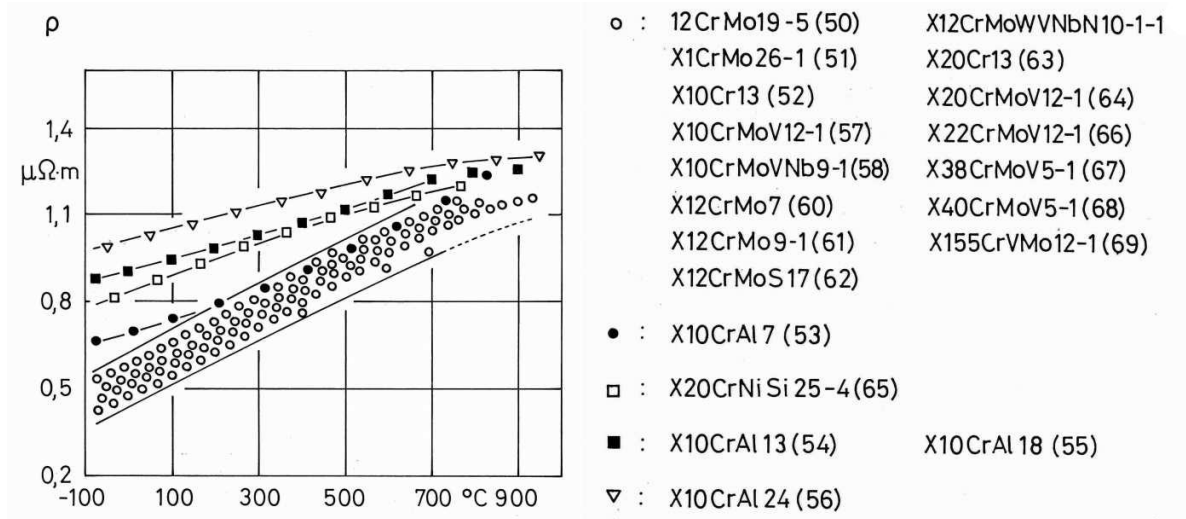


Fig. 3. Graph of the specific electrical resistivity of different high alloyed steels vs temperature from [6]

Similar physical properties were found for X10CrAlSi18 (obsolete standard X10CrAl18). Table 1 shows a direct comparison of some physical properties of the two materials and Table 2 the chemical compositions.

Table 1. Comparison of physical properties of X45CrSi9-3 and X10CrAl18

Physical property	X45CrSi9-3	X10CrAl18	Units
Electrical resistivity at 20°C	0.9	0.91	$\mu\Omega\text{m}$
Density	7.6	7.7	g/cm^3
Thermal conductivity	21	19	$\text{W}/\text{m K}$
Specific heat capacity	500	500	$\text{J}/\text{kg K}$

Table 2. Chemical compositions

	Fe	C	Cr	Ni	Si	Mn	Al
X45CrSi9-3	bal.	0.45	9	max. 0.5	3	max. 0.6	
X10CrAl18	bal.	max. 0.12	17 - 19		0.7 - 1.4		0.7 - 1.2

Using the values for material X10CrAl18 [6] for the temperatures from 20 °C to 700 °C, a linear regression can be applied with an excellent coefficient of determination of $R^2 = 0.999$ to express the temperature dependent specific electrical resistivity $\rho(T)$ as:

$$\rho(T) = 466.607 \cdot 10^{-6} \frac{\mu\Omega\text{m}}{^\circ\text{C}} \cdot T + 0.89 \mu\Omega\text{m} \quad (1)$$

