Designing Pulse Laser Surface Modification of H13 Steel using Response Surface Method

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Abstract. This paper presents a design of experiment (DOE) for laser surface modification process of AISI H13 tool steel in achieving the maximum hardness and minimum surface roughness at a range of modified layer depth. A Rofin DC-015 diffusion-cooled CO_2 slab laser was used to process AISI H13 tool steel samples. Samples of 10 mm diameter were sectioned to 100 mm length in order to process a predefined circumferential area. The parameters selected for examination were laser peak power, overlap percentage and pulse repetition frequency (PRF). The response surface method with Box-Behnken design approach in Design Expert 7 software was used to design the H13 laser surface modification process. Metallographic study and image analysis were done to measure the modified layer depth. The modified surface roughness was measured using two-dimensional surface profilometer. The correlation of the three laser processing parameters and the modified surface properties was specified by plotting three-dimensional graph. The hardness properties were tested at 981 mN force. From metallographic study, the laser modified surface depth was between 37 μm and 150 μm. The average surface roughness recorded from the 2D profilometry was at a minimum value of 1.8 μm. The maximum hardness achieved was between 728 and 905 $HV_{0.1}$.These findings are significant to modern development of hard coatings for wear resistant applications.

Keywords: AISI H13 tool steel, laser surface modification, hardness, surface roughness.

INTRODUCTION

In pulse laser surface processing, the laser modified surface mechanical and physical properties were controlled by several independent laser parameters namely; peak power, duty cycle, PRF and traverse speed [1, 2]. The pulse energy and laser-surface interaction time determined the temperature profile and also increased both width and depth of hardened surface [3]. In designing the laser surface processing, the pulse duration settings correspond linearly with the laser power to allow a range of heating rate at constant pulse energy. The pulse duration is the 'on' state period of the pulse, which was designed parallel with the sample traverse speed to determine the residence time. Therefore, the overlapped pulses can be achieved by designing the traverse speed. In previous work, the overlapped pulse was designed by increasing the PRF to obtain more pulses at fixed scan rate [3]. However, it was difficult to produce constant pulse energy at varied laser power when the overlap is dependant to PRF.

For most wear-resistant applications, high hardness and sound surface finish are crucial. For example, the allowable average surface roughness of high pressure die varied between 0.2 and 5.0 μm [4]. In previous work, samples processed by pulse laser exhibited lower surface roughness than samples processed using continuous wave mode [5]. However, in high energy beam processing, despite having excellent hardness surface properties, controlling the surface roughness is still a challenge [6]. This paper presents the laser surface modification of H13 tool steel design using response surface method to yield maximum surface hardness with minimum surface roughness at a range of layer depth. Laser peak power, PRF and overlap

were chosen as factors in the design of experiment to produce a constant average power of 274 W and three levels of pulse energy.

EXPERIMENTAL

The material used in this study was AISI H13 tool steel with 10 mm diameter. Chemical composition of the as-received H13 tool steel analysed using Inca X-Act and Microanalysis suit Oxford Instruments energy dispersive x-ray spectroscopy is shown in Table 1. A 1.5 kW Rofin DC-015 diffusion-cooled CO_2 slab laser with 90 µm spot size and TEM_{00} mode was used to process the samples. Energy coupling of the CO_2 laser with the surface of the samples was improved by increasing the sample surface roughness up to 3 µm and chemically treated prior to laser processing. Samples were attached to a rotating chuck which was in turn mounted on the x-y translation stage of the laser machine. The cylindrical rotating samples were moved on this translation stage with the laser spot focused onto the cylindrical surface such that the laser spot traced out a spiral path along the cylinder length.

TABLE 1. Chemical composition of AISI H13 tool steel

Element	C	Mn	Si	Cr	Ni	Mo	V	Cu	P	Si	Fe
weightt (%)	0.32-0.45	0.20-0.50	0.80-1.20	4.75-5.50	0.30	1.10-1.75	0.80-1.20	0.25	0.03	0.03	Bal.

