

EXCELlence in Robot Programming for Coating Applications

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Abstract

Impressive gains have been made in thermal spray coatings through material development and coating parameter selection. Nevertheless, it is usually up to shop personnel to develop a robot program to achieve the final coating. Coating programs are often developed using trial and error. Some motion and deposit analysis programs are available [1], [2]. However, they can be costly and require a level of expertise that is generally not available to the typical coating shop.

This paper discusses how Microsoft Excel® 2003 software can be used as an aid for off-line development of a robot program for coating applications. It starts with a discussion of the Normal Distribution characteristic of thermal spray patterns. It then goes through development of an example using standard Excel function and chart tools for interactive feedback of the coating layers. Also included is a discussion on the use of the program for sensitivity analysis regarding changes to the spray pattern.

Introduction

Typical coating specifications provide details on the powder chemistry, powder morphology, powder feed rate, gas flow rates, gun configuration, gun traverse speed and gun stand-off distance. But little if any information is provided to the coating technician regarding motions for the gun. This is understandable for coatings applied manually, using a hand-held gun. For such cases it is up to the operator to establish the motion pattern. With the advent of robotic gun manipulators, the coating engineer can specify the gun motions for optimum results.

This paper has two objectives: 1) to illustrate a technique for motion program development using tools available in Excel software and 2) to illustrate the cost-benefits of a well-engineered motion pattern. A sample program is developed to illustrate the technique and the benefits.

Procedure

Our starting point is to assume a Normal Distribution for the coating section. Values for the Normal Distribution are determined from coating tests. A mathematical representation of the object being coated is developed, a series of potential coating paths defined and trial paths evaluated. A representative section is developed using the Excel Chart Wizard. This allows for evaluation of the coating and determination of compliance to the specification.

Characterization of Spray Pattern

For the sample case, coating on a plate from multiple passes of the thermal spray gun results in a cross-section of the type illustrated in Fig. 1. The data in this figure is from vacuum plasma coating, but similar distributions have been observed in other thermal spray operations, including atmospheric plasma spray, flame spray and HVOF operations.

If the coating follows a Normal Distribution characteristic, the coating thickness (ordinate) can be defined as shown in the following equation:

$$(1) \quad \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{(X-\mu)^2}{2\sigma^2}}$$

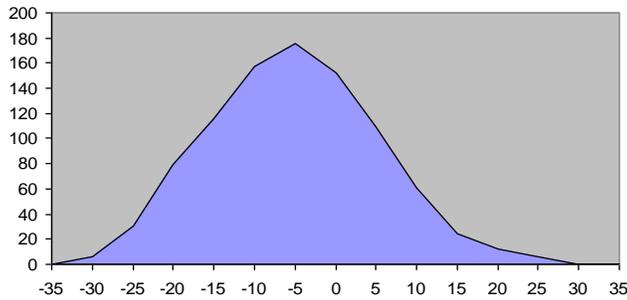


Figure 1: Normal Distribution characteristic of a coating cross-section from multiple passes over a single path.

In this equation, A is the cross-sectional area of the coating produced with a single pass of the gun, μ is the mean, σ is the standard deviation, π is the constant 3.14159, and e is the base of natural logarithms and is equal to 2.71828. x is the position along the coating section.

For the sample case, the coating thickness is stated in microns while the position is stated in mm. Therefore, “ A ” has units of micron-mm.

Many who recall their days struggling through the mathematics of Normal Distribution may find this to be a little intimidating. The tools available in Excel take most of the effort out of the task of developing a coating motion program.

Spray Tests

Assuming a Normal Distribution as the starting point, the next step is to determine the value of the area, the mean and the standard deviation. These are obtained from a coating sample produced by making multiple passes of the gun on a test coupon. For the sample case, the spray pattern has a bimodal characteristic. The gun orientation therefore influences the nature of the coating. Two spray patterns are produced for analysis; one with the bimodal feature orthogonal to the motion of the gun and one with the bimodal feature in-line with the gun motion. Other spray parameters (power, kinematics, etc.) are kept to reference values. The “zero” point is the centerline of the thermal spray gun. Seventy-five passes are made for each sample. Measured results are provided in Table 1. These

measurements were provided from a microstructure analysis of the cross-section of the coupon.