Increasing the wire nozzle height also increases the stick out of the wire. A higher stick out leads to higher temperatures of the wire and therefore more dilution. The calculation of the resistive heating power P of the wire has been done using Ohm's law:

$$P = I^2 \cdot R = I^2 \cdot \frac{l \cdot \rho}{A} \quad (2)$$

where I is the heating current and R the resistance of the wire. The resistance of the wire depends on its geometry, the length l and the cross sectional area A and the temperature dependent specific resistivity ρ . Since the wire is constantly fed into the processing zone, there is a temperature gradient from the wire nozzle to the tip of the wire. In [7] an average temperature has been used to simplify this behavior for the calculation. Since the temperature dependent specific resistivity in this case is linear, this is a valid procedure and which has also been used in this study since a measurement of the wire temperature is very difficult. A mean temperature of 700 °C has been estimated. The rise of the specific resistivity due to higher temperature when the stick out is prolonged has been ignored in the calculation of the heating power, but will be discussed in the results.

3. Results

The four wire nozzle heights lead to four stick out lengths, which have been measured at the end of each trial from the wire nozzle to the seam surface. Since these measurements vary due to the seam height, an arithmetic mean value of three different tests per height has been calculated. The stick outs are not evenly stepped, since the position where the wire enters the weld seam changes (see Fig. 1). Table 3 shows how changing the wire nozzle height by lifting up the processing head relates to the measured stick out of the wire and the calculated electrical heating power, which has been applied to the wire.

Table 3. Calculated heating power of the wire in relation to the measured stick out and relative height

Relative height in mm	Stick out in mm	Heating power in W
0	6.6	176
1	8.1	216
2	9.4	250
3	10.3	274

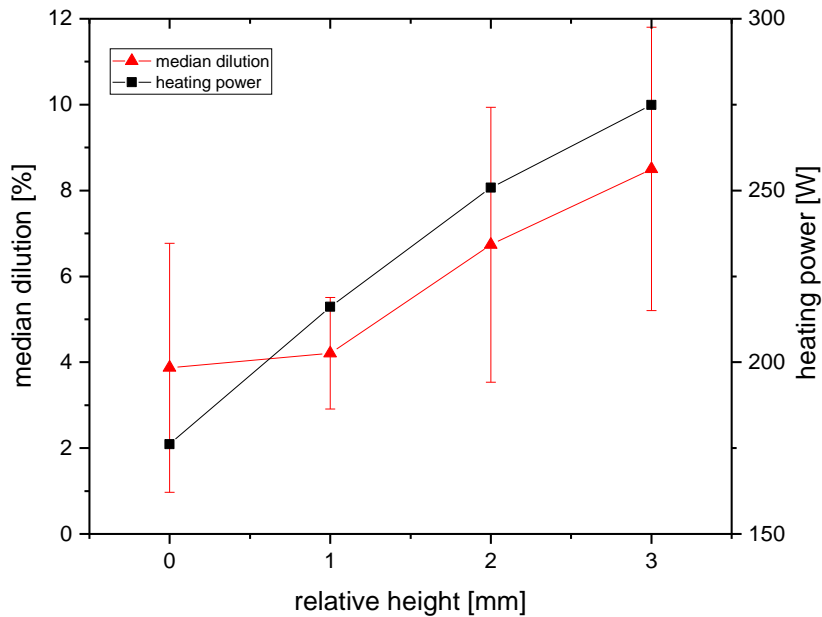


Fig. 4. Median dilution and heating power vs relative height

Fig. 4 depicts how the relative height influences the dilution and the heating power. A median mean value was chosen for the dilution. This is because the goal for dilutions is to minimize them towards the absolute minimum of zero, which means the values cannot be normally distributed. In addition, there are some outlier values, for example by cutting too close to the end of the seam. The median values and the standard deviations have been calculated from fifteen data points, which have been generated by cutting three seams per parameter into five cross-sections.

The graph shows, that there is no great influence on the average dilution from the relative height of 0 mm to 1 mm. A rise in average dilution can be seen from 1 mm to 3 mm relative height. Since the laser parameters are constant, only resistive heating power and wire positioning can cause such changes.

