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Influence of Operating Parameters on the Reciprocating Sliding Wear of Direct Metal Deposition (DMD) Components Using Taguchi Method

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Abstract

Direct metal deposition (DMD) is an advanced additive manufacturing technology used to repair and rebuild worn or damaged components, to manufacture new components, and to apply wear and corrosion resistant coatings. DMD produces fully dense, functional metal parts directly from CAD data by depositing metal powders pixel-by-pixel using laser melting and multiple material delivery capability, DMD can coat, build rebuild parts having very complex geometries.

The present work is aimed at determining the influence of operating parameters on the friction and wear of DMD components. The substrate chosen was mild steel and the deposited material was H13 tool steel. A design of experiments technique was adopted in the form of Taguchi's L9 orthogonal array. The selected parameters were coating thickness, applied load and temperature. Wear testing was done on the components using ball on flat reciprocating wear testing machine. The results were then analyzed and the major contributing factor towards wear was found out based on the ANOVA calculations. The general trend indicates that as the load increases the coefficient of friction decreases. Microstructure analysis using scanning electron microscope revealed adhesive wear and mild oxidation along the wear track. Porosity was also observed at various locations scattered along the wear track.

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1. Introduction

Direct metal deposition (DMD) is a rapid prototyping process used to repair and rebuild worn or damaged components, to manufacture new components, and to apply wear- and corrosion resistant coatings. DMD is a proprietary laser aided manufacturing (LAM) process. It consists of a closed-loop feedback control for the process, a coaxial nozzle with local shielding of melt pool and 5-axis moving optics for heavy parts. It is generally observed that porosity is one of the drawbacks in the volume of parts processed by DMD or other additive manufacturing technologies. These pores stem from process-induced defects originating from initial powder contamination, evaporation or local voids after powder-layer deposition. The increase in porosity leads to a decrease in corrosion resistance of the cladding metal. However, the corrosion resistance of the substrate metal is found to improve in comparison.

Guifang et al., 2015 DMD was used to form an AISI 4340 steel coating on an AISI 4140 steel substrate. The defect density and microstructural property of the DMD coating were analyzed. The defect density and microstructural property of the DMD coating were analyzed. The porosity ratio in the DMD coating was 3.3%, including voids and bonding defects. Stress relief reduces the elastic modulus of the as-deposited DMD coating from 237.5923 GPa to 206.296 GPa. Zhao et al., 2014 fabricated Ultra-fine Al–Si hypereutectic alloy by direct metal deposition of Silicon on 10 aluminum substrate at different scanning speeds and laser power. It was reported that, with increased scanning speed, the microhardness of deposition increases. Bhattacharya et al., 2011 in the studies on Cu–30Ni alloy was successfully laser deposited on a rolled C71500 plate substrate by Direct Metal Deposition technology. The microhardness of the clad was found to be less than the substrate but very consistent along the clad. Cu–30Ni clad specimen showed higher ultimate tensile strength but lower yield strength and percentage elongation as compared to the C71500 substrate. Zhang et al., 2011 studied the influences of laser DMD parameters and heat treatment on the microstructure, composition segregation and hardness of a deposited layer of Inconel 718 super alloy on an Inconel 718 high temperature alloy. The micro hardness of the laser DMD zone after heat treatment was higher than that after the as-deposited treatment. During the heat treatment process, some Nb- and Mo-rich phases precipitated and strengthened DMD layer. The optimal parameters recommended for the high build-up rate of Inconel 718 alloy were: actual laser power of 650 W, scanning speed of 5. 8 mm/s, beam diameter of 1 mm and a powder feed rate of 6.45 g/min, with a corresponding specific energy of 90-130 J/mm^2.