Table 1: Measurements from Coupon Tests

Position - mm	Thickness – Microns	
	In line	Orthogonal
-35	0	0
-30	0	7
-25	0	14
-20	6.1	43
-15	30	79
-10	79	100
-5	115	93
0	158	86
5	176	86
10	152	100
15	109	100
20	61	85
25	24	64
30	12	43
35	6.1	21
40	0	14
45	0	0

Data Graphing

A separate Excel worksheet is set-up for each case. The worksheet for the in-line data is labeled “in line” while the worksheet for the orthogonal case is labeled “ortho”. These titles are used later in the program development. The positions (-35 to 40) are entered in cells AJ3 through AY3 and the thickness measurements are entered in cells AJ4 through AY4. (The offset from the A column allows for subsequent use of the left area for calculations). Since the coating is assumed to present a homothetic growth, the thickness measurement data is divided by the number of passes with the results for a single pass entered in cells AJ11 through AY11. Graphs are developed using the Excel “Chart Wizard/Line/Line” tool. The results for both cases are shown in Figs. 2 and 3.

Inspection of Fig. 3 suggests a significant deviation from a Normal Distribution. This is a result of the

bimodal feature of the spray pattern and is handled by considering the representative curve as a composite of two Normal Distribution curves.

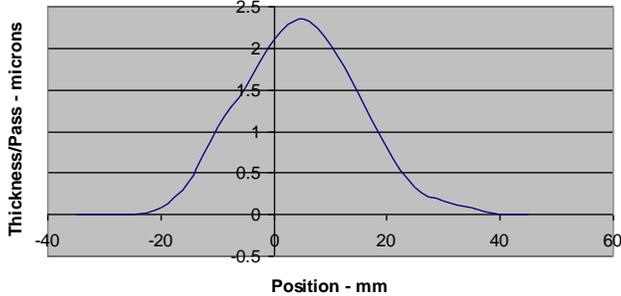


Figure 2: Results from tests with gun motion in-line with the bimodal feature of the spray pattern.

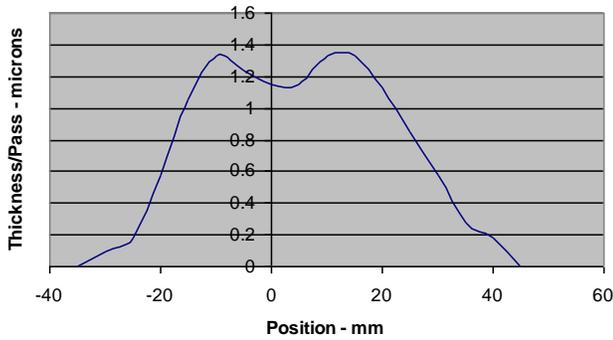


Figure 3: Results from tests with gun motion orthogonal to the bimodal feature of the spray pattern.

Determining Normal Distribution Values

The next step is to develop Normal Distribution charts that compare to the charts of the test results. This is where the power of the Excel standard tools comes into play. For the in-line example, cell B6 is used for the area, B7 for the mean and B8 for the standard deviation. Using the Excel Function Wizard/statistics/NORMDIST, the following equation is developed in cell AJ12.

$$(2) \\ =\$B6*NORMDIST(AJ3,\$B7,\$B8,FALSE)$$

This equation is then “dragged” across cells AK12 through AY12. A chart is developed for the range of AJ11 through AY12. While monitoring this chart, the area, mean and standard deviation values in cells B6 through B8 are manipulated until the two curves correlate. The Excel worksheet screen is shown in Fig. 4.

This may appear to be a trial-and-error approach, but an inspection of the test data curve provides a starting point. The midpoint of the curve appears to be approximately 5 mm from zero. The area under the curve is approximately the area of a triangle with a height of 2.5 microns and a base of 40 mm, for an area of approximately 50 micron-mm. The standard deviation is roughly ¼ of the base of the triangle or 10 mm. In the final manipulation of the three variables, an area of 61 micron-mm, a mean of 4 mm and a standard deviation of 10.5 produced the results as shown in Fig. 5. Notice that the results were developed using standard Excel tools and that only one equation required development. Also, notice that the data spacing is approximately ½ of the standard deviation in order to present a reasonably accurate presentation of the actual profile.

