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Statistical Process Design for Hybrid Layered Manufacturing

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Abstract: The welding parameters such as current, voltage, arc length, wire feed rates, wire stick-out distance etc will influence on the deposited weld bead geometry. Statistical design of experiments using orthogonal arrays and signal-to-noise (S/N) ratios are performed to constitute the core of the robust design procedure. Taguchi Methodology was employed with minimum number of trails as compared with classical statistical experiments. This study systematically revels the complex cause-effect relationships between design parameters and performance. Thus an optimized weld bead width and heights are formulated for the exterior contour weld path deposition and for the interior layer metal path deposition respectively.
Key Words: Rapid Prototyping (RP), MIG-MAG welding, Taguchi Method, Regression Analysis.

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1. INTRODUCTION

Direct production of the metal part is unique among current RP techniques [Asley 1997]. Preliminary works in adaptation of a weld cladding technique has enabled the production of parts wider than normally possible from single weld beads, but the results are not perfect [Song, et.al 1999; Zhang, 2003]. The shape and geometrical dimensions of the weld bead are key factors in making use of 3D welding as a RP system, since these will determine the limitations to the layer thickness that influences the quality of the metal layer deposited in attaining the desired contour profile.

Considering the research work carried at various universities and labs as shown in Table-1, it was concluded that in order to manufacture tools more accurately and rapidly, the Direct Metal Rapid Tooling process should have the following characteristics:
Sintering or melting of the hard material directly
Two-step processing of each layer; the first step yielding the near-net layer deposition/formation and the second step is the machining the layer to the required accuracy.
First order slicing of RP paradigm.
Elimination/minimization of staircase effect
High rate of material deposition
Ability to build support structures

TABLE 1. RESEARCH AT VARIOUS UNIVERSITIES

Welding based RP

- **Shape Welding -** Thyssen AG (Germany).
- **Shape Melting -** Babcock & Wilcox, Co.
- **3-D Welding -** Univ. of Notthingham, England.
- **Robotically controlled Fusion Welding -** Cranfield University, England
- **GTAW based RP –** Southern Methodist University, US
- **GMAW based RP -** University of Kentucky, Lexington, US

Welding and Milling based RP

- **Controlled Metal Buildup -** Laser cladding/welding with $2^1/_2$ dimensional milling, Fraunhofer Institute for Production Technology IPT, Aachen, Germany.
- **Shape Deposition Manufacturing –** Microcasting and Milling, Carnegie Mellon University US.
- **CO_2 Laser welding and Milling-** Korea Institute of Machinery and Materials, Korea.
- **3D Welding and Milling –** Korea Institute of Science and Technology, Korea

For achieving the these goals, a new paradigm for building metallic parts was proposed with an aim
To develop a low cost RP machine for making metal tools and dies by a numerical controlled system that integrates the synergic MIG-MAG welding process for

near-net layer deposition and CNC milling process for net shaping.

To develop the know-how to retrofit any exiting CNC machining center with the above RP capability.

2. STATISTICAL PROCESS DESIGN

Statistical experiments are well-planned, both with respect to the combination of settings of the different independent factors at which the experimental trails have to be run, and with respect to the manner in which the response data are analyzed. The objective of this well-planned effort is to uncover

a) Which design and environmental factors significantly affect performance and

b) What counter measures can be devised to minimize the effect of the adverse factors and conditions such that the final performance will be least sensitive particularly to factors that the user of the product/process is unable to economically or physically control

Researchers applied various statistical process design methodologies to optimize the arc welding parameters for attaining the better weld results. The main approaches that are implemented include a) Taguchi Methods and Classical Design of Experiments b) Fuzzy logic and Artificial Neural Networks. Neural networks are self-learning based on weights determinations and adjustments. These networks require an extensive amount of training time and lack explanation capabilities, but works better when the data set is sufficiently large. Statistical designed experiments are among the best-known approaches for empirically discovering cause-effect relationships. These experiments require the smallest number of trails, thereby providing the best economy.

The setting of a statistical experiment, also known as designing, involves several steps as

Selection of responses (performance characteristics of interest)

Identification of the factors (the independent or influencing conditions) to be studied.

The different treatment (or levels) at which these factors will be set in the different individual experiments.