Khalid et al., 2012 investigated the thermal fatigue performance of direct metal deposited H13 tool steel coating on copper alloy substrate for high pressure die casting applications. The H13 tool steel, coated with 316 stainless steel showed much less number of cracks compared to the directly coated H13 tool steel indicating superior thermal fatigue resistance. Moreover the first layer of the directly coated H13 tool steel showed vulnerable behavior under high temperature application showing numerous cracks. The use of 316 SS buffer layer improved the thermal fatigue resistance of the coating. Dinda et al., 2009 conducted a study on microstructural evolution and thermal stability of Laser aided direct metal deposition of Inconel 625 super-alloy. The substrate used was Inconel 625 rolled plate. To assess the effect of different parameters such as laser power, powder feed rate and laser scanning speed on the microstructure, design of experiments based on L9 orthogonal array of Taguchi method was used. From the analysis it was found that Inconel 625 was stable material for laser deposition with a wider process window since it does not produce any defects. The maximum deposition rate was found to be in the sample which had maximum power, maximum feed rate and minimum scanning speed. Naiju et al., 2014 investigated the tribological behavior of the DMLS components for functional applications, reciprocating wear tests under lubricated condition were carried out. Taguchi's modified L9 orthogonal table was used to carry out the experiments. Temperature, load and hardness were the three parameters considered for the tests. It has been found that the applied load, one of the selected test parameters had more influence on lubricated wear as compared to other parameters.

Direct Metal Deposition reduces energy consumption in case of manufacturing products with low solid to volume ratio over conventional methods such as CNC milling. This is because DMD being an additive manufacturing process reduces the overall wastage of product as well as decreases tooling lead times by up to 35% when compared to conventional processes. The selection of design factors is the important stage for the design of experiments. There are many design factors such as load, speed, temperature, materials selected, sliding velocity, which will affect the test results wear rate. The key step in Taguchi method is to optimize the process parameter to achieve best quality performance. If the number of process parameter increases, there are lots of experiments have to be conducted to get the optimized parameter. To make the task easy, Taguchi method uses design of orthogonal arrays (OA) to study the process parameter with small number of experiments. An optimal combination of parameters that causes least amount of wear can be found out using Taguchi's orthogonal array and ANOVA technique.

This study concentrates on the effects of load, temperature and hardness on the reciprocating wear testing of DMD components under lubricated condition. The results of this study aims for a better product which can satisfy functional application. It was evident from the literature survey conducted that there was limited work done on the wear properties of DMD coated samples. So, this research work is aimed at analysing the wear properties of DMD coated samples.

2. Materials and Processing

2.1 Materials

DMD components were manufactured using DMD 105D machine using H13 tool steel. The substrate material was chosen as mild steel because of cost factor and easier availability. The coating material was H13 tool steel which well known for its excellent mechanical properties. These include high hardenability, excellent wear resistance, hot toughness and good thermal shock resistance. H13 coating of various thicknesses on mild steel sample was done by using direct metal deposition process. H13 tool steel also has excellent wear resistant properties and is extensively used in tooling and die applications.

2.2 Sintering process

In this study, the coating of H13 steel on the samples was done using DMD process. It consists of a closed-loop feedback control for the process, a coaxial nozzle with local shielding of melt pool and 5-axis moving optics for heavy parts. The metal powder is fed to the coaxial nozzle from the hopper. A metal melt pool is created by the laser and the metal powder fuses with the melt pool. Argon and helium mixture is used as both shaping and shielding gas. Charge-Coupled Device (CCD) cameras are used for closed loop feedback control of the process.

Nine test specimens of the size 30×30×10 were manufactured as per the CAD data using mild steel. EDM wire cutting was used for preparing the base sample components. These were cleaned carefully as per the standards for coating with H13 using DMD process. The photograph of the prepared samples is shown in Fig. 1.

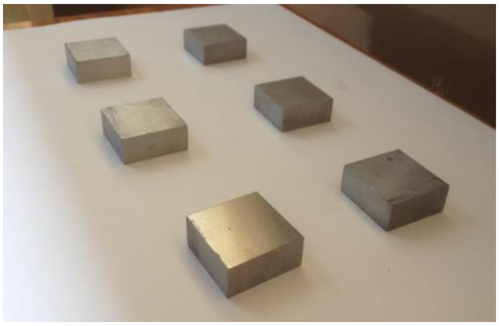

Fig. 1. Photograph of the substrate samples before coating

The 3-D CAD model for the coating is created in Solidworks® software and converted to stereolithography (STL) file and slicing. The laser path generation and numerical control (NC) file generation was generated using DMD-CAM software. Initially, a powder flow calibration test is done for the DMD105D machine to ensure that the powder delivery rate is accurate. For this purpose, the powder is made to flow into a container for a specific period of time which is then weighed. The experiment is repeated three to four times to reduce the error. If the observed value varies from the desired value, the flow parameters are altered accordingly. A Single track experiment is also carried out to examine and select the optimal process parameters. From the previous studies carried out at, these were found to be the optimal process parameters for the desired mechanical properties. The Table 1 presents the parameters used for deposition onto the substrate.