3.1. Resistive heating

The resistive heating power has to be evaluated in relation to the absorbed laser power. In surfacing processes, laser radiation is not absorbed very well. Wirth et al. [8] measured the absorption coefficient for high power diode laser radiation at around 0.6 on solid steel and between 0.4 and 0.3 on liquid steel surfaces. With the laser spot on the melt pool, a good assumption for the absorptivity is 0.35, which would reduce the absorbed laser power to 630 W. In this case, the portion of resistive heating to the complete process power would be 22% for a relative height of 0 mm and 30% for a relative height of 3 mm. In absolute values, this is a raise from 806 W process power to 904 W. Such a change of the process power is very likely to influence the dilution. Since the effect of higher resistivity due to higher temperature with more stick out has been neglected in the calculations, the effect is probably even greater than shown here.

3.2. Wire positioning

The dilution chart in Fig. 4 exhibits rather big standard deviations ranging from 2.9% to 3.3% for all relative heights besides 1 mm. At the relative height of 1 mm the standard deviation is only 1.3% what can be interpreted as a position with better process stability. This goes along with the observations of the seam surfaces and the experiments by Syed et al. [9]. In Fig. 5 the positioning of the wire for the most stable setting can be seen. The laser beam was used to burn a line across the seam as a reference position.

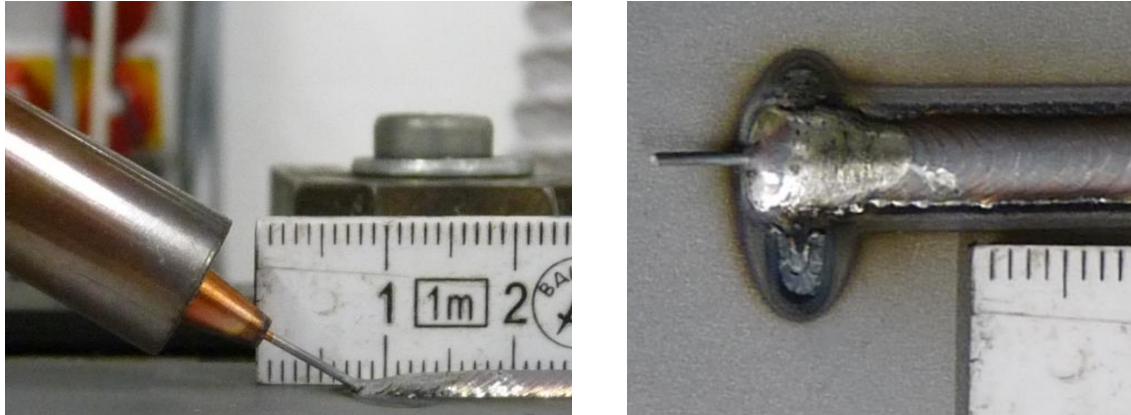


Fig. 5. Positioning of the wire at the relative height setting of 1

4. Conclusion

Wire nozzle height variations can arise by different situations. The most obvious are changes in the work piece geometry, an unevenly positioning or mistakes in the NC programming. Not so obvious are changes regarding the wire stick out, like wire positioning and weld bead height of either the actual or the previous weld bead. Since the efficiency of the resistive heating (100%), is much higher than the efficiency of the laser heating, with roughly 35%, small changes in stick out length have a big impact on the dilution. The wire stick out, the distance from the wire nozzle to the weld bead, cannot easily be calculated by the height difference and the wire angle. It has been shown, that the stick out does not have a linear relation to the wire nozzle height. This is because of the change in wire position in front or on the weld bead. Four conclusions can be derived from the results of this study:

- Resistive heating can influence the dilution even with changes of the wire nozzle height as small as 1 mm. A raise of 3 mm in wire nozzle height doubles the median dilution from 4% to 8%.
- The positioning of the wire has a great effect on the process stability.
- Resistive heating can raise the process efficiency drastically.
- The stick out should be defined as the distance from the wire nozzle to the weld bead instead to the work piece surface.

Acknowledgements

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