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Optimization of laser melting parameter to enhanced surface properties in hot press forming die

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Abstract. This paper presents laser melting process with various parameter to enhanced surface properties of AISI H13 tool steel. The design of experiment (DOE) optimisation was conducted to obtain significant model using regression analysis. DOE were analysed using response surface method (RSM) with Box-Behnken design approach. Design Expert 7 software was used to design parameter of laser melting process. The laser melting processes was conducted using Nd:YAG laser system with pulsed mode at a constant average power of 100 W, overlapping rate of 30 to 50%, peak power of 1700 to 2500 W and pulse repetition frequency (PRF) of 50 to 70 Hz respectively. The responses were characterised for sub-surface hardness, melt depth and surface roughness. The results show that optimum parameter of 2500 W peak power, 60 Hz PRF and 30% overlapping rate produced highest surface hardness of 793.7 $HV_{0.1}$ with 0.21 mm melted depth and 3.89 µm surface roughness from experimental data. This finding was important to enhance properties of AISI H13 tool steel for hot press forming die using laser process.

Keywords: Laser Melting; DOE optimization; Processing Parameter.

1. Introduction

Laser process is preferable due to its high precision, localised surface melting and solidification. Laser modified surface have been shown to have enhanced hardness up to 4 times of the substrate due to grain refinement, secondary carbides and hard non-equilibrium microstructure formation [1, 2]. Control of laser parameter setting yields different effects on the modified surface properties [3]. Optimization of laser parameter is a very important factor to enhanced surface properties in laser surface modification due to cracking tendency at laser modified layer during laser surface melting process [4]. Control of overlapping laser spots yields different effects on the modified surface properties due to additional heating of melted layer. The laser power and scan speed or material-laser interaction time have previously been shown by the applicant to have a strong influence on the resultant temperature profile, modified microstructure, chemical composition, and modified layer depth [5]. Varied processing parameter such as scanning speed and laser power in similar based material produce different microstructure and microhardness [6].

Selection of proper processing parameter is necessary to prevent the high residual stress concentration [7]. Laser parameter play a crucial role in determining the microstructures and surface topography of alloyed zone [8]. To decrease the production time, high processing speeds should be aimed. Furthermore, the surface quality of generated parts has to be improve [9]. Combination of interaction time and power density essential to improve surface properties. Surface properties improved due to short interaction time with high power density caused grain structure refined [10]. Laser surface processing provides a unique tool for high precision surface modification using the heat source to enhance surface integrity of used die.

Major causes of die failures during operations are high thermal shock, mechanical strain, cyclic loading and corrosion which resulting in heat checking, wear, plastic deformation and fatigue [11-13]. Besides, during hot working processes the prolonged contact period between die surfaces and the working material leads to plastic deformation of the die along with the high pressure and temperature [14]. The high temperatures and cyclic loading caused the HPF dies surface to lose strength, hardness and lead to failure and reduce quality product produced from HPF process [11]. To obtained optimum production and reduce production cost, the properties on die surface such as hardness and thermal conductivity must be improved [15]. Die material require for higher hardness caused the typical hardness for dies today is in the range of 44 to 50 HRC. Increase the surface hardness of AISI H13 die is significant to endure wear at elevated temperature during applications [16]. In this study, surface of AISI H13 die insert were modified using laser melting process to improve die properties in hot press forming environment.

2. Experimental

A preliminary study was conducted to determine the lower and upper range of peak power, spot overlap and PRF prior to DOE development. Laser surface melting process was designed using Box-Behnken design with three factors. The Box-Behnken design used in this study to select the combination of factor level that produced optimal response with minimal numbers of experiment. Laser process was conducted at a constant average power of 100 W, spot overlap of 30 to 50%, peak power of 1700 to 2500 W and PRF of 50 to 70 Hz respectively. The responses were sub-surface hardness, melt depth and surface roughness which were analysed using response surface methodology (RSM). The RSM analysis was to select optimised parameters for laser melting of ASSAB 8407 (AISI H13) steel surface. Laser processing setup is shown by a schematic diagram in Figure 1. Hardness properties and melted depth of the sample were characterized using Wilson Hardness Tester. The surface roughness was measured using marSurfPS1 roughness tester.