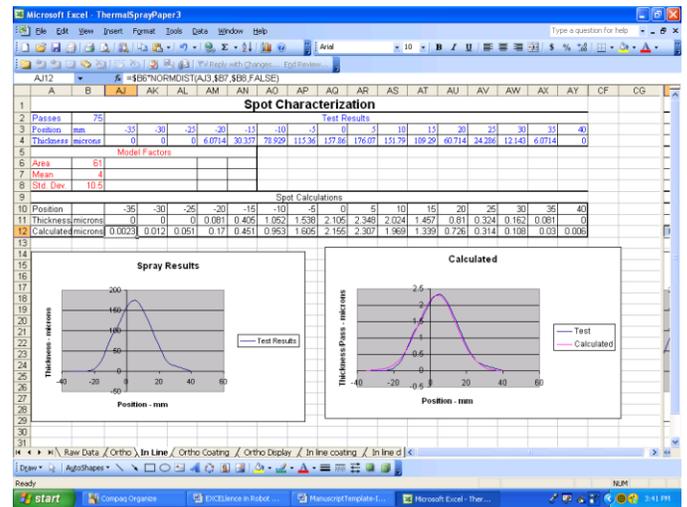


Figure 4: Screen for determining Normal Distribution values for the in-line case.

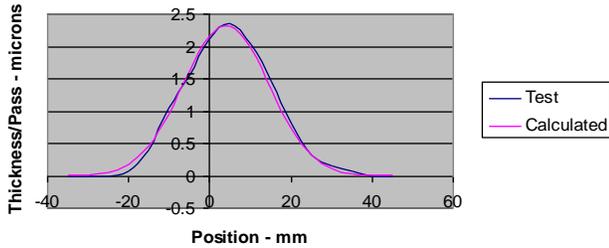


Figure 5: Comparison of test and calculated results for the in-line case.

The orthogonal case is slightly more complex since two Normal Distribution curves required development. For the first curve, cell B6 is the area, B7 the mean and B8 the standard deviation. For the second curve, cell AM6 is the area, AM7 the mean and AM8 the standard deviation. Cell AJ12 is set up with the following equation using the standard Excel NORMDIST function.

$$(3) \\ =\$B6*NORMDIST(AJ3,\$B7,\$B8,FALSE)+\$AM6 \\ *NORMDIST(AJ3,\$AM7,\$AM8,FALSE)$$

Notice the sum for the two curves in equation 3. As with the first case, this equation is “dragged” across cells AK12 through AY12. A chart is developed for the range of AJ11 through AY12. While monitoring this chart, the Area, Mean and Standard Deviation values in cells B6 through B8 and AM6 through AM8 are manipulated until the two curves correlate. For the first curve, the Area is set at 21 micron-mm, the Mean at -11.5 mm and the Standard Deviation at 7.5. For the second curve, the Area is set at 40 micron-mm, the Mean at 13 mm and the Standard Deviation at 12. The results are shown in Fig. 6.

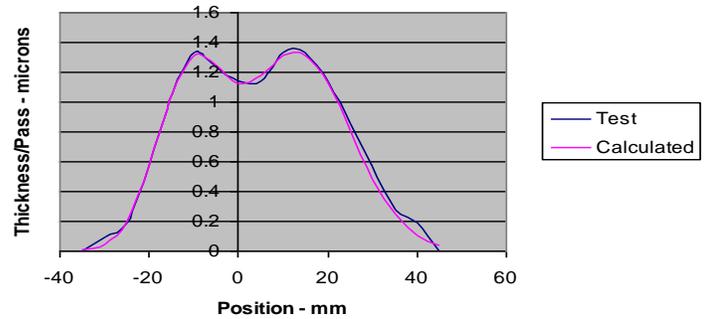


Figure 6: Comparison of test and calculated results for the orthogonal case.

Notice that the sum of the two areas for the orthogonal case is equal to the area for the in-line case. Also, both cases show an offset from zero. This indicates that the center of the spray pattern does not correspond to the center of the gun. This needs to be compensated for in the coating application.

There is one final point in the development of the single-pass thickness array. A LOOKUP function is to be used for virtual coating of the virtual part. This function will be “looking” in areas of the single-pass array beyond the information presently contained in the table. Even though the single-pass coating thickness in these areas is zero, the look-up table will want to find a corresponding position. Therefore, the “position” information, presently limited to cells AJ3 through AY3 (-35 to 40), must be expanded to cells C3 through CE3 (-200 to 200 in 5 mm increments).