Table 1 DMD process parameters

Parameter	Value
Laser Used	Diode Laser
Laser Power	400W
Nozzle Standoff Distance	10 mm
Laser Scan speed	300 mm/min
Powder Flow rate	4.8g / min
Hatch spacing	0.15 M

The coating on the substrate was done at varying thicknesses of 0.5, 1.0 and 1.5 mm. The Fig. 2 presents the samples after H13 tool steel coating.

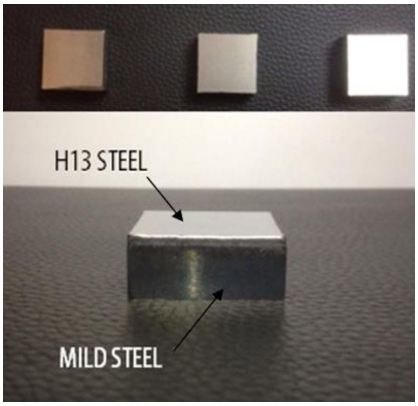

Fig.2. Photograph of Samples after coating

Grinding operation was carried out on the coated samples in order to reduce surface roughness to the value required for wear testing and also to improve surface finish.

3. Wear Testing

There are several parameters that can affect the wear. Load, temperature and thickness are the three main parameters which are considered here for the wear tests and the following parameters were varied accordingly depending on the runs. Here the H13 coated sample was made to wear against a wear testing steel ball of diameter 10mm under lubricated conditions. The lubricant used was commercially available 4T oil. The sample and the wear testing ball were mounted in their respective holders and verified for the proper alignment. Load and temperature of each sample were adjusted according to the experimental design. The actual tests of 9 runs were conducted for 2 hours. Fig. 3 shows the wear test setup.

Fig. 3. Wear Testing Machine

Samples were cleaned with acetone. The contact surface was covered with at least 5 ml of the selected lubricant and the specimens were fixed in their respective holders. Specimens were mounted in the testing machine and the specific alignment was verified. Heater was turned on and the temperature was adjusted accordingly. Load was raised to the desired test load. Test was run for the desired period of time and different parameters like friction force, wear, temperature etc. were monitored. After completing the test, specimens were allowed to cool with the load removed. Test specimens were removed and both contact surfaces were inspected. Specimen surface damage, including the dimensions of the wearing contact area were observed and recorded. The parameters that were used for wear testing and their respective range values are indicated in the Table 2.

Table 2. Working range of Parameters

Parameter	Range
Load	20-80N
Temperature	35-150ºC
Thickness	0.5-1.5mm
Duration	2 hrs

For carrying out the wear studies, nine experiments were carried out. The selected parameters for each experiment are shown in the Table 3.

Table 3. L9 Orthogonal Array

Sl. No	Thickness(mm)	Load (N)	Temperature (deg C)
1	0.5	50	100
2	0.5	20	35
3	0.5	80	150
4	1	20	100
5	1	50	150
6	1	80	35
7	1.5	20	150
8	1.5	50	35
9	1.5	80	100

The Table 4 indicates the average values of the coefficient of friction (COF) and friction force for the nine experiments that were conducted. The first digit of the three digit parameter indicates the coating thickness, the second digit indicates the load applied and the third digit indicates the temperature.

Table 4. Wear Testing Results

Parameter	**Experiments**								
	122	111	133	212	223	231	313	321	332
Average COF	0.143	0.204	0.129	0.2	0.149	0.111	0.249	0.166	0.122
Average Friction Force	6.976	4.15	10.253	3.988	7.25	9.027	5.363	8.231	9.876

From the below two plots it is inferred that as load increases, friction force also increases and co-efficient of friction decreases. From the Fig. 4, it is observed that the friction force increases as load increases which verifies the friction force law. From the Fig. 5 it is observed that the COF decreases as the load increases which is due to the formation of oxide layers.