Consideration of blocks (the observable noise factors that may influence the experiments as a source of error or variability)

To minimize the required number of experiments for analyzing the process parameters, Taguchi methods utilizes the Orthogonal Arrays (OA) to study the entire parameter domain. An orthogonal array allows mathematically independent assessment of the effect of all experimental factors. Experimental matrices ensure that there exits a balance in the way that different levels of control factors are changed within the experiment. A loss function is then defined to calculate the deviation between the experimental vale and the desired value. The value of loss function is then transformed into signal-to-noise (S/N) ratio. The S/N ratio is used to measure the performance characteristic deviating from the desired value. S/N ratio is used as a measurable value instead of standard deviation due to the fact that as the mean decreases, the standard deviation also decreases and vice versa, i.e. the standard deviation cannot be minimized first and the mean brought to the target. Two of the applications in which the concept of S/N ratio is useful are the improvement of quality through variability reduction and the improvement of measurement. The S/N ratio characteristics can be classified into three categories when the characteristic is continuous:

Nominal the best characteristics

$$S/N = 10*\log_{10}\left(mean^2 / \text{variance} \right)$$

$$\text{Mean}= \sum_{i=1}^{n} Y_i \Big/ n \qquad \text{Variance}= \sum_{i=1}^{n} \left(Y_i - Mean\right)^2 \Big/ (n-1)$$

Smaller the better characteristics

$$S/N = -10*\log_{10}\left(\sum_i Y_i^2 \Big/ n \right)$$ and

Larger the better characteristics

$$S/N = -10*\log_{10}\left(1 \Big/ n \sum_i Y_i^2 \right)$$

Where ‘n’ is the number of observations and ‘Y’ is the observed data.

For each type of the characteristics, with the above S/N ratio transformation, the higher the S/N ratio corresponds the better result. Therefore, the optimal level of the process parameter is the level with the highest S/N ratio.

3. HLM METHODOLOGY

The proposed HLM process consists of the following stages:

Building a near-net shape of the tool.

Rough Machining the near-net shape of the tool to final dimensions

Heat treatment for stress relieving and strengthening

Finish Milling to get the required surface finish and quality.

3.1 Building the near-net shape of the tool

The substrate plate is rigidly placed with proper fixtures on the XY table, and its motion is guided by motor drives. The required weld path uses the zeroth order edge approximation uniform slicing strategy of the RP paradigm for deposition of the layer thickness. The necessary functions for the operation of synergic MIG-MAG welding machine with shielding gas were monitored through the numerical control. While majority of the welding process parameters such as current, voltage, arc gap, shielding gas composition etc are controlled externally.

A simple zig-zag weld path pattern is used to deposit the bottom most layer with required contour profile shape. The weld path is optimized to transfer heat uniformly over the layer, as the heat build-up due to the welding process may result in part malformation and collapse of the structure [Zheng, 2001]. After completing the metal deposition in the bottom most layer the shielding gas nozzle is turned off and the switching functions are invoked to change over between welding and face milling process by halting the welding process and activating the face milling process and vice versa. For this operation a pneumatic system is used to swivel between welding gun and the milling cutter. So that at any time either welding or milling operation will only take place.

Face milling operation is performed on the top surface of each deposited metal layer to get the required thickness of the layer. The instability of arc welding process may cause a malfunction/defect in the middle of the weld bead.

To minimize and correct the deviation in successive multiple layer deposition, face milling operation is performed. Face Milling also ensures the correct vertical height accuracy of the built layer. Repeating the above process of layer deposition and face milling operations to generate near net layers deposited one over the other from bottom most to top layer till a casting like rough shape is obtained.

3.2 Machining the near-net shape of the tool to final dimensions

All the horizontal surfaces of the deposited layer are machined by face mill during the deposition stage. Taking onto consideration of shrinkage and weld defects the size of the deposited layer is made to be a little bit larger than the actual required profile shape, thus the edges of the layers are still rough. With the welding process, attaining the accurate contour profile shape of the deposited layer is difficult. For that end milling operation is performed to attain the shape and accuracy. The tool path of the end mill is generated for machining the final casting like rough shape from top to bottom layer direction of the deposited metallic layers to attain the required contour profile shape with user specified accuracy.

methodology will not require support structure, thus making the process less complicated.

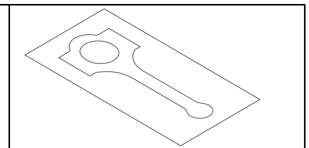
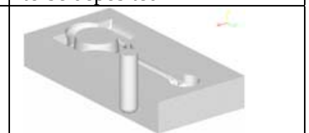
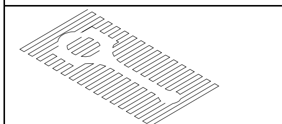
	
Metal Layer to be deposited	Contour profiles of the layer to be deposited
	
Face Milling the horizontal faces to maintain the vertical slice height alignment.	Casting like deposition attained at the end of the sequence of welding and face milling operations is end milled to attain the required surface finish
	