Defining Part Surface and Gun Orientation

Next, a new worksheet is started for developing the virtual coating on the virtual part. It is beneficial to use the Drawing Tools available in Excel to draw a representation of the part to be coated. For this example, the part is a long, flattened tube with a total width of 75 mm and thickness of 10 mm as illustrated in Fig. 7. A coating is to be applied to one face and to both edges. In addition, the coating is to extend 5 mm into the back face from each edge. The coating thickness is to be in a range of 45 and 55 microns. Note that the part is long and is to

be coated with the gun traversing along a direction perpendicular to the paper.

Potential coating paths are defined next. Spacing between potential paths is the same as the spacing for the original single-pass profile or 5 mm. Twenty-one potential coating paths were therefore considered as shown in Fig. 7. Note that the direction of the arrow represents the gun orientation for each path.

Developing the Coating Table

A table is then developed in the new worksheet for calculation of the coating operations. (Fig. 8) This table assumes that the coating is “unwrapped” from the tube in order to show a flat coating.

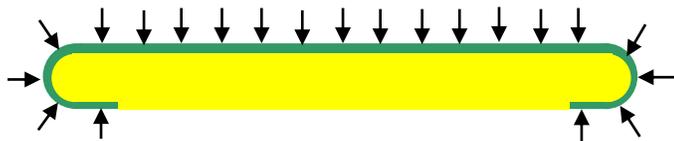


Figure 7: Part to be coated and potential coating paths. The dark area represents the coating to be applied with a thickness range of 45 to 55 microns. Gun motion is perpendicular to the paper. The gun is oriented along the arrow for each path.

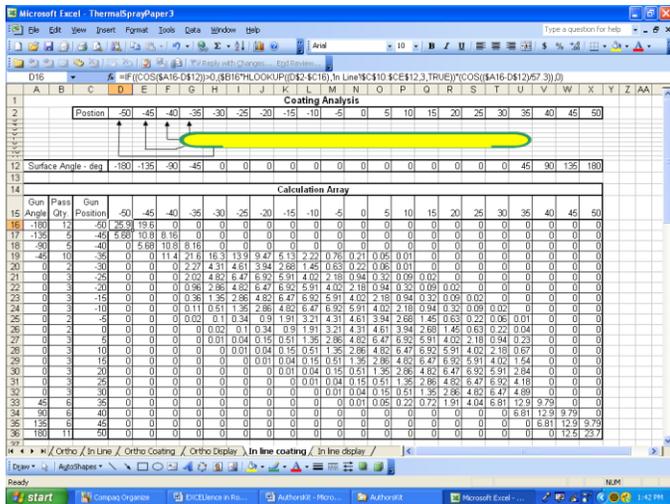


Figure 8: Screen for coating operations worksheet.

The full width of the coating is 105 mm (65 mm for the face, 15 mm for each edge and 5 mm for each

side of the back face). In the new table, the part position is along the x axis of the table. The positions are entered into cells D15 through X15 in 5 mm increments (-50 to 50). The angle of the surface at each path is entered in cells D12 through X12.

The y axis of the table is for the gun geometry and gun position. The possible gun positions are entered in cells C16 through C36 (-50 to 50). The gun angle for each path is entered in cells A16 through A36 (the gun is considered here to be always perpendicular to the surface along the path being followed). The number of passes to be made along each path will be entered into cells B16 through B36.

One point that needs to be considered is the effect on the coating when the gun is not perpendicular to the surface. As the gun deviates from the perpendicular, the coating is spread over a greater area and the deposition efficiency is decreased while the porosity is increased. If the spray angle does not differ significantly from the normal angle, a simple correction is made by multiplying the coating thickness by the cosine of the angle between the gun and a line normal to the surface where the coating is being applied. Note that this is true only if the cosine is positive. A negative cosine indicates that the gun is behind the surface and therefore the applied thickness is zero.