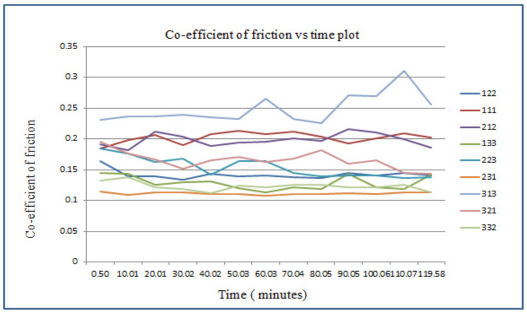

Fig. 4. Coefficient of Friction Vs Time

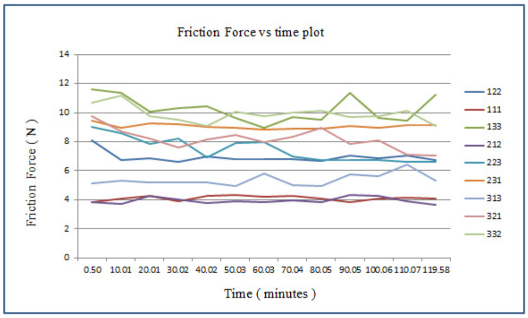

Fig. 5. Friction Force Vs Time Plot

4. Results and Discussion

The results were analyzed using Analysis of Variance (ANOVA) statistical method. The contribution of each factor to the wear behavior of components was determined. Average wear rate by each of the test parameters were calculated and are shown in Table 4. The influencing factors with their percentage contribution towards wear rate are tabulated. The table 7 represents the varying COF and average values for different levels of thickness, load and temperature which are used for further calculations.

Table 5 ANOVA table for Coefficient of friction

Factors	Level		Coefficient of friction			Average
			1	2	3	
Thickness	A1	0.500	0.129	0.143	0.204	0.159
	A2	1.000	0.111	0.150	0.200	0.154
	A3	1.500	0.122	0.166	0.250	0.180
Load	B1	20.000	0.250	0.204	0.200	0.218
	B2	50.000	0.166	0.150	0.143	0.153
	B3	80.000	0.129	0.122	0.111	0.121
Temperature	C1	35.000	0.111	0.166	0.204	0.161
	C2	100.000	0.122	0.143	0.200	0.155
	C3	150.000	0.129	0.150	0.250	0.176

From the Table 6 it is evident that load the most influencing parameter of COF while coating thickness and temperature are found to have minimal influence. The Table 7 presents the varying friction force and average values for different levels of thickness, load and temperature which are used for further calculations.

Table 6 ANOVA result table for coefficient of friction

Source	Sum of Square(SS)	Degree of Freedom(V)	Variance Ratio (SS/V)	% Contribution
Coating thickness (A)	0.0012	2	0.0006	7.28
Load (B)	0.0146	2	0.0073	89.02
Temperature(C)	0.0007	2	0.0003	3.7
Error for coating thickness(E_A)	0.0156	6	0.0026	
Error for load(E_B)	0.0053	6	0.0008	
Error for temperature(E_C)	0.0161	6	0.0028	
Mean(M)	0.2417	1	0.2417	
Total(T)	0.2585			

Table 7 ANOVA table for friction force

Factors	Level		2 Hours test at 10 Hz			Average
			1	2	3	
Thickness	A1	0.500	4.150	6.970	10.250	7.123
	A2	1.000	3.988	7.250	9.020	6.753
	A3	1.500	5.360	8.230	9.870	7.820
Load	B1	20.000	3.988	4.150	5.360	4.499
	B2	50.000	6.970	7.250	8.230	7.483
	B3	80.000	9.020	9.870	10.250	9.713
Temperature	C1	35.000	4.150	8.230	9.020	7.133
	C2	100.000	3.988	6.970	9.870	6.943
	C3	150.000	5.360	7.250	10.250	7.620

Table 8 ANOVA result for Friction force

Source	Sum of Square (SS)	Degree of Freedom(V)	Variance Ratio (SS/V)	% Contribution
Coating thickness(A)	1.761	2	0.881	4.04
Load (B)	41.063	2	20.531	94.28
Temperature(C)	0.732	2	0.365	1.68
Error for coating thickness(E_A)	42.095	6	7.015	
Error for load(E_B)	2.793	6	0.466	
Error for temperature(E_C)	43.124	6	7.187	
Mean(M)	470.716	1	470.716	
Total(T)	514.572			