Zig-Zag weld path for the filler wire metal deposition	Final end Product

Figure 1: Sequence of Hybrid Layered Manufacturing

3.3 Heat treatment for stress relieving and strengthening

The temperature variation within the deposition layer with the severity of cooling influences on the generation of internal stresses and on the resulting microstructure of the tool. The final stress distribution consists of nearly uniform tension in the newly deposited layer, tension at the top of the substrate and nearly uniform compression at the bottom half of the substrate. To relieve these undesirable residual stresses, a suitable heat treatment is performed using normalizing and annealing processes. As these residual stresses are unchecked, they may induce warping, loss of edge tolerance and delaminating thereby reducing the strength and influencing on the tool life. The material homogeneity of the prototype to be obtained in the proposed method is between those of cast and machined parts. Thus, this process is not suitable for making forging dies where very high impact forces are encountered. The die used in injection molding, die casting and sheet metal forming undergo considerably less fatigue loading during the operation, so these tools can serve the purpose even without any homogenization operation such as Hot Isostatic Pressing (HIPping) process. Further these die halves are free from overhanging features, as they need to open and close in operation. Building such dies and mold with free from re-entrant profiles by the proposed

3.4 Finish machining

Finish mill all the contour profiles of the tool to the required surface finish.

The proposed HLM process does not pose any restriction or loss of accuracy on the prototype as its size grows. Since the part size is limited only by the traverse available on the CNC machine, a larger CNC machine can be used to produce larger tools. The tools produced using this process may be inferior to their conventional counterparts in composition and tool life but these will be as accurate as any other tool. In this context, it is interesting to note that the die halves used in injection molding, pressure die casting, sheet metal forming etc. will be free of reentrant features and overhanging features since they need to open and close in operation. Therefore, building such dies in the proposed will not require support structures.

Figure 2: Hybrid Layered Manufacturing Experimental Setup

4. DESIGN OF EXPERIMENT APPROACH

The Taguchi method is a systematic application of design and analysis of experiments for the purpose of designing and improving product quality. This method determines the parameter settings, which maximizes the S/N ratio in each problem by performing the designed experiment systematically. The procedure of the Taguchi method is as follows.

Step 1) Identify the performance characteristic to be observed.

Step 2) Identify important noise factors and their ranges.

Step 3) Identify the control factors and their levels.

Step 4) Construct inner array and outer array. The inner array is a designed experiment using the control factors, and the outer array using the noise factors.

Step 5) Conduct the designed experiment. If the inner array is made up of m rows and the outer array n rows, the m rows can obtain each n performance characteristics, through actual experiments. These n experimental data are used to calculate the S/N ratio for each row of the inner array.

Step 6) Analyze the data and determine optimal levels for each control factor. The optimal parameter settings are then determined by analyzing the S/N ratio data

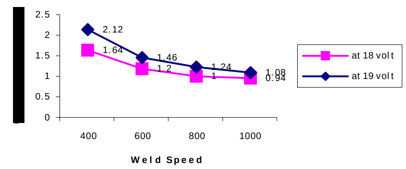


Figure 3a: Weld Speed Vs Bead Height at 12mm wire stick out

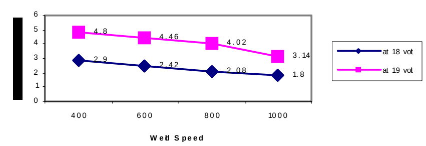


Figure 3b: Weld Speed Vs Bead Width at 12mm wire stick out

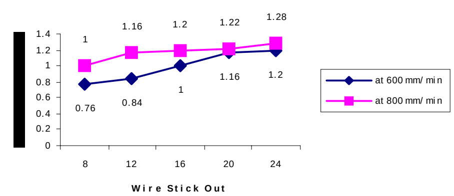


Figure 3c: Wire Stick Out Vs Weld Bead Height

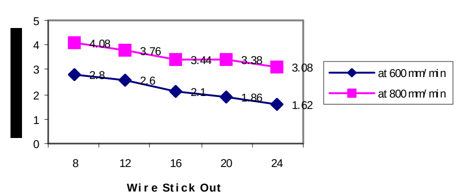


Figure 3d: Wire Stick Out Vs Weld Bead Width

Experiments are carried out initially to determine the upper and lower limit bounds of the each controlling factor so that their range of influence can be identified