With this information, the thickness for each path at each gun position along the part can be calculated. The representative equation is developed using a lookup function that refers to the thickness previously calculated. This equation is first developed for cell D16 as shown in equation 4.

$$(4) \text{ =IF}((\text{COS}(\$A16-\text{D}\$12))>0,(\$B16*\text{HLOOKUP}((\text{D}\$2-\text{\$C16}),'\text{In Line}'!\text{\$C}\$10:\text{\$CE}\$12,3,\text{TRUE}))*(\text{COS}((\$A16-\text{D}\$12)/57.3)),0)$$

This equation “LOOKS” back at the table in worksheet “In Line”. It will be “looking” in areas

that were not part of the original Normal Distribution calculation. This is the reason that the in-line worksheet table had to be expanded beyond the range of interest.

The table is completed by first dragging the equation in D16 from E16 to X16 and then dragging the line of equations from D16 through X16 down to line 36.

Display of the Coating Section

The chart is next developed from this array. For this chart, cells D16 through X36 are highlighted and the Excel Chart/Area/Area tool is used. Category X labels are from cells D15 through X15.

This chart can be displayed on the worksheet where the calculations have been made but it is beneficial to move the chart to a new worksheet as shown in Fig. 9. The area, mean, standard deviation and number of passes for each path can then be entered on this new sheet and set-up to automatically copy the respective values to the appropriate cells in the other worksheets. Also, by copying the part drawing to this new worksheet and scaling it to fit the table of passes, a real time, interactive display of the results is presented. The results are shown in Fig. 10.

In describing coating operations, painting is sometimes used as an analogy. In painting with a brush, the artist usually orients the brush with the width orthogonal to the stroke. Also, in spray painting where the spray pattern is wide, the technician usually orients the width such that it is orthogonal to the direction of motion. As a result, it may be believed that the “broad brush” or orthogonal approach is the best coating configuration. In order to evaluate this assumption, the orthogonal configuration needs to be analyzed.

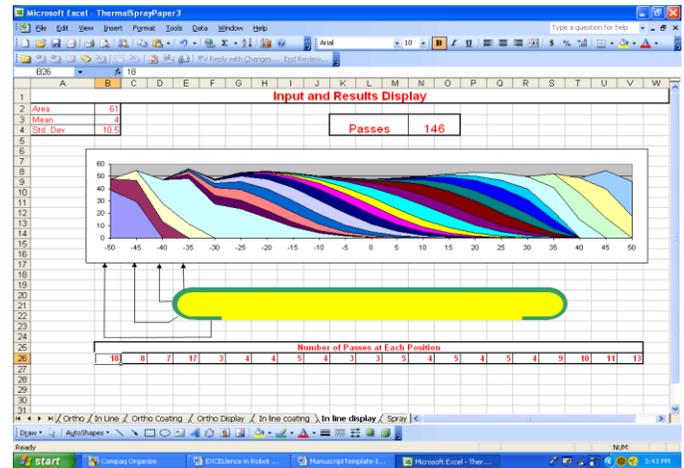


Figure 9: Interactive screen for testing various spray patterns. The display changes as modifications are made to the input data.

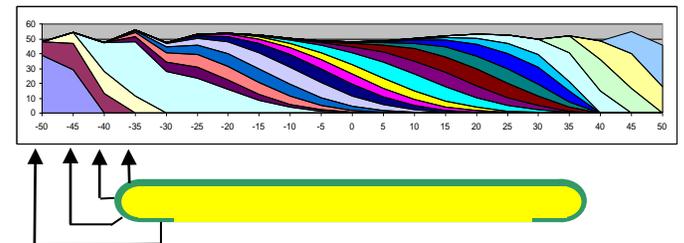


Figure 10: Excel chart for the in-line coating configuration.

As in the first case, twenty-one potential paths are considered and the number of passes for each path are adjusted to achieve the required thickness in the fewest passes.

The analysis indicates that a total of 146 passes will be required to achieve the specified coating thickness using the in-line approach while a total of 208 passes will be needed to achieve the required coating thickness using the orthogonal configuration.

From these results, it is seen that the orthogonal configuration requires 42% more passes than the case where the gun is oriented with the bimodal feature in line with the gun path. The results are displayed in Fig. 11 and the passes for each case listed in Table 2.

This equates to the use of 42% more powder for the orthogonal configuration with a similar increase in the coating time. When the “broad brush” approach is used, the spray width is significantly wider than the thickness of the part and the width of the two sections on the back face. Therefore, most of the spray is lost as overspray on either side of the section being coated. Selection of the orthogonal configuration for gun motion would obviously be a very costly decision.