TABLE 2. DOE of H13 tool steel laser surface modification process

Sample	Peak power (W)	PRF (Hz)	Overlap (%)
F1	760	2300	0
F2	1515	2300	0
F3	760	3500	0
F4	1515	3500	0
F5	760	2900	-10
F6	1515	2900	-10
F7	760	2900	+10
F8	1515	2900	+10
F9	1138	2300	-10
F10	1138	3500	-10
F11	1138	2300	+10
F12	1138	3500	+10
F13	1138	2900	0
F14	1138	2900	0
F15	1138	2900	0
F16	1138	2900	0
F17	1138	2900	0

The processing parameters were designed using the Design Expert 7 software. The response surface method with Box-Behnken design approach resulted in 17 runs of sample processing condition as shown in Table 2. Three parameters varied in the DOE were peak power, pulse overlap percentage and PRF. The duty cycle for each parameter condition was computed from the peak power to produce three different pulse energies of 0.8, 0.10 and 0.12 J. The duty cycles were 36, 24 and 18 % for 760 W, 1138 W and 1515 W respectively. The sample traverse speed range was from 188 to 350 mm/s and corresponding to PRF settings to produce overlaps.

Laser surface modified samples were prepared for metallographic study and surface profilometry. Metallographic study of transverse sections of processed cylindrical samples was conducted using EVO LS-15 scanning electron microscope (SEM) and Beuhler Omnimet

Enterprise image analyser software. The surface profile and average surface roughness, R_a, were measured using TR-200 two-dimensional stylus surface profilometer. The R_a was computed from five measurements. The modified layer hardness properties were measured using Leitz miniload tester with 981 mN force.

RESULTS AND DISCUSSION

The resulted laser modified layer maximum depth was between from 37 µm and 150 µm. Figure 1 shows the SEM micrographs of laser modified sample cross-section at 0.12 J pulse energy and four different residence times. At lower residence time of 0.079 ms, the peak power was at 1515 W which produced a modified layer depth of 72 µm. In Figure 1 (b) and (c), the resulted depths were 66 and 90 µm respectively due to 1138 W peak power at two different residence times. At lower peak power of 760 W and longer residence time, the modified layer depth was inconsistent with maximum and minimum depth of 150 and 50 µm respectively.

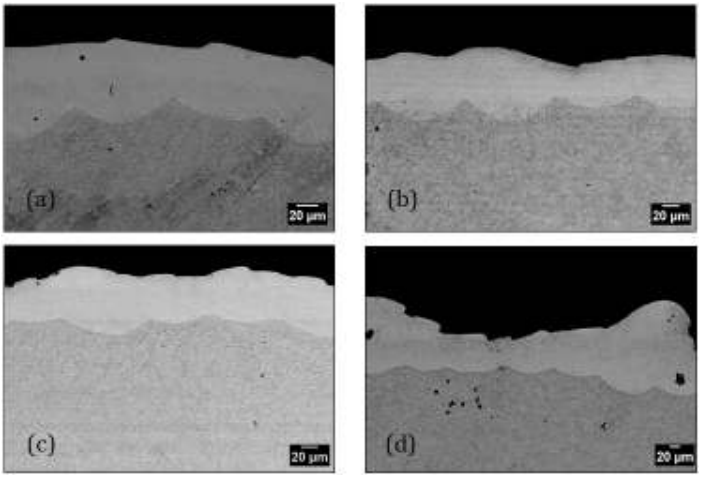

FIGURE 1. SEM micrographs of laser modified surface cross-section processed at 0.12 J pulse energy and residence time of (a) 0.079, (b) 0.094, (c) 0.115 and (d) 0.157 ms

The pulse energy resulted from laser power and pulse repetition frequency controlled the surface temperature. At higher pulse energy and residence time, the sample temperature raised which decreased sample surface reflectivity [7]. Though surface absorptance increased, the molten pool profile on the upper surface was irregular. The combination of high pulse energy and residence time resulted in a bulging geometry of modified layer. At longer residence time the molten pool was dragged by the stage translation due to increased surface temperature. At shorter residence time of 0.079 ms, the molten pool was self-quenched and solidified after each pulse. Whereas, at longer residence time of 0.157 ms the solidification delayed after several pulses due to heat sink formation on the surface which entrapped heat during processing.