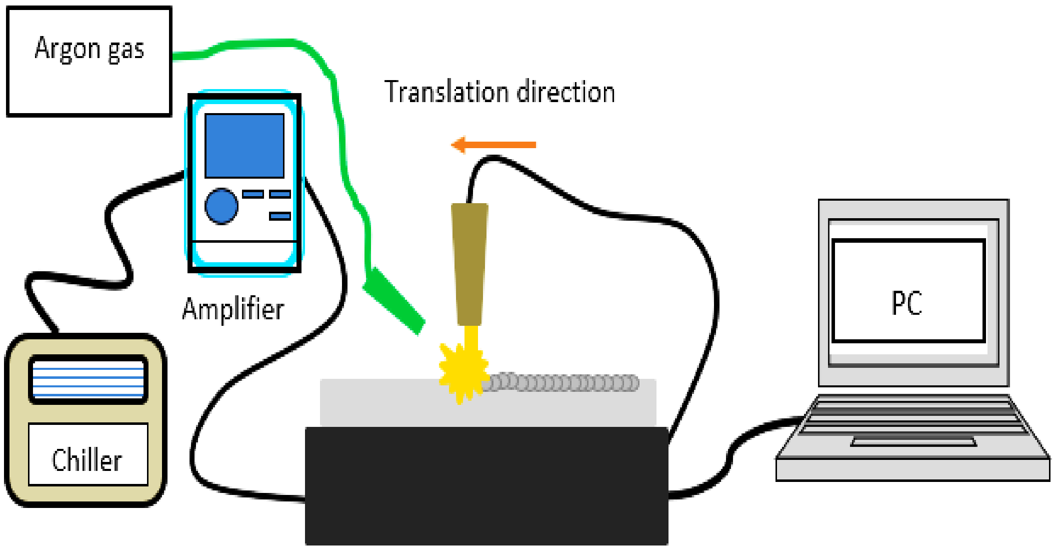

Figure 1. Schematic diagram of laser surface melting process setup.

Design of experiment (DOE) optimisation was conducted to obtain significant model using regression analysis. The model reduction using stepwise regression performed to get fit model with eliminates automatically insignificant term. The analysis variance (ANOVA) and optimisation were performed for hardness, roughness and melted depth response. The optimisation processes start with set desired goal of model factor and response. The goal for response were set to maximum for hardness, in range for roughness and minimize for melted depth. The lower and upper limit of factor and response was set and result for optimisation solution and desirability graph were displayed.

3. Result and discussion

Set of laser processing parameter were generated using Design Expert Software. The experimental data were analysed using response surface method (RSM) with Box-Behnken technique to analysed surface response on the melted surface. DOE analysis shows the effect of peak power, pulse repetition frequency (PRF) and overlapping percentage on hardness properties, surface roughness and melted depth of the samples. The five centre point was meant for obtaining a precise model and investigate random error of the model. The goal, limit and importance level for setting and outcome parameter from DOE are shown in Table 1. The goals of peak power, PRF, and overlapping rates were set within the appropriate range of is in range. The hardness properties goals were set to maximize, while melted depth was set to minimize and surface roughness set is in range. The importance level for factor parameters were set at Level 3 for all parameters. The importance levels of hardness were set at Level 5, while the roughness was set at Level 3 and melted depth was set at Level 2. The changes on the importance level would affect the desirable solution.

Table 1. Constrain selected in design optimization of laser melted processes.

Name	Goal	Lower Limit	Upper Limit	Lower Weight	Upper Weight	Importance
Peak Power	is in range	1700	2500	1	1	3
PRF	is in range	50	70	1	1	3
Overlapping rate	is in range	30	70	1	1	3
Hardness	maximize	684.4	793.7	1	1	5
Melted depth	minimize	0.10	0.33	1	1	2
Roughness	Is in range	1.89	5.20	1	1	3

Design solution in Table 2 shows 23 solution of parameter setting. The highest desirability factor was 0.847 and the lowest solution was 0.416. As for optimisation analysis, the surface hardness was set to maximum limit, while the surface roughness was set to in range limit, and melted depth set to minimize to ensure the highest hardness with better surface roughness after laser melting process. The prediction of setting parameters included peak power of 2500 W, PRF of 58.27 Hz, overlapping rate of 30% produce maximum surface hardness of 793.7 $HV_{0.1}$, roughness of 4.08 µm, and melted depth of 0.2 mm at the highest desirability factor of 0.847. Table 2 shown solution number 1 and 9 with peak power of 2500 W, PRF of 58.27 and 60.1 Hz with overlapping rate of 30% similar with parameter used during experimental process with (peak power of 2500, PRF of 60 Hz and overlap rate of 30%).

The generated optimal condition criteria in the desirability contour plot are shown in Figure 2. The desirability function served to optimise the experimental conditions for maximised surface hardness. The best combination of factors included peak power of 2500 W, PRF of 58.27 Hz, and overlapping rate of 30%. The plotted desirability contour graph of peak power and PRF at the overlapping rate of 30% revealed that desirability factor increased with the increase of peak power. The predicted desirability in the contour plot after model reduction recorded the value of 0.847. The contour plot of optimised surface hardness, melted depth and roughness of melted surface.

Table 2. Design solution for maximised surface hardness and melted depth.