Control Factors	a) Weld Voltage, b) Weld Speed and c) Wire Stick Out (Since in synergic MIG-MAG welding all the voltage, current, wire feed rate are inter-related, we have selected only the weld voltage.)
Noise Factors	P: Filler Wires made by different manufactures (ESAB, Lincoln, Advani-Kirloskar) Q: Weld machines built by different manufacturers (Fronious, ESAB, Miller, Lincoln) R: Nature of the Arc (Soft, Neutral, Hard) this influences on the spatter
No. of Levels	3 level (each factor). The three levels of each factor are represented by a ‘0’ or a ‘1’ or a ‘2’ in the matrix
Orthogonal Array	L9 In this experiments the interaction among the factors was not considered, so with three factors each at three levels (0, 1, 2) the fractional factorial design used is a standard L9 34 orthogonal array.
Weld Machine Specifications	Pulse Synergic MIG-MAG machine 1.2mm ER70S-6 Filler wire 80% Ar + 20% CO2 Shielding Gas

(see Figure 4a-d).

Case Study:

From the conducted test & trail methods and various other welding literature reviews the bounding limits of the controlling factors are constrained as shown in the following table

Control Factor		Level		
		0	**1**	**2**
A	Weld Voltage (Volts)	18.2	19	19.8
B	Weld Speed (mm/min)	600	800	1000
C	Stick Out (mm)	10	14	18

The objective of the statistical designed experiment is to optimize the welding parameters to get better surface roughness of the deposited layer with required weld bead width and height. For this the nominal the best and the smaller the better characteristics are used for the weld bead width and height respectively.

For the Weld Bead Width, Nominal the best

$$S/N = 10 * \log_{10}\left(mean^2 / variance\right)$$

Exp No	Factor			Designation	Replicated Observations of Weld Width			Mean Weld Width	S/N ratio Width
	A	**B**	**C**		**W1 (mm)**	**W2 (mm)**	**W3 (mm)**		
1	0	0	0	A0B0C0	3.36	3.32	3.30	3.3267	4.0739
2	0	1	1	A0B1C1	2.52	2.30	2.60	2.4733	2.4039
3	0	2	2	A0B2C2	2.10	1.94	1.88	1.9733	2.4787
4	1	0	1	A1B0C1	3.96	3.92	3.82	3.9000	3.4661
5	1	1	2	A1B1C2	3.44	3.38	3.50	3.4400	3.5168
6	1	2	0	A1B2C0	3.02	3.06	2.90	2.9933	3.1114
7	2	0	2	A2B0C2	4.32	4.28	4.38	4.3267	3.8686
8	2	1	0	A2B1C0	3.84	3.78	3.70	3.7733	3.4603
9	2	2	1	A2B2C1	3.24	3.18	3.28	3.2333	3.6156

Response table for the average S/N ratio for the Weld bead Width

Symbol	Parameters	Mean S/N ratio			
		Level 0	**Level 1**	**Level 2**	**Max – Min**
A	Weld Voltage	2.9855	3.3648	3.6482	0.66264
B	Weld Speed	3.8029	3.1270	3.0686	0.73435
C	Stick Out	3.5486	3.1619	3.2880	0.38666

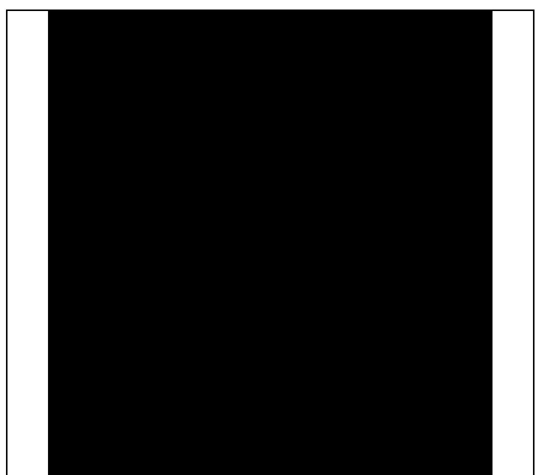


Figure 4: Nominal the best S/N graph for the weld bead width

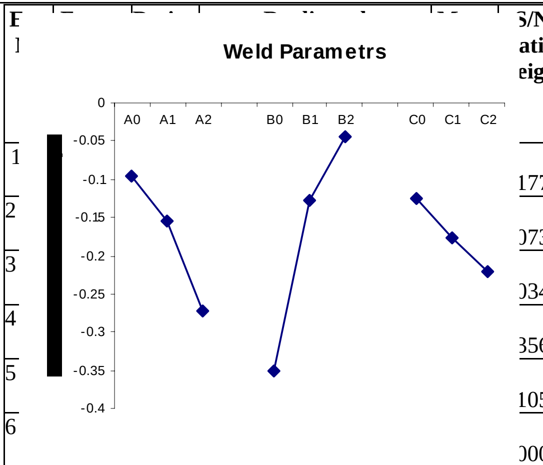


Figure 5: Smaller the better S/N graph for the weld bead height

E	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	S/N ratio eight
1	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1778
2	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0736
3	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0342
4	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	3563
5	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1059
6	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0009
7	2	0	2	A2B0 C2	1.88	1.82	1.76	1.8200	-0.5205
8	2	1	0	A2B1 C0	1.28	1.22	1.28	1.2600	-0.2009
9	2	2	1	A2B2 C1	1.12	1.14	1.10	1.1200	-0.0985