The laser parameter and modified layer depth relationship was plotted in Figure 2. At 760 W peak power and 0 % overlap, the resulted modified layer range was between 131 and 150 µm. The maximum and minimum layer depth was both measured at 0 % overlap. The maximum layer depth was produced on samples processed at 760 W peak power and 2300 Hz PRF while the minimum layer depth was from sample processed 1515 W peak power and

3500 Hz. The layer depth increased at 2300 Hz PRF and 760 W peak power due to high pulse energy of 0.12 J and longer pulse duration settings. The highest frequency of 3500 Hz generated low pulse energy of 0.08 J while 1515 W peak power was designed with shorter pulse duration which further limited the energy penetration into sample surface. The combination of lower power and longer pulse duration, or higher power and shorter pulse duration was significant to melt the surface and maximise the modified layer depths at constant pulse energy.

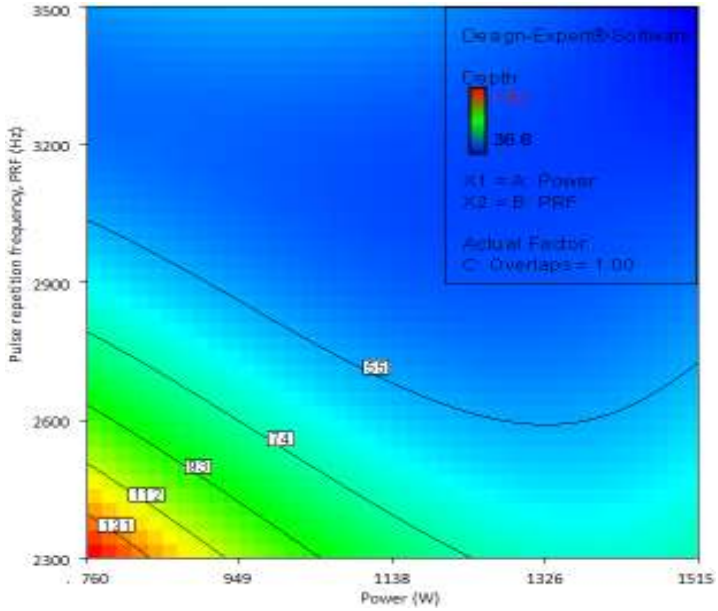

FIGURE 2. Pulse repetition frequency, laser power and modified layer depth relationship.

The average surface roughness, R_a, measured from laser modified samples was plotted on three-dimensional graph corresponding to peak power and PRF settings at -10 % overlap as shown in Figure 3. Out of 17 samples, 13 samples were measured with R_a of 5.0 µm and less. The minimum R_a of 1.8 µm was measured at -10 % overlap, 1138 W peak power and 3500 Hz PRF. At the lowest PRF and peak power, the R_a was at maximum due to bulging surface morphology produced. Lower pulse energy produced at PRF more than 3000 Hz coupled with peak power of 760 W or high pulse energy and 1138 W peak power combination exhibited minimum surface roughness. In Figure 4, the maximum hardness of modified layer was plotted against the laser PRF and overlap percentage settings. The maximum hardness measured was 905 $HV_{0.1}$ in sample processed at 1515 W peak power, 2300 Hz PRF and 0 % overlap. The minimum surface hardness was 728 $HV_{0.1}$, where sample was processed at 1138 W peak power, 3500 Hz PRF and -10 % overlap. At 1138 W peak power, the hardness increased with decreasing PRF and increasing overlap percentage.

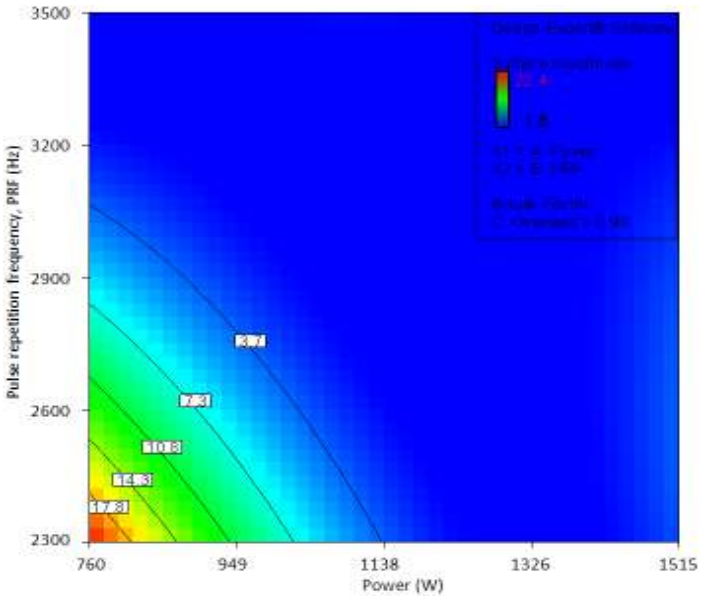

FIGURE 3. PRF, peak power and surface roughness relationship at -10 % overlap.