Number	Peak power	PRF	Overlap rate	Hardness	Melted depth	Roughness	Desirability
1	2500.00	58.27	30.00	793.7	0.20	4.08	0.847
2	2496.63	58.18	30.00	793.7	0.20	4.08	0.846
3	2499.90	58.02	30.32	793.7	0.20	4.12	0.845
4	2500.00	57.80	30.61	793.7	0.20	4.16	0.844
5	2398.23	54.60	30.00	793.7	0.22	4.12	0.815
6	1864.27	70.00	30.00	773.2	0.14	2.10	0.812
7	1861.26	70.00	30.00	773.1	0.14	2.10	0.812
8	1850.11	70.00	30.00	772.7	0.14	2.08	0.812
9	2500.00	60.10	30.00	785.2	0.20	3.91	0.810
10	2496.75	53.34	30.00	814.2	0.23	4.48	0.795
11	2500.00	60.79	30.00	781.9	0.19	3.83	0.794
12	2184.03	68.95	30.00	765.2	0.18	2.63	0.715
13	1803.07	50.00	30.25	760.9	0.19	3.69	0.670
14	2076.59	50.00	30.00	770.4	0.23	3.70	0.666
15	1846.89	70.00	63.74	761.1	0.21	1.89	0.644
16	1886.24	70.00	65.18	761.5	0.21	1.89	0.643
17	1941.68	70.00	66.89	760.7	0.21	1.89	0.636
18	1750.79	70.00	53.49	752.0	0.18	2.17	0.623
19	2005.62	70.00	68.45	757.9	0.21	1.89	0.622
20	2009.76	70.00	68.53	757.7	0.21	1.89	0.620
21	2046.41	69.99	69.23	755.0	0.21	1.89	0.607
22	2500.00	51.74	61.33	762.5	0.25	4.53	0.581
23	2251.86	61.97	70.00	726.4	0.21	2.80	0.416

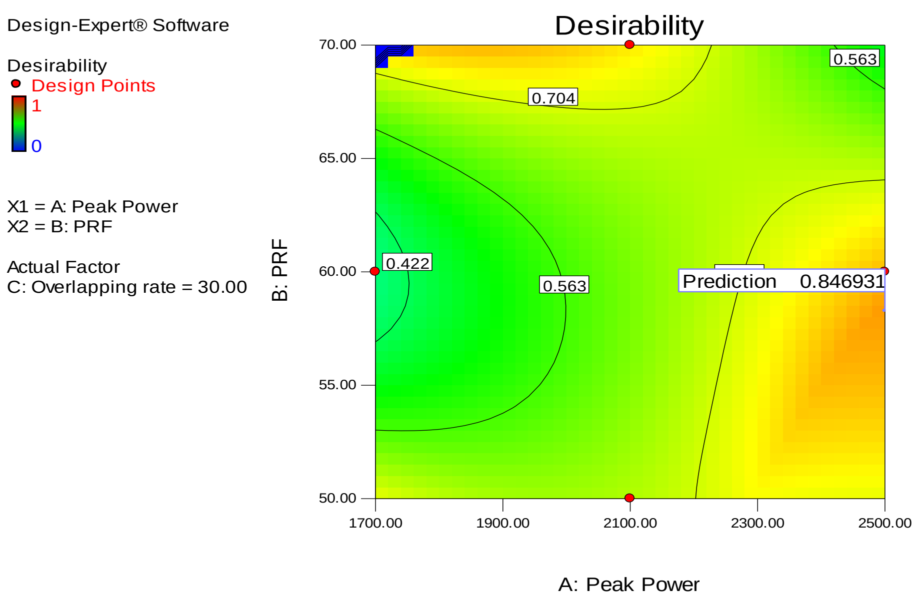

Figure 2. Desirability Contour plot of melted surface with highest desirability factor of 0.847.

Based on the result from DOE optimization of laser melted die insert, the optimum parameter of 2500 W peak power, 58.27 PRF and 30% overlapping rate with maximum surface hardness of 793.7 $HV_{0.1,}$ melted depth of 0.2 mm and 4.08 µm surface roughness with 0.847 desirability factor. While, the experimental data shown highest surface hardness were 793.7 $HV_{0.1}$ with 0.21 mm melted depth and 3.89 µm surface roughness using laser processing parameter of 2500 W peak power, 60 Hz PRF and 30% overlapping rate. The validation processes done to assess amount of the 95% confidence interval between the predicated value from DOE optimisation and experimental result. The 95% confidence interval for surface hardness and roughness was calculated by using the formula as shown;

$$95\%\ confidence\ interval = \frac{Predicted\ value - Actual\ value}{Predicted\ value} \times 100 \quad (1)$$

The amount of the 95% confidence interval between the predicated value from DOE optimisation and experimental at 2500 W peak power, 60 Hz PRF and 30% overlapping shown hardness of predicted value was 785.2 $HV_{0.1}$ while the experiment value was 793.7 $HV_{0.1}$ with 95% confidence interval of 1.1%. While the surface roughness value from experiment yield 3.89 mm and the predicted value was 3.91 with 0.5% of 95% confidence interval. It can be validated, that the laser parameter used can be produce the expected properties within the investigated range.

4. Conclusion

The response surface analysis was performed on the experimental data to examine the hardness, melted depth and roughness properties using Box-Behnken design which involved the quadratic model with model reduction (to improve the model). The box-Behnken analysis was used to identify the independent variables or factors that affect the process and product, and also to study the effects of dependent variables or responses. The optimisation analysis shows optimum laser parameter to produce suitable die insert for HPF process is at 2500 W peak power, 58.27 Hz PRF and 30% overlapping rate with higher surface hardness of 793.7 $HV_{0.1}$. These findings were important to produce optimum parameters for enhanced surface properties in laser melting process.

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