Inspection of these results also provides additional insight into optimum coating operations. The number of passes is greatest towards the sides of the face being coated. The center section of the part being coated receives most of the required coating during the coating of the two sides of the face.

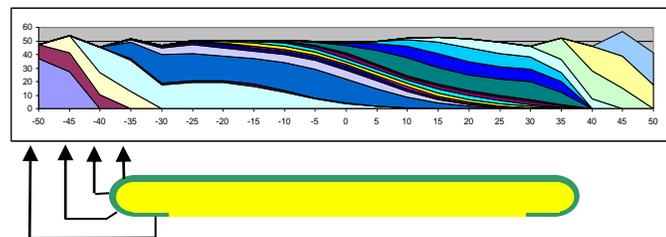


Figure 11: Excel Chart for the orthogonal coating configuration.

Table 2: Passes for each path.

Position [mm]	Area	Surface Angle [deg]	Number of Passes	
			In-Line	Ortho
-50	Back Face	-180	18	33
-45	Back Left Edge	-135	8	12
-40	Left Edge	-90	7	15
-35	Face Left Edge	-45	17	21
-30	Face	0	3	1
-25	Face	0	4	0
-20	Face	0	4	16
-15	Face	0	5	5
-10	Face	0	4	2

-5	Face	0	3	1
0	Face	0	3	2
5	Face	0	5	2
10	Face	0	4	2
15	Face	0	5	1
20	Face	0	4	10
25	Face	0	5	8
30	Face	0	4	8
35	Face Right Edge	45	9	9
40	Right Edge	90	10	18
45	Back Right Edge	135	11	21
50	Back Face	180	13	21

Robot Programming and Test

Once the spray pattern is defined, the program is entered into the robot controller. For the virtual coating, the coating is “applied” by proceeding from left to right and completing all passes along each path before proceeding to the next path. For the actual case, the paths should be alternated to avoid stratification of the coating. The results will not change as long as the number of passes along each path remains the same.

Advanced robots such as Plasma Powders & Systems, Inc. (Marlboro, NJ, USA) Model TRM 1000 (appropriately using an acronym for “The Right Moves”), can be programmed to accept these values directly. This can also include the mean from the calculations to compensate for any offset in the spray gun. Note that a 7th axis for position control of the part is required.

Sensitivity Analysis

Once set up, this analytical tool can be used to test out the sensitivity of the results to variations in the operation. Multiple test coupons can be prepared to determine the variability of the area, the mean and the standard deviation. The range of numbers can then be entered to evaluate the impact on the coating due to process variations.

The tool also provides a measurement of the expected “target efficiency”, the material applied to the part compared to the material that would have

been applied to a flat plate. For the in-line case, the area sprayed per pass was calculated as 61 micron-mm. With 146 passes, a total cross sectional area of 8906 micron-mm could have been sprayed. The cross sectional area of the actual coating is 50 microns times 105 mm or 5250 micron-mm, showing a target efficiency of 59%

Optional Parts

Once the program is developed, it can be used for similar parts of a similar size. The virtual part and potential paths are developed as previously discussed and the angles determined. A representative figure of the same type as shown in Fig. 8 is developed and the part “unwrapped” for a straight-line representation.

Summary and Conclusion

The purpose of this paper is to champion the engineering of robot motion programs. Excel software provides a powerful tool for off-line development of cost-effective robot programs. Other approaches are probably available and the example can be refined. For example, the program could be modified to consider the effect that the angle of incidence could have on the deposit efficiency.

Excel expressions used in the development of this example are not explained since they are covered in the Excel software Help section. Some familiarity with the Excel functions and Excel charts is required. Someone who really enjoys working with Excel is an ideal candidate to take on the task of defining a recommended robot motion program. These are usually those individuals who write their memos, maintain their appointment calendar and track their investments in Excel.

Once one program is developed, other programs can often be developed through modification of the first program. Additionally, other ways may be found to use the Excel tool; for example, coating of multiple parts.

References

1. “RobotStudio” Off-line Programming Software, ABB Robotics, Auburn, MI
2. K. Hartmann, R. Kirshnan, R. Merz, G. Neplotnik, F. B. Prinz, L. Schultz, M. Terk, L. E. Weiss, Robot-assisted shape deposition manufacturing, *1994 IEEE International Robotics and Automation Conference Proceedings*.