Table 9 Wear testing result of as received H13 tool steel

Parameter	Value
Average COF	0.189
Average Friction Force	3.784 N

From the Table 8 it is evident that load is the most influencing parameter of friction force while coating thickness and temperature is found to have minimal influence. From the above results it is inferred that the load applied significantly affects the wear properties of H13 tool steel coating on mild steel samples. The average values of COF and friction force as given in the Table 9 are within the range of values obtained for various thicknesses of H13 coating on mild steel samples.

SEM Analysis

Fig. 6 presents the SEM images taken at the middle of the wear track with a magnification of 3000X and 5000X. Fig. 7 presents the SEM images taken with a magnification of 3000X at the left and right end of the wear track. From the above images, areas of oxide formation are found on the wear track. This oxide formation could affect the friction characteristics of the coating. The images also indicate regions of plastic flow, which confirms the excellent wear resistance of H13 steel. Pores are observed on the surface of the wear track which could have occurred due to improper fusion of the melt pool during DMD, due to entrapment of shielding gases or due to hydrogen or oxygen embrittlement.

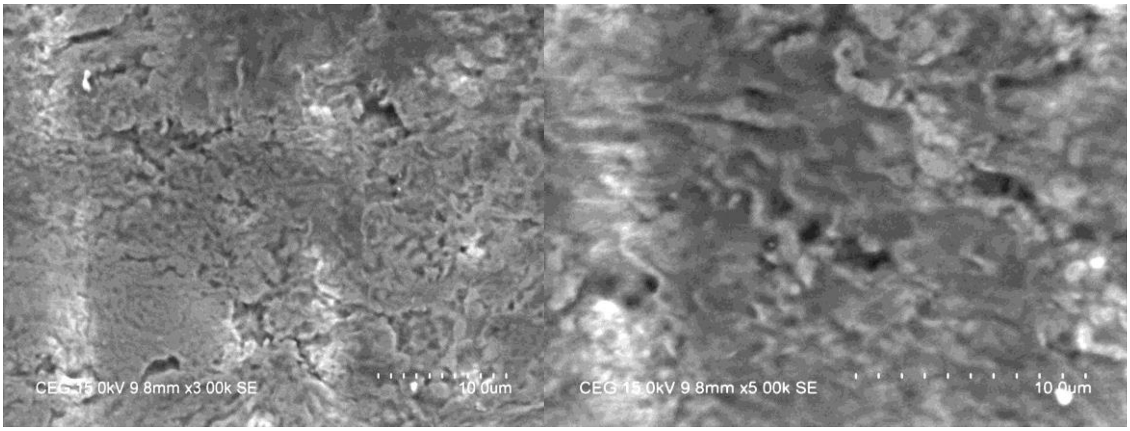

Fig. 6 SEM Image at the middle of the wear track 3000X and 5000X

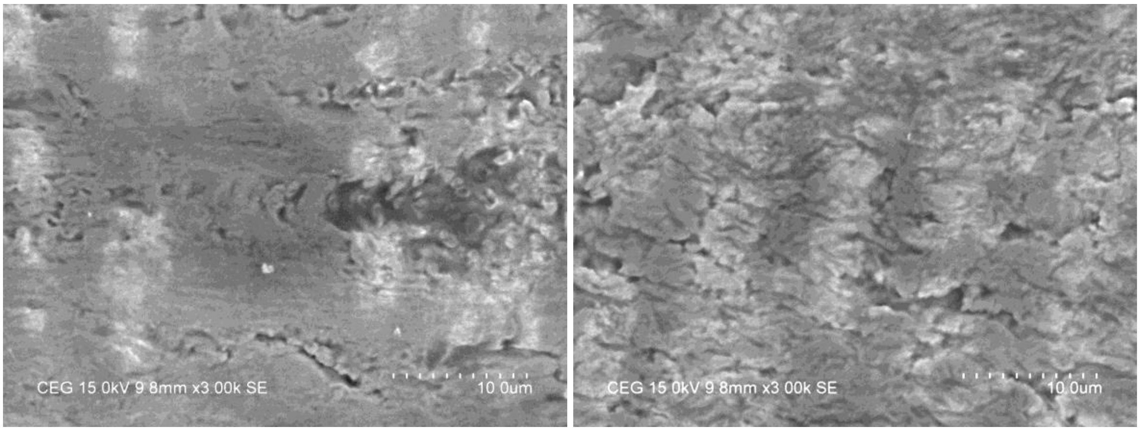

Fig. 7 SEM image at the right and left end of the wear track

During the interaction of the two surfaces atmospheric interaction causes oxides to be formed on the surface due to frictional heating. This may happen even with the presence of a lubricant. Small pieces of oxide film are flaked off due to continuous rubbing. The friction increases as this happens. While the contacting surfaces are sliding on the oxide films, the friction stays at a low level. If several pieces of debris are produced at the same time, the friction will rise to the top of the range. Since the normal load is low, the coefficient of friction will be comparably higher. The general trend observed is that as the normal load increases the proportion of oxide patches increases along the wear track. Furthermore, the metallic lustre that is observed at lower temperatures is lost at increased temperatures and loads. The amount of oxide layer formation substantially increases with elevation in temperature.

5. Conclusion

A study on the influence of operating parameters on the wear properties of the DMD components was performed. The results of the same were used to perform ANOVA to determine the individual influence of operating parameters on wear properties such as COF and friction force. Various other tests such as micro-hardness test and surface roughness measurements were also carried out.