For the Weld Bead Height, Smaller the better characteristics S/N = -10* $\log_{10}\left[\sum_i Y_i^2 / n\right]$

Response table for the average S/N ratio for the Weld bead Height

Symbol	Parameters	Mean S/N ratio			
		Level 0	Level 1	Level 2	Max – Min
A	Weld Voltage	-0.0952	-0.1537	-0.2733	0.17813
B	Weld Speed	-0.3515	-0.1268	-0.0439	0.30759
C	Stick Out	-0.1259	-0.1761	-0.2202	0.09425

With these optimum parameters found from the above DOE, metal layers are deposited of weld bead size and thickness for smoother metal surface layer. Thus the top surface layer will have to undergo minimum or with out face milling operations to achieve the required layer thickness and the surface finish.

5. ANALYSIS and DISCUSSION

From the experimental investigation it was found that the control factors weld voltage and speed play a vital role in formation of the weld bead width and height as compared to the wire stick out. To attain the nominal weld width in the given experimental domain, the feasible parameters are higher weld voltage and lower weld speed with minimum wire stick out distance (A2B0C0). Further to achieve the smaller deposited weld bead heights the feasible parameters are lower weld voltage and higher weld speed with minimum wire stick out distance (A0B2C0). While the ‘wire stick out distance’ has a least effect at minimum range of distances up to 14mm but has a greater influence above the 14mm distance. With the increase in the wire stick out the arc becomes more instable and resulting in the uneven deposition of the weld bead and formation of more spatter. This phenomenon is quite visible in standard synergic MIG-MAG weld compared to pulse synergic MIG-MAG welding. It was also observed that the metal impenetrate into the base plate was reduced with the increased wire stick out. So low wire stick out distance is maintained in the proposed HLM process for the first layer deposited on the base metal to have high weld metal impenetrate and for the subsequent layer depositions optimal level wire stick out was opted.

A verification experiment is carried out to prove the analysis of the results as shown in Table 2. Weld path deposition with the determined optimal levels of control factors are shown in Figure 9aq and 9b. In relevant to RP principle to achieve the smaller weld bead height of the deposited weld layer, the low weld voltage and high weld speed parameters are to be preferred with A0B2C0 level. The nominal the best weld bead width deposition with A2B0C0 level weld process parameters are opted for the multi layer weld metal cladding to build the metal tool and dies. During the initial stages of the formulation of the process parameters for the HLM to fabricate the metallic tools and dies, the weld parameters are selected purely based on the past experience. The statistical designed experiments performed to analyze the cause-effect of process parameters and in the selection of the optimized welding process parameters for attaining the desired weld bead width and height. Experimental results showed with these optimum levels based multi layer metal deposition, the amount of metal deposition increased to an maximum extent of 61% and milling operations can be minimized to nearly 20% in attaining the desired contour profile shape. Thus with the reduced overall lead time and increased filler material utilization the molds and dies are build with the proposed HLM process. To establish the process further experiments are fine tuned.

7. CONCLUSIONS

Statistical experiments varies several influencing factors together from trail to trail in a pre-planned, systematic fashion such that maximum information can be generated from a minimum number of trails. The main objective in the implementation of the statistical process design for HLM process is to find a combination of weld parameters to perform minimum surface machining for achieving the desirable contour profile shape of the deposited metal layer. The preliminary experimental results show the weld bead width is directly proportion to the weld voltage. With the increase in the weld voltage the increased heat input caused by higher arc energy results in the larger weld bead width. The weld bead height is inversely proportional to the weld voltage. The test-trail experimental results showed that the weld bead height is directly proportion to the weld speed. The bead width is inversely proportional to the weld speed but the weld speed has a very small effect on the bead width. The weld speed can change the bead width by affecting the heat input. During the metal deposition for the optimal levels of process parameters for nominal the best weld width condition, due to its high metal deposition rate and heat input into the base metal it was desired to implement the conformal cooling channel for the minimization of the heat distortions and metal wrapping defects.

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