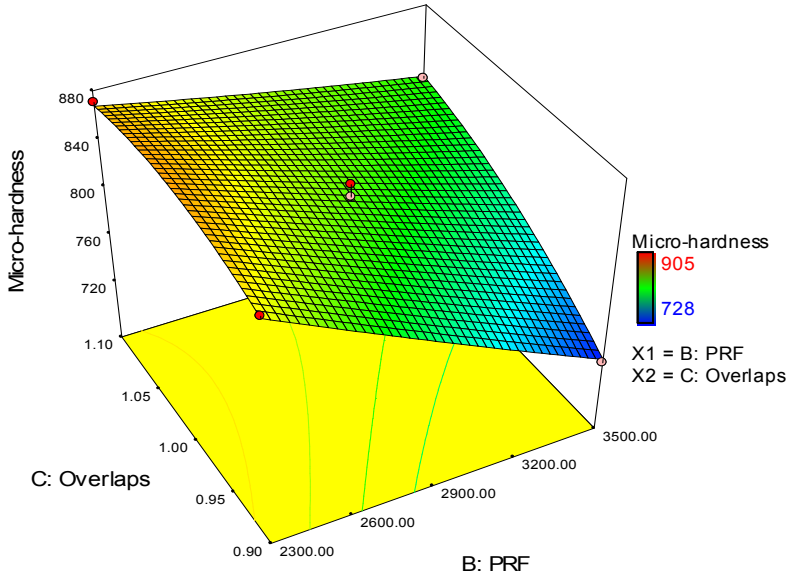

FIGURE 4. PRF, overlaps and micro-hardness relationship at 1138 W peak power.

In this design, the surface roughness decreased in samples processed at 0 % or -10 % overlap due to short residence time. The residence time or material-laser interaction time at -10 % overlap was shorter than the time computed at 10 % overlap due to changes in sample traverse speed. The residence time was computed from laser spot size, traverse speed and duty cycle. The resulted actual interaction time between laser and material surface during processing was decreased as the overlap decreased at constant peak power and PRF. Low PRFs tend to produce high pulse energies which roughened the surface at prolonged exposure to the laser energy [8, 9]. This explanation supports the surface roughness decreased with

increasing PRF and decreasing residence time. Rapidly melted and solidified H13 surface by high pulse energy yields smaller grain size in the modified layer that exhibit high hardness. Due to various possible laser parameter settings, the heating and cooling rate varied and resulted in a range of high hardness values between 728 and 905 HV. The maximum hardness was caused by rapid heating rate of surface using high pulse energy of 0.12 J which melted the surface at 0.079 ms residence time and consequently solidified at approximately at the same quick period. The minimum hardness was measured from sample processed at 0.08 J pulse energy and 0.060 ms residence time. Though the heating time was rapid, however the pulse energy might insufficient to increase the surface temperature and melt it within 0.060 ms period. Heating and cooling rates are significant values in laser surface modification in order to control the size of the microstructurally altered region and comply with the Hall-Petch relation.

CONCLUSION

The optimised processing parameter was designed at 1138 W peak power, 3500 Hz PRF and -10 % overlap to produce a hardened surface of 728 $HV_{0.1}$ with minimum average surface roughness of 1.8 μm and modified layer depth range between 42 and 50 μm. The parameter setting was selected from minimum surface roughness properties due to its importance in many engineering applications. The modified layer depth range at minimum surface roughness was also sufficient to act as a thermal barrier coating and protect the substrate. The hardness of sample processed at optimized parameter was 2.6 times higher than measured in the substrate. These findings are significant to the development of high hardness surface in dies application.

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