From the study performed, it was observed that load was the major contributor to the wear properties while the other two parameters such as temperature and coating thickness have a relatively insignificant effect on wear. Thereby controlling the load, the wear on the material can be controlled.

From the SEM analysis, layers of oxide formation were found on the wear track. This oxide formation could affect the friction characteristics. Regions of plastic flow were also seen in the SEM images which indicate the excellent wear resistance of the H13 coating. From the wear analysis performed on as received H13 tool steel sample, it was observed that the average coefficient of friction was found to be low which indicates that rather than making functional components of H13 tool steel, a coating of the same on a cheaply available substrate would be more economically feasible.

Future studies on the influence of operating parameters on the wear properties of DMD components can be performed by selecting different parameters to study their individual influence on wear properties. The values of the process parameters could be varied more to get good results.

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References

[1] Guifang Sun, Rui Zhou, Jinzhong Lu, Jyotirmoy Mazumder. Evaluation of defect density, microstructure, residual stress, elastic modulus, hardness and strength of laser-deposited AISI 4340 steel. Acta Materialia 2015; 84: 172–189.

[2] Zhao LZ, Zhao MJ, Song LJ, Mazumder J. Ultra-fine Al–Si hypereutectic alloy fabricated by direct metal deposition. Materials and Design 2014; 56: 542–548.

[3] Bhattacharya S, Dinda GP, Dasgupta AK, Natu H, Dutta B, Mazumder J. Microstructural evolution and mechanical, and corrosion property evaluation of Cu–30Ni alloy formed by direct metal deposition process. Journal of Alloys and Compounds 2011; 509: 6364–6373.

[4] Zhang Qun-li, YAO Jian-hua, Jyoti Mazumder. Laser direct metal deposition technology and microstructure and composition segregation of inconel 718 superalloy. Journal of Iron and Steel Research, International 2011; 18:73-78.

[5] Khalid Imran M, Masood SH, Milan Brandt, Sudip Bhattacharya, Stefan Gulizia, Mahnaz Jahedi, Jyotirmoy Mazumder. Thermal fatigue behavior of direct metal deposited H13 tool steel coating on copper alloy substrate. Surface & Coatings Technology 2012; 206: 2572–2580.

[6] Dinda GP, Dasgupta AK, Mazumder J. Evolution of microstructure in laser deposited Al–11.28%Si alloy; Surface & Coatings Technology 2012; 206: 2152–2160.

[7] Naiju CD, Anil PM, Mohan Prashanth M, Karthik S. Investigations on the lubricated wear of direct metal laser sintered components for functional applications. ARPN Journal of Engineering and Applied Sciences 2014; 9:296-299.